Available online at www.sciencedirect.com
ScienceDirect
LWT 40 (2007) 1000–1007
LWT
www.elsevier.com/locate/lwt

Influence of Refractance Window evaporation on quality of juices from small fruits

C.I. Nindo[a], J.R. Powers[b], J. Tang[a,*]

[a]Department of Biological Systems Engineering, Washington State University, Pullman WA 99164, USA
[b]Department of Food Science and Human Nutrition, Washington State University, Pullman WA 99164, USA

Received 7 February 2006; received in revised form 4 July 2006; accepted 7 July 2006

Abstract

A new type of evaporator (Refractance Window® (RW) evaporator) has been developed that operates at atmospheric conditions and uses thermal energy from hot water to concentrate foods. The influence of product temperature and dissolved solids on vitamin C in blueberry juice and color of cranberry juice was evaluated in this new evaporation method in comparison with conventional falling film multi-effect evaporators. During RW evaporation, vitamin C in blueberry juice was reduced by 32% and 48% with product temperatures at 55.5 and 59.0 °C, respectively. Concentration of the same juice from single strength to 65°Brix in an industrial falling film evaporator operating at 68 °C reduced vitamin C content by 70.1%. The color of cranberry juice, defined by the hue angle, was not significantly different between the concentrates from the RW and falling film evaporation methods. Further investigation is needed for complete insights into the mechanism for vitamin C loss in RW evaporation.

Keywords: Atmospheric evaporator; Blueberry and cranberry juice; Color; Ascorbic acid

1. Introduction

Several types of evaporators can be used for evaporating liquid foods. In choosing a particular type of evaporator, food quality, evaporation capacity, and energy/cost are major considerations. High-temperature short-time evaporation systems such as thermally accelerated short-time evaporators, where products are heated to a maximum temperature of 90–105 °C within a few seconds, are currently the preferred method in the citrus industry for concentrating heat-sensitive juices (Chen & Hernandez, 1997; Saravacos & Kostaropoulos, 2002). The juice processing industry also relies on recovery and returning of volatiles (or essence) to maintain the quality of juices after concentration in multi-effect (ME) falling film evaporators. Medium- to small-scale processors usually prefer batch recirculation-type evaporators because they cannot afford the large investments associated with ME evaporators that operate under vacuum. However, batch recirculation-type evaporators tend to expose liquid foods to high temperatures over long periods of time, resulting in low-quality products. This problem is worsened when fouling of evaporator surfaces occur because the fouling lowers the rate of heat transfer to the liquid product.

A new type of evaporator under consideration called the Refractance Window (RW) evaporator (Nindo, Tang, Powers, & Bolland, 2004) uses a plastic film with unique properties to facilitate heat transfer between the heating medium and liquid foods. The system utilizes circulating process water, usually at 95–98 °C, to convey thermal energy via a transparent plastic interface to concentrate fluid products that make several passes on the surface of the plastic sheet (Fig. 1). The evaporator can function either as stand-alone equipment or be used to pre-concentrate fluid foods before drying. The use of hot water to transfer thermal energy in this manner is unique to RW evaporation and product temperatures seldom exceed 70 °C due to evaporative cooling. The rapidly circulating process water increases the heat transfer co-efficient on the water–plastic side while a controlled inflow of cool air over the product exhausts the evaporated water. Since the

*Corresponding author. Fax: +1 509 335 2722.
E-mail address: jtang@mail.wsu.edu (J. Tang).

0023-6438/$30.00
doi:10.1016/j.lwt.2006.07.006

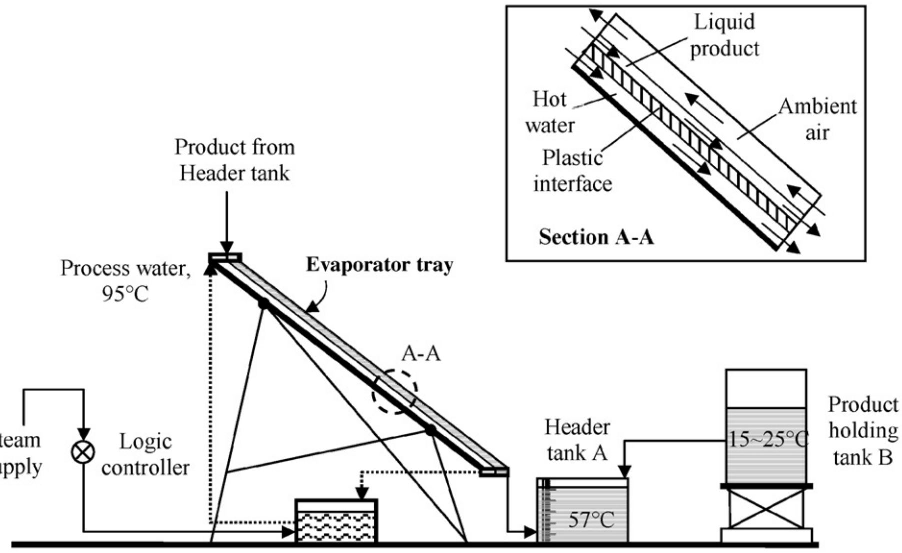

Fig. 1. Layout of Refractance Window® evaporator.

plastic sheet is very thin (approximately 0.2 mm) it reaches thermal equilibrium with the process water almost immediately. Thermal energy from the hot water is transmitted through it by conduction and radiation in proportions depending on the resistance it provides to these heat-transfer mechanisms. The plastic sheet made from Mylar® (DuPont Polyester Film Enterprise, Wilmington, DE) allows transmission of infrared energy with the wavelengths that match the absorption spectra of water molecules in liquid food. This infrared transmission is important because it enables rapid evaporation at low temperature and more than compensates for the low thermal conductivity of the plastic (0.155 W/mK compared to 15 W/mK for stainless steel).

Most foods contain nutrients that are easily lost or degraded during thermal processing and concentration by evaporation (Rodrigues et al., 2004). These nutritional changes vary with type of food, the process and the degree of control used. For certain concentrated foods, the color usually darkens because of high solid content and chemical changes, especially the Maillard reaction, which is influenced by changes in water activity (Rojas & Gerschenson, 2001). These changes are time–temperature dependent and, hence, from a food engineering perspective, short residence times and mild temperatures are necessary to produce concentrates with superior quality. Color, flavor, aroma, vitamin content, acidity, and soluble solids are frequently used to measure quality of fruit juices and purees (Stewart, 2005). The appealing color of most fruits and their derivative juices are due to anthocyanin pigments. Anthocyanin preservation in fruit juices is important because they contribute antioxidants that promote human health (Kalt, Forney, Martin, & Prior, 1999). Pectolytic enzymes preparations used in commercial juice processing to breakdown cell wall materials and improve juice yield sometimes contain glycosidase side activity, which degrade anthocyanin pigments into the unstable anthocyanidin form. This discoloration is more likely to happen if recommended dosage and treatment times are not followed closely (Höhn, Sun, & Nolle, 2005; Iversen, 1999). Skrede, Wrolstad, and Durst (2000) reported up to 50% loss of anthocyanin pigments during blueberry juice processing in a pilot study that followed a typical industrial process. The pectolytic enzyme activity was identified as a major cause of this anthocyanin destruction. Wrolstad (2000) also showed that anthocyanins are more stable at higher concentration and low water activity. Other than those studies on pigment destruction, no information was found on the loss of ascorbic acid during concentration of juices from small fruits.

The evaporation in juice processing involves tremendous exchange of thermal energy between process fluid and liquid product. This necessitates the design and optimization of processing conditions to reduce the potential impact on heat-sensitive compounds in foods. Change in juice color can be an indirect measure of break down of anthocyanin pigments while degradation of vitamin C would indicate the loss of nutritional quality (Lee & Chen, 1998). The objectives of this study were to investigate (a) the influence of a new evaporation method, the RW evaporator, on vitamin C in blueberry juice and color of cranberry juice in comparison with a conventional ME falling film evaporator; and (b) the effect of process water and product temperatures on evaporation rate.

2. Materials and methods

Experiments were carried out using blueberry juice containing dissolved solids between 11.4 and 14.1°Brix, and cranberry juice of approximately 6.5°Brix. These were commercial products purchased from a company that utilizes 4-effect APV falling film evaporators in its juice-processing scheme (Fig. 2). The scheme in Fig. 2 includes raw material reception, washing and maceration, heating

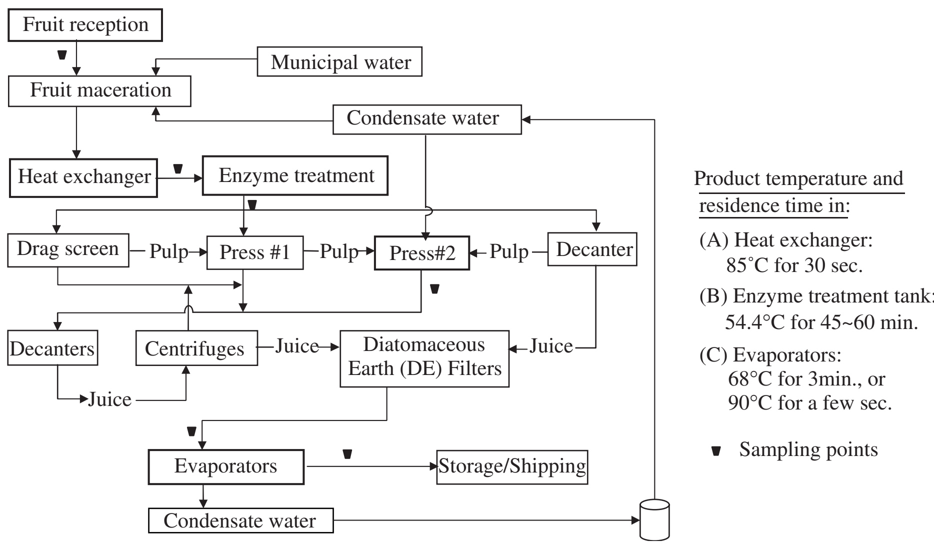

Fig. 2. Typical flow chart for industrial processing of juices from small fruits.

and enzyme treatment to enhance juice extraction, pressing, separation using decanters and centrifuges, filtration, concentration to required solids content, and packaging. Two replicate samples of blueberry juice were collected from six different processing stages as indicated in Fig. 2 and stored at −39 °C in 125 ml brown Nalgene® plastic bottles for later analysis.

The RW evaporation equipment (Fig. 1) was used for evaporation of cranberry and blueberry juices. A full-scale RW evaporator with a 6.9-m^2 evaporation surface tilted at 37° from the horizontal was used to concentrate cranberry juice while a pilot evaporator with one-sixth the surface area (1.2 m^2) and similarly tilted from the horizontal, was used for evaporating blueberry juice. Process water and product was circulated through the full-scale evaporator at 6.8 and 2.7 kg/s, respectively, with corresponding flows in the pilot equipment scaled down by about one-sixth. Other information on the performance characteristics of RW evaporator was reported previously (Nindo et al., 2004). The full-scale RW evaporator requires relatively large quantities of product to ensure that enough concentrated material remains in the system to keep the pump running. Both pilot- and full-scale evaporator experiments were initially planned to be conducted with blueberry juice. However, due to unavailability of adequate amount of blueberry juice, cranberry juice was used for experiments on the latter unit. The cranberry and blueberry juices needed for RW experiments were collected after the final filtration stage of the industrial processing protocol (Fig. 2) and packaged in 200- and 20-litre containers, respectively, before freezing at −39 °C. The materials were shipped to the experiment site in Tacoma (WA) in the frozen state then thawed for evaporation. The pilot-scale evaporator experiments were done at four process water temperature settings of 95.0, 92.2, 89.4, and 85.0 °C using approximately 62 kg of blueberry juice for each setting. The cranberry juice, on other hand, was divided into three

Table 1
Concentration of blueberry juice in pilot Refractance Window evaporator

Residence time (min)	Temperature (°C)			°Brix		Evaporation rate (kg/h)
	Water	Juice	LMTD[a]	Initial	Final	
100	95.0	59.0	35.7	14.1	66.0	30.8
103	92.2	57.0	34.7	11.4	66.5	27.8
105	92.2	57.6	34.3	13.8	70.0	29.1
106	89.4	56.3	32.6	11.5	70.6	29.6
105	89.4	56.6	32.3	13.0	68.6	28.8
114	85.0	55.5	29.8	13.8	66.3	26.5
104	85.0	54.8	29.8	12.0	67.5	27.1

[a]LMTD is log mean temperature difference defined in Eq. (2).

equal batches of about 324 kg each and concentrated on the full-scale RW evaporator with process water temperature set at 95 °C. While efforts were made to maintain this temperature throughout the experiments, fluctuations within 1.5 °C were observed on thermocouple readings taken at the outlet port. Cranberry juice was pumped into the evaporator from a small header tank with fresh liquid from a larger holding tank being added periodically. This was continued until all the juice in the holding tank was emptied into the header tank (Fig. 1). The pilot-scale evaporation experiment did not involve this periodic addition of fresh juice because it is designed for continuous operation with small quantity of starting material in a single tank. In both pilot- and full-scale setups, the liquid product was passed several times through the evaporator until the desired concentration was reached. The water temperature (Table 1) was controlled using a programmable logic controller with a type-T thermocouple connection to the inlet of the evaporator. Typical temperature profiles for product, process water and air streams during pilot- and full-scale evaporation are shown in Fig. 3. Juice samples for ascorbic acid analysis were

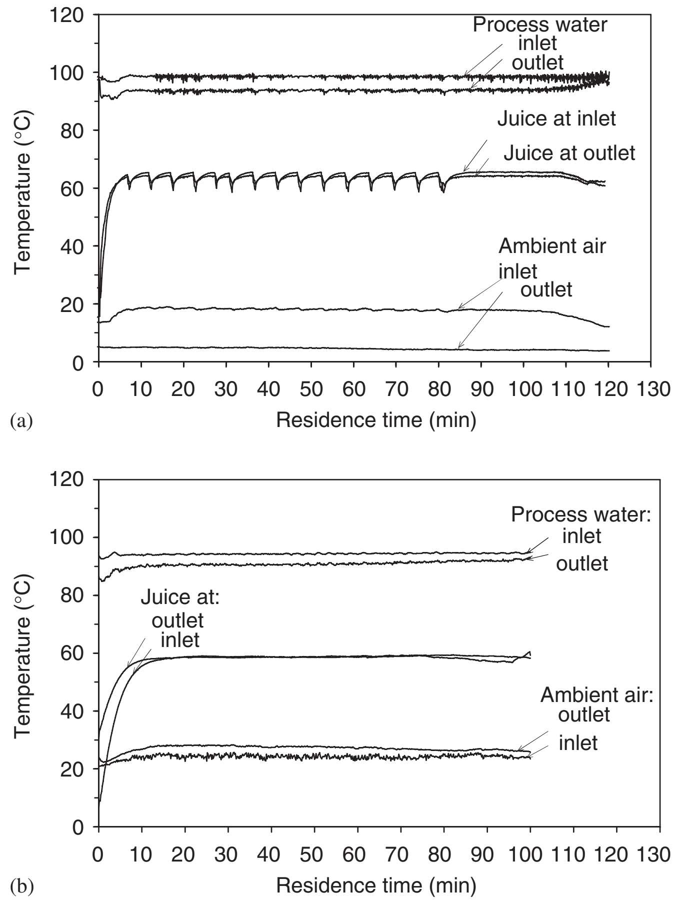

Fig. 3. Temperature profiles in Refractance Window evaporator during concentration of (a) cranberry juice in full-scale system, and (b) blueberry juice in the pilot system. Process water temperature was controlled at 95 °C in both cases.

collected from the header tank at different Brix levels, sealed in brown bottles, then cooled immediately in ice water before transferring to a −39 °C freezer.

Ascorbic acid content of samples was determined using a standard microfluorometric method (AOAC Int. 967.22, 1995). Twenty-gram juice samples were standardized to the same Brix and made up to 50 ml volume with 8% acetic acid/3% metaphosphoric acid extracting solution. The extract was oxidized with activated charcoal, filtered, and then reacted with *o*-phenylenediamine (Sigma-Aldrich, St. Louis, MO) to produce a fluorescent quinoxaline compound. The fluorescence was measured with a Flur-omax-3 spectrofluorometer (Jobin Yvon Inc., Edison, NJ) at 350 nm excitation and 430 nm emission wavelengths. Three (1.0, 2.0, and 4.0 mg/100 ml) ascorbic acid standards were prepared to determine the concentration of AA in blueberry juice. The juice color of cranberry juice, indicated by Hunter values L, a^*, and b^*, was measured using Minolta Chroma CR-200 color meter (Minolta Co., Osaka, Japan). Then, for easy comparison, hue angle ($\tan^{-1} b^*/a^*$) and total color change (ΔE) was calculated and plotted against Brix number.

3. Results and discussion

The relationship between process water and product temperature and their effect on evaporation rate are shown in Table 1. A previous investigation showed that evaporator tilt angle, product and process water flow rates and temperatures have an effect on evaporator capacity (Nindo et al., 2004). However, an issue of greater importance to food processors is how equipment design affects food nutrients and color. Therefore, the effect of progressive increase in juice Brix number and change in ascorbic acid and color are presented.

3.1. Effect of process water and product temperature on evaporation

Proper control of temperature of circulating water, referred to as process water, is crucial for smooth operation, improvement of system throughput, and for retention of heat-sensitive compounds in juice. If the process water temperature comes close to boiling point, vapor will fill the water–plastic side of the evaporator's heat exchange area and distort the flexible evaporation surface causing a reduction in the transfer of thermal energy to the liquid product. Fig. 3 represents typical temperature profiles of process water and products tested in the full-scale and pilot RW evaporators. Alternating rise and fall in juice temperature profile in a full-scale RW evaporator (Fig. 3a) is due to periodic mixing of low-temperature juice from holding tank with juice in the evaporator that has attained a specific evaporation temperature. The evaporation rate decreases in the phase where juice mixing occurs because extra energy is used for sensible heating of the fresh juice. As opposed to the full-scale evaporator, the cyclic rise and fall in product temperature profile was not experienced in the pilot-scale evaporator because it was operated continuously with juice moving in and out of one tank (Fig. 3b).

A linear relationship was obtained between the temperature of product and that of process water when the latter was properly controlled within the temperature limits investigated (Table 1). The product temperature remained fairly constant so long as the flow of air within the system was constant. The process water vs. product temperature relationship (Eq. (1)) had R^2 of 0.97:

$$T_{\mathrm{p}} = 0.3534(T_{\mathrm{w}}) + 25.2, \qquad (1)$$

where T is the temperature (°C) while subscripts p and w represent product and process water, respectively. Therefore, controlling the water temperature should be a good way of maintaining the product temperature at a desired level. However, the product vs. process water temperature model may only be used for conditions within the limits of temperatures investigated.

The evaporator capacity (the amount of water evaporated per hour) is also affected by magnitude of logarithmic mean temperature difference (LMTD) defined as

$$\mathrm{LMTD} = \frac{\Delta T_{\mathrm{in}} - \Delta T_{\mathrm{out}}}{\ln\left(\Delta T_{\mathrm{in}}/\Delta T_{\mathrm{out}}\right)}, \tag{2}$$

where ΔT_{in} and ΔT_{out} are temperature differences between process water and liquid product at the evaporator inlet and outlet, respectively. With the RW evaporation system regarded as a heat exchanger operating within defined temperature limits, a higher evaporation potential (LMTD) should theoretically result in a higher rate of evaporation (Table 1). Due to a shortage of blueberry juice needed for the experiments, the data in Table 1 were inadequate for a statistical analysis, but nonetheless are important in showing the effect of process water temperature on evaporation rate. Nindo et al. (2004) previously gave more detailed information on the effect of varying process water flow rate and temperature and product flow rate on thermal energy exchange during RW evaporation.

3.2. Effect of dissolved solids and residence time on evaporation

The rate of cranberry juice evaporation in the full-scale RW evaporator as a function of Brix number and the reduction in water content (M/M_{o}) in relation to juice residence time in evaporator are illustrated in Figs. 4a and b, respectively. It is observed that the rate of evaporation was very high initially then gradually decreased as solids content increased. This behavior is expected because the solid matrix binds the water molecules tightly while the product becomes more viscous due to an increase in sugar concentration. However, the cyclic mixing of product previously described for the full-scale evaporator results in an initial drop followed by a rise in evaporation rate at the point where the influx of low temperature juice into the system is ended. The product temperature also stabilized after addition of fresh juice was stopped (Fig. 3a).

The average evaporation rates for cranberry juice in experiments 1, 2, and 3 conducted on the full-scale evaporator were 110, 134, and 144 kg/h, respectively. With respect to evaporation surface area, the rates corresponded to 16.6, 20.2, and 21.7 kg/h m^2, respectively. To increase and maintain the evaporation rate at a high level, it may be advantageous to pre-heat the juice in the holding tank to avoid the temperature depression that occurs when fresh juice is mixed with the 'in-process' juice that has already attained the evaporation temperature. The evaporation rate constant, given by the slope of log (M/M_{o}) against the time of evaporation, increased almost fivefold after pumping low Brix fresh juice from the holding tank was stopped. In stage I (Fig. 4b), the rate constant was 0.012 ($\pm$0.002) min^{-1} compared to 0.058 ($\pm$0.006) min^{-1} for stage II. Therefore, pre-heating the feed can potentially lead to improvements in throughput and evaporation efficiency. Even though the same quantity of juice was used in each of the three experimental runs, fluctuations in process water temperature may have contributed to the observed differences in residence times (Fig. 4b).

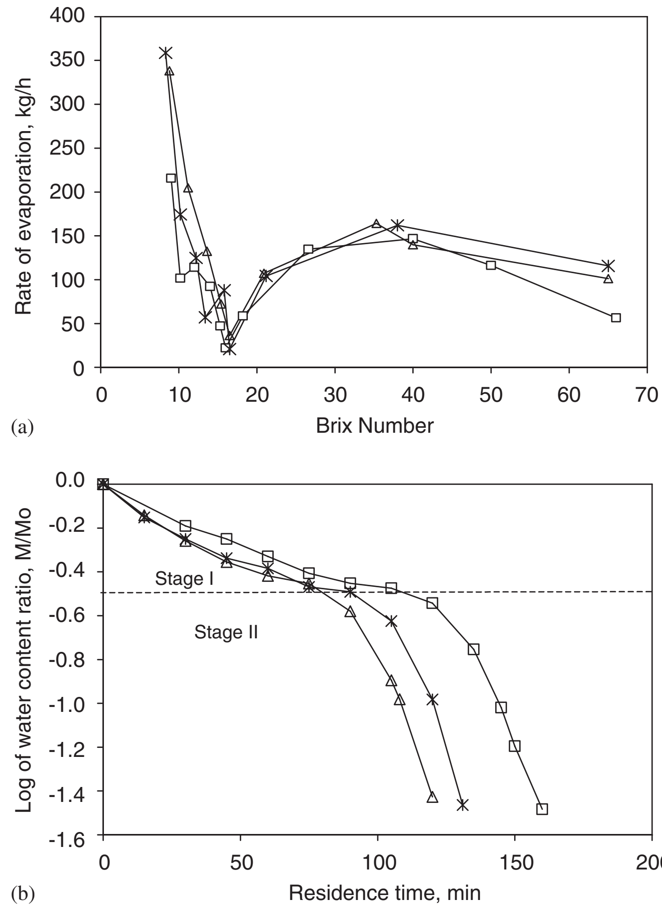

Fig. 4. Experiments #1 (□), #2 (∗), and #3 (Δ) showing (a) evaporation rate vs. Brix number, and (b) log of water content ratio against residence time of cranberry juice in full-scale RW evaporator. Horizontal line in (b) indicates transition from stage I where fresh juice is mixed with 'in-process' juice to stage II with no such inflow.

4. Influence of evaporation on quality of berry juices

4.1. Effect of industrial falling film evaporation on ascorbic acid content

Industrial juice processing stages, including raw fruit maceration, heating, depectinization, enzyme treatment, filtration, and final concentration of juice to 65°Brix caused over 90% reduction in ascorbic acid initially present in blueberries (Fig. 5). Even though some reduction in ascorbic acid may have occurred between the time of sampling and analysis, the trend in Fig. 5 reflects the influence of each processing stage. Based on the concentration of AA remaining in the juice at each stage, the evaporation stage resulted in 70.1% loss compared to 44.1%, 39.3% and 44.7% losses that occurred during maceration and heat treatment, enzyme treatment, and filtration processes, respectively. To meet the recommended nutrition standards, the AA lost after evaporation

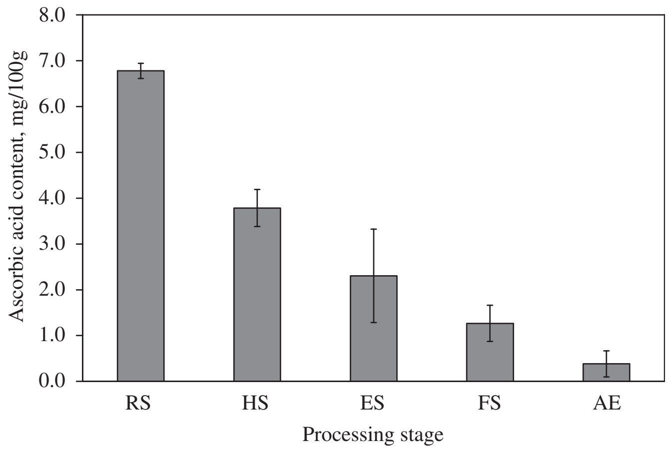

Fig. 5. Ascorbic acid content of blueberry juice from industrial processing: raw (RS), heat-treated (HS), enzyme-treated (ES), filtered (FS), and evaporated (AE) sample.

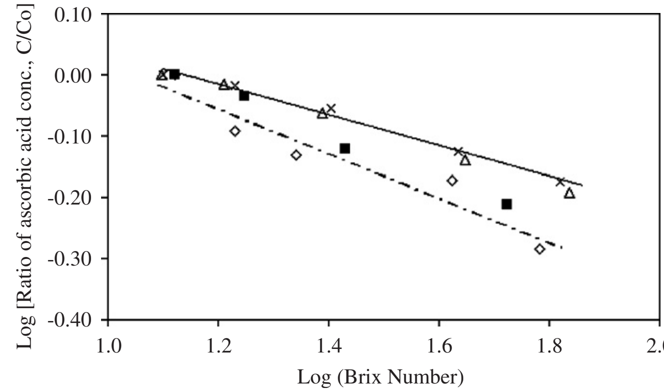

Fig. 6. Ascorbic acid content vs. Brix number of blueberry juice during RW evaporation with data points representing average of two replicate tests at 59.0 °C (◇), 57.5 °C (■), 57.0 °C (Δ), and 55.5 °C (×). The continuous and dotted lines are respective model fits at 55.5 and 59.0 °C using Eq. (3).

is normally replenished by fortifying juices. Apart from the heat labile ascorbic acid, volatile compounds in extracted juice are usually lost within the first few minutes of evaporation. The standard industry practice involves stripping the volatiles and either returning them into the concentrate or selling separately.

4.2. Effect of RW evaporation on ascorbic acid content of blueberry juice

When blueberry juice was concentrated in the RW evaporator, a progressive decline in the amount of ascorbic acid was noted. Fig. 6 shows the change in ascorbic acid concentration vs. Brix number at four different heating water temperatures (95.0, 92.2, 89.4, and 85.0 °C). The corresponding product temperatures were 59.0, 57.5, 57.0, and 55.5 °C, respectively. Since the juice used at the start of each experiment had slightly different concentrations of AA, the ratio of ascorbic acid concentration C/C_0 is used as a convenient way to investigate the effect of Brix number and temperature on AA. At the beginning of the process when $t = 0$, the ratio C/C_0 is equal to 1. This ratio showed a general decrease with Brix number according to the relationship:

$$C/C_0 = A(^\circ\text{Brix})^n, \tag{3}$$

where A and n are fitting parameters. The co-efficient A decreased from 2.41 to 1.93 while the exponent n increased from -0.366 to -0.250 when the product temperature decreased from 59.0 to 55.5 °C. The co-efficient of determination (R^2) at the four product temperatures was between 0.92 and 0.99 (Fig. 6). More ascorbic acid was lost at higher product temperatures. For example, only 52.4% of AA in blueberry juice concentrated to 65Brix at a temperature of 59.0 °C was retained compared to 67.8% for juice concentrated at 55.5 °C. The power index n decreased linearly with temperature of product (Eq. (4)):

$$n = -0.034(T) + 10.76, \quad R^2 = 0.73, \tag{4}$$

where T is the product temperature (°K).

Loss of ascorbic acid during thermal process is generally considered to follow a first-order kinetic relationship (Vieira, Teixeira, & Silva, 2000; Vikram, Ramesh, & Prapulla, 2005):

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -kC, \tag{5a}$$

where C is the concentration of nutrient at any time (t, min) and k is the reaction rate (min^{-1}). If C_0 is initial concentration of ascorbic acid, then integration of Eq. (5a) yields

$$C/C_0 = \exp(-kt). \tag{5b}$$

Therefore,

$$\text{Log}(C/C_0) = \frac{-kt}{2.304}. \tag{5c}$$

The reaction rate k, represented by the slope of log (C/C_0) vs. residence time (Fig. 7), varied from 0.003 min^{-1} at 55.5 °C to 0.006 min^{-1} at 59.0 °C with R^2 values between 0.90 and 0.97. This rate increase cannot be attributed to change in temperature alone, since the concentration of dissolved solids also increases during evaporation. However, Esq. (3) and (5) are useful for explaining the influence of both temperature and Brix number on loss of ascorbic acid during RW evaporation. Using the reaction rates calculated with Esq. (5c), the residuals of C/C_0 were plotted against time (Fig. 8). The errors from these plots are less than 10%, though positively skewed between 15 and 25Brix. This skew ness may be due to inadequate mixing and sampling of juice with different residence times in the evaporator. It is also worth noting that the rate constants for ascorbic acid loss are lower than those for water removal. Further investigation is necessary to validate these

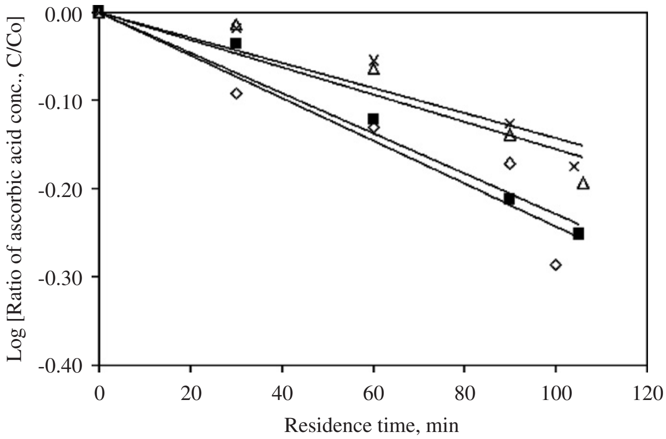

Fig. 7. Kinetics of ascorbic acid degradation during RW evaporation of blueberry juice with each data point representing the average of two replicate tests at 59 °C (◇), 57.5 °C (■), 57.0 °C (Δ), and 55.5 °C (×).

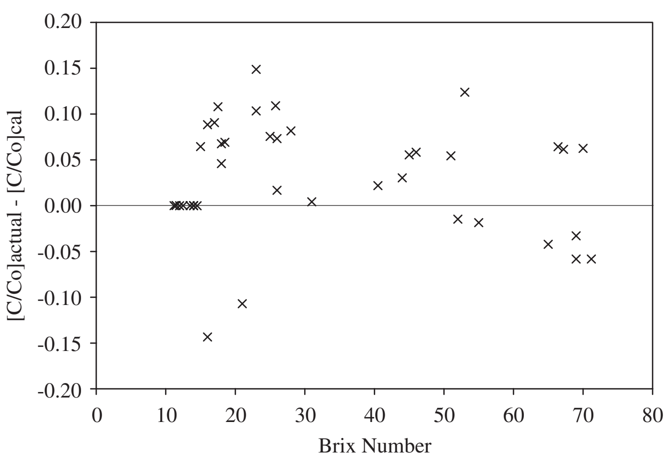

Fig. 8. Residual plots of concentration ratio of ascorbic acid vs. Brix number.

results by collecting and analysing evaporation rate and ascorbic acid loss data over the widest product temperature range that can be achieved with this evaporator.

4.3. Effect of RW evaporation on color of cranberry juice

The single strength cranberry juice showed a very intense red color. Both the redness and yellowness parameters changed remarkably as the juice Bricks number increased from 6 to 26 during RW evaporation (Fig. 9a). Thereafter, both redness (a^*) and yellowness (b^*) continued to decrease, but rather gradually. As was expected, the lightness (L) also decreased with increase in Bricks number (data not shown). The total color difference delta $E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2}$ with subscript—0, indicating color of single strength juice, increased from 1.7 to 22.8 when the cranberry juice was concentrated from 6Brix to 65Brix. The RW evaporated and the industrially processed cranberry juice had comparable hue angle of

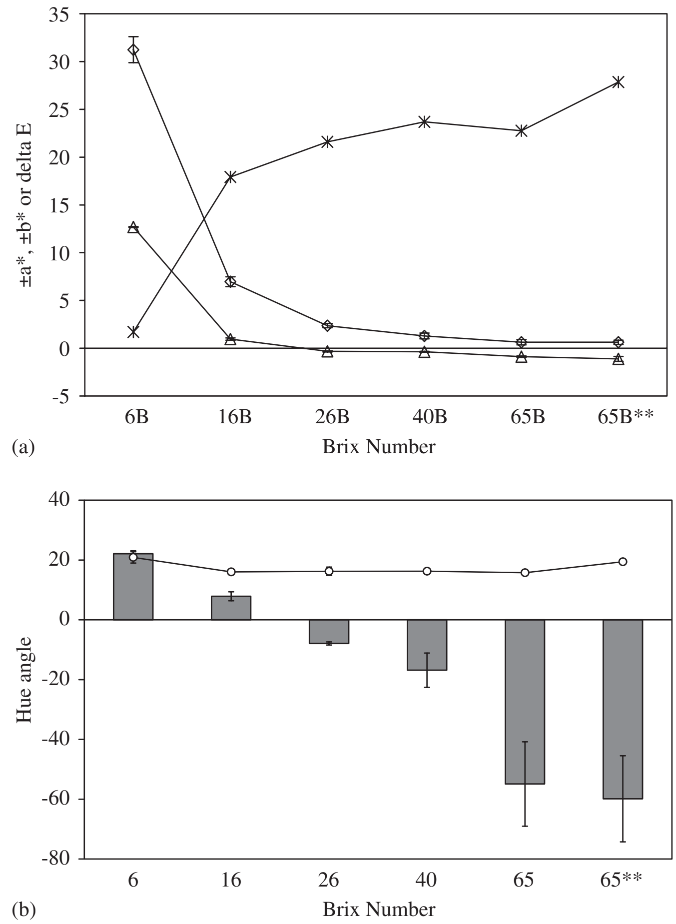

Fig. 9. Change in color of cranberry juice during pilot-scale RW evaporation. (a) Redness/greenness (◇), yellowness/blueness (Δ), and total color change (∗) vs. Brix number, (b) hue angle vs. Brix number before (bar chart) and after (○) dilution of juice to 6Brix. **Indicates sample from industrial process.

about 60° at 65Brix (Fig. 9b). It is interesting to note that when the juice samples initially containing high amounts of dissolved solids were reconstituted with de-ionized water back to 6Brix, the resulting hue angles were nearly the same. The implication of this is that color alone may not be sufficient for distinguishing RW and industrially evaporated cranberry juice.

5. Conclusion

The influence of temperature, residence time, and concentration of dissolved solids on ascorbic acid content and color of blueberry and cranberry juices during RW evaporation were investigated to provide a better understanding of the process. A well-controlled process water temperature is very important for smooth and efficient operation of the system. When the process water temperature in a pilot evaporator was increased from 85 to 95 °C, corresponding to product temperature increase from 55.5 to 59.0 °C, a 16% increase in the evaporation rate (26.8–31.1 kg/h) was observed. The reaction rate for ascorbic acid loss increased from 0.003 to 0.006 min^{-1}.

Both RW and industrial evaporation processes caused substantial degradation of ascorbic acid and a general change in color from intense red to bluer products. Hue angle and total color difference for cranberry juice changed from +21 to −55 and 1.7 to 22.8 after RW evaporation from single strength to 65Brix, respectively. Dilution of RW and falling film cranberry juice concentrates to 6Brix did not show significant differences in hue angle.

Acknowledgements

This research was conducted with grant support from Washington Technology Center and Washington State Agricultural Research Center. Mention of RW® as model evaporation equipment does not imply its endorsement by the authors over other evaporators designed to perform similar function.

References

AOAC. (1995). *Official methods of analysis* (16th ed). Washington, DC: Association of Official Analytical Chemists.

Chen, C. S., & Hernandez, E. (1997). Design and performance evaluation of evaporation. In K. J. Valentas, E. Rotstein, & R. P. Singh (Eds.), *Handbook of food engineering practice* (pp. 211–251). Boca Raton, FL: CRC Press.

Höhn, A., Sun, D., & Nolle, F. (2005). Enzymes in the fruit juice and wine industry. In D. M. Barrett, L. Somogyi, & H. Ramaswamy (Eds.), *Processing fruits: Science and technology* (pp. 97–112). Boca Raton, FL: CRC Press.

Iversen, C. K. (1999). Black currant nectar: Effect of processing and storage on anthocyanin and ascorbic acid. *Journal of Food Science*, *64*, 37–41.

Kalt, W., Forney, C. F., Martin, A., & Prior, R. L. (1999). Antioxidant capacity, vitamin C, phenolics, and anthocyanins after fresh storage of small fruits. *Journal of Agricultural Food Chemistry*, *47*, 4638–4644.

Lee, H. S., & Chen, C. S. (1998). Rates of vitamin C loss and discoloration in clear orange juice concentrate during storage at temperatures of 4–24 °C. *Journal of Agricultural Food Chemistry*, *46*, 4723–4727.

Nindo, C. I., Tang, J., Powers, J. R., & Bolland, K. (2004). Energy consumption during Refractance Window evaporation of selected berry juices. *International Journal of Energy Research*, *28*, 1089–1100.

Rodrigues, R. B., Menezes, H. C., Cabral, L. M. C., Dornier, M., Rios, G. M., & Reynes, M. (2004). Evaluation of reverse osmosis and osmotic evaporation to concentrate camu-camu juice (*Myrciaria dubia*). *Journal of Food Engineering*, *63*, 97–102.

Rojas, A. M., & Gerschenson, L. N. (2001). Ascorbic acid destruction in aqueous model food systems: An additional discussion. *Journal of Science of Food and Agriculture*, *81*, 1433–1439.

Saravacos, G. D., & Kostaropoulos, A. E. (Eds.). (2002). *Handbook of food processing equipment* (p. 313). New York, NY: Kluwer Academic/Plenum.

Skrede, G., Wrolstad, R. E., & Durst, R. W. (2000). Changes in anthocyanins and polyphenolics during juice processing of highbush blueberries (*Vaccinium corymbosum, L.*). *Journal of Food Science*, *65*, 357–364.

Stewart, K. (2005). Processing of cranberry, blueberry, currant, and gooseberry. In D. M. Barrett, L. Somogyi, & H. Ramaswamy (Eds.), *Processing fruits: Science and technology* (pp. 563–584). Boca Raton, FL: CRC Press.

Vieira, M. C., Teixeira, A. A., & Silva, C. L. M. (2000). Mathematical modeling of thermal degradation kinetics of vitamin C in cupuacu (*Theobroma grandiflorum*) nectar. *Journal of Food Engineering*, *43*, 1–7.

Vikram, V. B., Ramesh, M. N., & Prapulla, S. G. (2005). Thermal degradation kinetics of nutrients in orange juice heated by electromagnetic and conventional methods. *Journal of Food Engineering*, *69*, 31–40.

Wrolstad, R. E. (2000). Anthocyanins. In G. J. Lauro, & F. J. Francis (Eds.), *Natural food colorants: Science and technology* (pp. 237–252). New York, NY: Mercel Dekker.