Energy consumption during Refractance Window® evaporation of selected berry juices

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SUMMARY

The Refractance Window® evaporator represents a novel concept in the design of evaporation systems for small food processing plants. In this system thermal energy from circulating hot water is transmitted through a plastic sheet to evaporate water from a liquid product flowing concurrently on the top surface of the plastic. The objectives of this study were to investigate the heat transfer characteristics of this evaporator, determine its energy consumption, and capacity at different tilt angles and product flow rates. The system performance was evaluated with tap water, raspberry juice, and blueberry juice and puree as feed. With a direct steam injection heating method, the steam economy ranged from 0.64 to 0.84, while the overall heat transfer coefficient (U) was 666 W m⁻² °C⁻¹. Under this condition, the highest evaporation capacity was 27.1 kg h⁻¹ m⁻² for blueberry juice and 31.8 kg h⁻¹ m⁻² for blueberry puree. The energy consumption was 2492–2719 kJ kg⁻¹ of water evaporated. Installation of a shell and tube heat exchanger with better temperature control minimized incidences of boiling and frequent discharge of condensate. The steam economy, highest evaporation rate and overall heat transfer coefficient increased to 0.99, 36.0 kg h⁻¹ m⁻² and 733 W m⁻² °C⁻¹, respectively. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: falling liquid film; steam economy; energy consumption; blueberry; raspberry; juice

1. INTRODUCTION

Intensive use of thermal energy and loss of product quality of heat sensitive liquid foods are two major concerns in the design and operation of evaporators used in the food industry. Multi-stage evaporators have been developed that operate at sub-atmospheric pressures to increase energy efficiency and reduce thermal degradation of products (APV CREPACO, 1992). Those systems are, however, very expensive and operate well only within a narrow range of fluid viscosity. The Refractance Window® (RW) evaporator, developed by MCD Technologies Inc., is relatively simple, inexpensive and can be used with a diverse range of products, including those with high sugar and pulp content. It basically uses hot water at normal atmospheric

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pressure to evaporate water from liquid foods. Small fruit and vegetable processors who cannot afford expensive capital investments in multi-effect vacuum evaporators may find this equipment very useful. In addition to concentrating food products, the RW evaporator is versatile and has potential for use in processing nutraceutical, pharmaceutical, biotechnology, and chemical products, as well as in waste recovery and remediation for a diverse range of industries.

Before a new type of food processing equipment is commercialized, it is important to conduct adequate experiments to evaluate its performance. For an evaporator, the measures of performance usually include steam economy (energy efficiency), amount of water it can evaporate per hour (i.e. its capacity), operating temperature range, and nature or type of products it can handle. The procedures for determining energy use and other performance indices for vacuum evaporators are outlined by Minton (1986), Rumsey (1986), and Chen and Hernandez (1997). Similar performance characteristics are needed for the RW evaporator in which the energy for evaporation is obtained from hot water.

In the present configuration of RW evaporator (Figure 1), the water that acts as the heat source is first heated by directly injecting steam into a water tank. The water is heated to the temperature required for the process, usually a few degrees below boiling point (96–98℃), and maintained at that level to avoid formation of bubbles that would reduce heat transfer to the product. The hot water is then circulated beneath a transparent plastic with the product flowing concurrently on the upper part of the inclined flat surface of the plastic. The energy from the hot water is transmitted through the plastic sheet for heating and evaporation of water from a liquid product that makes a number of passes through the evaporator until the desired concentration is reached. Compared to conventional falling film evaporators, the design of RW evaporator makes it possible to attain higher solids concentration without fouling of the evaporation surface. The plastic surface only needs cleaning at the end of the process or whenever a different product is to be processed.

The objective of this study was to determine the performance characteristics of the RW evaporator, and particularly to document its energy consumption per unit weight of water evaporated, heat transfer per unit of surface area, evaporation capacity at different tilt angles, and ways of improving the system.

Figure 1. Layout of RW evaporator showing temperature measuring points.

2. THEORETICAL CONSIDERATIONS ON HEAT AND MASS BALANCES IN RW EVAPORATOR

The evaporator capacity, which is a measure of the amount of water evaporated per hour, can be estimated from the overall mass balance and dry matter balance:

\[ m_{\text{p,in}} = m_{\text{p,out}} + m_w \]  

(1)

\[ m_{\text{p,in}} \times x_{\text{in}} = m_{\text{p,out}} \times x_{\text{out}} \]  

(2)

where \( m_{\text{p,in}} \) and \( m_{\text{p,out}} \) are the mass flow rates (kg s\(^{-1}\)) of fluid product at the inlet and outlet of evaporator, respectively; \( m_w \) is evaporation rate (kg s\(^{-1}\)); \( x_{\text{in}} \) and \( x_{\text{out}} \) are the solids concentration (decimal) at the inlet and outlet points, respectively.

Combining Equations (1) and (2) yields:

\[ m_w = m_{\text{p,in}} \left( 1 - \frac{x_{\text{in}}}{x_{\text{out}}} \right) \]  

(3)

By measuring the solids content \( x_{\text{out}} \) during the evaporation process, the evaporation capacity \( (m_w) \) at different elevations and product flow rates can be calculated (Figure 2).

The rate of heat transfer per unit surface area is an important parameter that is necessary for evaluating the performance of evaporators. To determine the heating rate, the overall heat transfer coefficient \( (U) \), the effective evaporation surface \( (A) \) and the temperature difference (LMTD) between the hot and cold fluids must be known. The relevant equation is

\[ Q_1 = UA(LMTD) \quad \text{and} \quad \text{LMTD} = \frac{\Delta T_{\text{in}} - \Delta T_{\text{out}}}{\ln(\Delta T_{\text{in}}/\Delta T_{\text{out}})} \]  

(4)

where \( Q_1 \) is the energy for evaporation and sensible heating of product (kW); \( \Delta T_{\text{in}} \) the temperature difference between circulating hot water and liquid product at the inlet (°C); \( \Delta T_{\text{out}} \) the temperature difference between circulating hot water and liquid product at the outlet (°C).

Apart from pre-heating of juice to evaporation temperature, thermal energy from steam condensing in the circulating hot water or within the heat exchanger is used mostly for evaporating water from the product. The energy supplied by saturated steam is the same as the amount released when the steam condenses. Therefore, for steady state conditions, the latent heat of condensation \( (Q_s) \) is utilized for heating the product to evaporation temperature \( (Q_p) \) and evaporating water from the product \( (Q_w) \), with the remainder constituting thermal losses to the surrounding \( (Q_L) \). Most of these losses occur through the bottom stainless-steel plate supporting the plastic. If the condensate that normally circulates back to the boiler hot well is

![Figure 2. Representation of heat and mass transfer within the evaporator.](https://example.com/image2.png)

collected and weighed, then $Q_L$ also includes the enthalpy in discharged condensate. Therefore,

$$Q_s = Q_p + Q_w + Q_L$$

where

$$Q_p = m_p c_p \Delta T_p, \quad Q_w = m_w \lambda_w, \quad \text{and} \quad \Delta T_p = T_{p,\text{out}} - T_{p,\text{in}}$$

For fruit juices, the specific heat capacity ($c_p$, kJ/kg°C) and latent heat of evaporation ($\lambda_w$, J/kg) at a known temperature $T_p$(°C) are given by the following equations (Rao and Vitali, 1999; Chen and Hernandez, 1997):

$$c_p = 4.187 \{1 - x_m(0.57 - 0.0018(T_p - 20))\}$$

$$\lambda_w = 2499 \exp(-0.001016 T_p)$$

After determining $Q_p$ and $Q_w$, it is possible to calculate the heat transfer coefficient, $U$. The value of the product side heat transfer coefficient $h_p$ is a measure of how efficiently the latent heat from steam is transferred to the product being concentrated. Given that the temperature of the plastic surface on the hot water side is nearly the same as the bulk water temperature, the overall resistance to heat transfer between the circulating hot water and the vapor bulk is then provided by the plastic sheet and fluid food being concentrated. The value of $h_p$ depends on the superficial velocity of the liquid product and its physical and thermal properties such as viscosity and thermal conductivity.

$$\frac{1}{UA} = \frac{1}{h_w A} + \frac{\delta}{k A} + \frac{1}{h_p A}$$

The Mylar® plastic sheet used has a thermal conductivity of 0.155 W mK⁻¹, a thickness of 0.2 mm, and covered a surface area of 6.64 m². The resistance to heat transfer by conduction across the plastic sheet is fixed. Therefore, the magnitude of $U$ depends on the combined radiation and convective heat transfer on both sides of the plastic sheet. From the above relationships, it is possible to calculate the ratio of energy used for evaporating water from product ($Q_1$) to the net thermal energy supplied by condensing steam ($Q_s$). The evaporator performance can be expressed in terms of steam economy, i.e. the amount of water evaporated per kilogram of steam consumed, namely:

$$\text{Steam economy} = \frac{m_w}{m_s} = \frac{(m_{p,\text{in}} - m_{p,\text{out}})}{m_s}$$

3. MATERIALS AND METHODS

Experiments were conducted with water (to establish baseline parameters), raspberry juice, blueberry juice and blueberry puree after diluting the commercially available concentrates to about 10% solids content. The raspberry juice concentrate was supplied by Milne Fruit Products Inc. (Yakima, WA) while blueberry products were obtained from Valley Processing Inc. (Sunnyside, WA) courtesy of Overlake Foods Corp. (Olympia, WA). The berry juice concentrates and puree were shipped overnight to MCD Technologies Inc. (Tacoma, WA), allowed to thaw, then mixed and diluted as required for the RW evaporation tests.

Steam for heating the circulating water was supplied from a boiler (Steam generator model E-40, Clayton Industries, CA) and either directly injected into water contained in an insulated 200-gallon
tank or passed through a shell and tube heat exchanger. The latter had a length of 0.95 m with shell
diameter of 0.21 m. A PID controller that responded to the set water temperature in the tank was
used to regulate the steam supply to both heating systems. For the direct steam injection, the water
overflowing from an outlet pipe near the top of the tank was collected and weighed to determine
the quantity of steam supplied. The condensate discharged from the shell and tube heat exchanger
was measured similarly. The circulating water was heated to a temperature of about 97°C before
starting product circulation. For easy adjustment of product flow rates, an electronic speed control
was connected to a 3HP positive displacement rotary lobe pump (Waukesha Cherry-Burrell,
Delavan, WI). During calibration, with speed settings at 184, 169 and 150 rpm, the pump
respectively discharged 160, 147, and 130 kg of diluted product per minute. Besides the setting of
feed pumping rates, experiments were done with the evaporator tray tilted at 24, 30, and 37° from
the horizontal position. The rate of evaporation was measured by recording the decrease in the
weight of product contained in a 200 kg capacity barrel, which was placed on a platform scale.
Another small compressed air pump actuated by a float device in the evaporator header tank
intermittently pumped more of the dilute feed product into the header tank to maintain the
product level. To measure the evaporation rate, the decrease in volume in the supply tank was
recorded until all the product was emptied into the header tank. At this point, the constant level in
the header tank could no longer be sustained.

The total solids content of juice was measured using automatic temperature compensating
type hand refractometers (Atago ATC-1E and ATC-2E for brix ranges 0 ~ 32% and 28 ~ 62%,
respectively). For higher total solids contents, concentrates were diluted before the measurement
of brix. The brix number of the concentrates was then calculated from the dilution factor and
measured brix of the diluted samples. For temperature measurements, type-T thermocouples
were connected to a data logger (Model 21X, Campbell Scientific Inc., Logan, UT) and their
output relayed to a computer to display the temperature profiles of product and circulating hot
water at various points (Figure 1). The overall heat transfer coefficient, energy consumption and
evaporator capacity were determined from the recorded temperature and flow rate data.

4. RESULTS AND DISCUSSION

4.1. Baseline study with tap water as feedstock

Table I shows the results of evaporation tests that were conducted on a prototype production
machine using tap water as feedstock at a fixed evaporator tilt of 37°. Each of those experiments
lasted 1.0 h. The quantity of water evaporated from the 6.64 m² surface ranged from 131 to
158 kg h⁻¹ (19.7–23.8 kg h⁻¹ m⁻²), while the energy consumption was from 2533–2787 kJ kg⁻¹ of
water evaporated. Modification of the air handling system and increase in circulating hot water
flow rate increased the evaporation rate from 143 to 173 kg h⁻¹ (21.5–26.0 kg h⁻¹ m⁻²) (Tables I
& II(a)). Further adjustment of the airflow pattern within the evaporator using a baffle reduced
the splashing that occurred on the top cover and the inner walls. The amount of evaporated
water condensing on the top cover and falling back onto the feedstock was also minimized.
Since the flow direction of air is opposite to that of fluid, residence time of fluid product
increased at higher airflow, leading to more evaporation. This countercurrent flow of air against
the inclined evaporation surface created some beneficial turbulence and ripples on the fluid
product. Zheng and Worek (1996) showed the positive influence of such ripples on heat and
mass transfer in thin film evaporation by using equally spaced agitated glass rods on an inclined
stainless-steel evaporation surface. The rods produced waves or eddies that increased the heat and mass transfer several times. For the RW evaporator, a balance is needed between fluid turbulence and the amount of splashing that is acceptable. Despite the good results of airflow adjustments, the direct steam injection system used during these baseline studies was not very effective.

Table I. Capacity and energy consumption of a prototype RW evaporator using water as feedstock (evaporator tilt angle: 37°, hot water flow: 0.9 kg s⁻¹).

<table>
<thead>
<tr>
<th>Feed circulation rate (rpm)</th>
<th>Evaporation rate (kg h⁻¹)</th>
<th>Condensate flow (kg h⁻¹)</th>
<th>Heat transfer (kW)</th>
<th>Water evaporation</th>
<th>Product heating</th>
<th>Steam supply</th>
<th>Evaporation heat (kJ kg⁻¹)</th>
<th>Steam economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>184</td>
<td>145</td>
<td>195</td>
<td>94.5</td>
<td>12.1</td>
<td>112</td>
<td>2778</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>131</td>
<td>181</td>
<td>85.1</td>
<td>10.8</td>
<td>101</td>
<td>2787</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>137</td>
<td>186</td>
<td>89.0</td>
<td>11.1</td>
<td>105</td>
<td>2771</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>144</td>
<td>181</td>
<td>94.1</td>
<td>10.7</td>
<td>101</td>
<td>2533</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>158</td>
<td>200</td>
<td>103.3</td>
<td>12.3</td>
<td>112</td>
<td>2538</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>143 ± 7</td>
<td>189 ± 7</td>
<td>93 ± 5</td>
<td>11.4 ± 0.6</td>
<td>106 ± 5</td>
<td>2681 ± 117</td>
<td>0.76 ± 0.03</td>
<td></td>
</tr>
</tbody>
</table>

Table II. Capacity and energy consumption of RW evaporator after modification of airflow system (evaporator tilt angle: 37°, hot water flow: 6.8 kg s⁻¹).

<table>
<thead>
<tr>
<th>Feed circulation rate (rpm)</th>
<th>Evaporation rate (kg h⁻¹)</th>
<th>Condensate flow (kg h⁻¹)</th>
<th>Heat transfer (kW)</th>
<th>Water evaporation</th>
<th>Product heating</th>
<th>Steam supply</th>
<th>Evaporation heat (kJ kg⁻¹)</th>
<th>Steam economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Tap water as feedstock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>184</td>
<td>169</td>
<td>225</td>
<td>109</td>
<td>20</td>
<td>147</td>
<td>2778</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>170</td>
<td>250</td>
<td>111</td>
<td>18</td>
<td>163</td>
<td>2727</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>174</td>
<td>234</td>
<td>114</td>
<td>22</td>
<td>152</td>
<td>2811</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>169</td>
<td>177</td>
<td>230</td>
<td>116</td>
<td>18</td>
<td>150</td>
<td>2828</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Mean @184 rpm</td>
<td>173 ± 4</td>
<td>235 ± 8</td>
<td>113 ± 3</td>
<td>20 ± 2</td>
<td>153 ± 5</td>
<td>2746 ± 49</td>
<td>0.74 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>(b) Blueberry juice and blueberry puree as feedstock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>184†</td>
<td>139</td>
<td>194</td>
<td>90</td>
<td>15</td>
<td>127</td>
<td>2571</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>184‡</td>
<td>148</td>
<td>192</td>
<td>96</td>
<td>14</td>
<td>124</td>
<td>2557</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>169‡</td>
<td>135</td>
<td>185</td>
<td>88</td>
<td>13</td>
<td>121</td>
<td>2685</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>150‡</td>
<td>126</td>
<td>183</td>
<td>82</td>
<td>14</td>
<td>120</td>
<td>2729</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>172 ± 12‡</td>
<td>137 ± 7</td>
<td>189 ± 5</td>
<td>89 ± 4</td>
<td>14 ± 1</td>
<td>123 ± 3</td>
<td>2636 ± 72</td>
<td>0.73 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>184§</td>
<td>211</td>
<td>274</td>
<td>137</td>
<td>19</td>
<td>179</td>
<td>2492</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>(c) Raspberry juice as feedstock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>132</td>
<td>169</td>
<td>85.8</td>
<td>18.4</td>
<td>95</td>
<td>2601</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>124</td>
<td>171</td>
<td>81.2</td>
<td>18.0</td>
<td>97</td>
<td>2796</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>154</td>
<td>212</td>
<td>100.7</td>
<td>15.7</td>
<td>118</td>
<td>2761</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>137 ± 12</td>
<td>184 ± 19</td>
<td>89.2 ± 7.6</td>
<td>17.4 ± 1.1</td>
<td>103 ± 10</td>
<td>2719 ± 79</td>
<td>0.75 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

Feed type: †blueberry juice; ‡blueberry puree.

stainless-steel evaporation surface. The rods produced waves or eddies that increased the heat and mass transfer several times. For the RW evaporator, a balance is needed between fluid turbulence and the amount of splashing that is acceptable. Despite the good results of airflow adjustments, the direct steam injection system used during these baseline studies was not very effective.
efficient. The water temperature was difficult to control leading to supply of more steam than was necessary. The energy consumption therefore increased, causing a slight reduction in steam economy (Table II(a)). In later experiments, a new controller was installed and the direct steam injection system replaced with the shell and tube heat exchanger.

4.2. Evaporation of blueberry and raspberry juices

Blueberry and raspberry juices are usually concentrated to 65°Brix in commercial operations, while their puree counterparts are limited to about 28°Brix. The change in total solids content and viscosity of fruit juices and purees has an influence on the energy usage during evaporation. For the RW evaporator, the tilt angle, temperature and flow of both fluid product and circulating hot water, may also influence the evaporator performance. To evaluate the performance of the evaporator, temperatures at different points (Figures 3 and 4), evaporation rates (Figure 5), and steam economy (Figure 6) were plotted for different tray elevations and product flow rates.

Figures 3 and 4 are typical temperature profiles showing the effect of circulating water flow rate on fluid temperatures during evaporation of blueberry juice. At a water flow rate of 0.9 kg s⁻¹, about 18–20°C temperature difference between hot water at inlet and outlet points was observed (Figure 3). However, when the water flow rate was increased to 6.8 kg s⁻¹, the temperature of circulating hot water dropped only by an average of 3.2°C. For both cases of low and high water flow rates, the product temperature at the inlet and outlet differed by less than 1.2°C. As water in the product changes into vapor, it causes product cooling which prevents any significant product temperature rise between the inlet and outlet points. Tsay and Lin (1995) observed that liquid vaporization tends to be high at higher product inlet temperature. Since the product temperature in an evaporator operating at atmospheric conditions mainly depends on the heating medium temperature, it is advantageous to have the highest possible product temperature that does not lead to quality degradation.

Figure 3. Typical temperature profiles during evaporation of blueberry juice under direct steam injection heating with water circulating at 0.9 kg s⁻¹.
With stable thermal input conditions, the log mean temperature difference (LMTD), defined in Equation (3) and plotted in Figures 3 and 4, can be used to monitor the performance of the evaporator. The temperature profiles indicate that LMTD increased from 25°C to about 30°C when the circulating hot water flow rate was increased from 0.9 to 6.8 kg s⁻¹, respectively. This increase in LMTD as a result of increase in water circulation rate might have contributed to the high evaporation (Table I and II(a)). To maintain the high evaporation rate, the rest of the

Figure 4. Typical temperature profiles during evaporation of blueberry juice under direct steam injection heating with water circulating at 6.8 kg s⁻¹.

Figure 5. Evaporation rate for blueberry juice at different evaporator tilt angles and juice flow rates under direct steam injection heating.

experiments with berry products were conducted with hot water circulating at 6.8 kg s\(^{-1}\). Yan and Soong (1995) investigated heat and mass transfer along an inclined heated plate with film evaporation and reported that a reduction in the inclined angle causes an increase in the air-liquid interfacial temperature, which in turn leads to a larger latent heat exchange. In the present study, the very high ratios of feed flow to evaporation rates might have masked the influence of tilt angle on the interfacial temperature. Apart from inclined angle, the viscosity and total solids content of fluid product, and the heat capacity rates of the fluids flowing on both sides of the plastic sheet might also influence the heat and mass transfer. For the three evaporator bed tilt angles used in this study, evaporation rates were higher at higher product circulating rates (Figure 5). The foregoing observations suggest that higher circulating water flow rate is preferable because it results in higher interfacial air-liquid temperature which increases the latent heat flux. The magnitude of the evaporative latent heat flux we obtained is several times that of the sensible heat flux (Table IV). This indicates efficient conversion of latent heat from condensing steam into heat flux for evaporation and agrees with conclusions made by Yan and Soong (1995).

When the evaporator tray was tilted at 37\(^\circ\) from the horizontal with hot water circulating at 6.8 kg s\(^{-1}\), the average energy required to evaporate 1 kg of water from blueberry juice, blueberry puree and raspberry juices were 2636, 2492 and 2719 kJ, respectively (Table II(b) and (c)). Commercial fruit juice concentrates are usually at higher brix than their puree counterparts, so the high amount of dissolved solids binds the water molecules more tightly resulting in a rise in boiling temperature. At a higher circulating water flow rate, the water temperature is nearly invariable and since the boiling point rise of the higher brix juice is more than that of puree, slightly more energy was used in the evaporation of blueberry juice to the higher brix than in the puree. With the direct steam injection heating method, the highest evaporation rates recorded during the concentration of blueberry juice and blueberry puree were 180 and 211 kg h\(^{-1}\) (i.e. 27.1 and 31.8 kg h\(^{-1}\) m\(^{-2}\)), respectively (Tables II(b) and III(a)). After the direct steam injection heating system was replaced with shell and tube heat exchanger, the highest evaporation rate for blueberry juice was 239 kg h\(^{-1}\) (38.0 kg h\(^{-1}\) m\(^{-2}\)) (Table III(b)).
The average mass of water evaporated per unit mass of steam used (steam economy) was 0.64–0.84 with direct steam injection heating method (Figure 6). These figures improved to 0.80–0.99 after the shell and tube heat exchanger was installed (Table III(b)). The direct steam injection is by design a more efficient heating method, but during this study it was difficult to control the temperature to avoid boiling of circulating water. The boiling led to enthalpy loss in discharged hot water that could have been used for the evaporation process. Therefore, replacement of the direct steam injection with the shell and tube heat exchanger reduced the wastage of circulating hot water and improved steam economy. The results of steam economy for both heating systems are very representative of the overall system performance since the data for each combination of tilt angle and product pumping speed were obtained for residence times of more than 1 h after reaching steady state operation condition. Aboabboud et al. (1996) analysed an atmospheric evaporator that included thermal energy recycling and obtained a steam economy of 2.83. Budin et al. (1998) reported a steam economy of 0.91 for a single effect vacuum evaporation process, while the 2- and 3-effect tomato paste evaporators investigated by Rumsey (1986) had economies between 1.38 and 2.60. Fellows (1988) reported steam economy values between 1.67 and 3.33 for one- to three-effect vacuum evaporators with vapor recompression, and 0.91 to 2.5 for those without vapor recompression. The steam economy obtained for the RW evaporator with shell and tube heat exchanger was from 0.80–0.99. Considering that the RW evaporator is operated at atmospheric conditions, its steam economy is comparable to 0.7–0.9 reported by Aboabboud et al. (1996) for evaporators without thermal energy recycling. Though operating it at higher inclines facilitates gravity flow of fluid product on the evaporation surface, steam economy values at 37 and 30° tilt angles did not appear different (Figure 6).

Table III.

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>Feed circulation rate (rpm)</th>
<th>Evaporation rate (kg h⁻¹)</th>
<th>Condensate flow (kg h⁻¹)</th>
<th>Evaporation heat (kJ kg⁻¹)</th>
<th>Steam economy</th>
<th>LMTD (°C)</th>
<th>Coeff. U (W m⁻²°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37°</td>
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<td>190</td>
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<td>0.69</td>
<td>29.1</td>
<td>479</td>
</tr>
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<td>144</td>
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<td>543</td>
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<td>114</td>
<td>161</td>
<td>2609</td>
<td>0.71</td>
<td>28.8</td>
<td>430</td>
</tr>
<tr>
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<td>97</td>
<td>151</td>
<td>2611</td>
<td>0.64</td>
<td>28.8</td>
<td>367</td>
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</table>

(a) Steam economy and energy for evaporation of blueberry juice at different tilt angles and feed pumping rates (direct steam injection system)³

(b) Performance of the evaporator after replacing steam injection system with shell and tube heat exchanger⁴

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>Feed circulation rate (rpm)</th>
<th>Evaporation rate (kg h⁻¹)</th>
<th>Condensate flow (kg h⁻¹)</th>
<th>Evaporation heat (kJ kg⁻¹)</th>
<th>Steam economy</th>
<th>LMTD (°C)</th>
<th>Coeff. U (W m⁻²°C⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>37°</td>
<td>184</td>
<td>196</td>
<td>246</td>
<td>2718</td>
<td>0.80</td>
<td>36.0</td>
<td>619</td>
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<td>2587</td>
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<td>685</td>
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<td>228</td>
<td>229</td>
<td>2624</td>
<td>0.99</td>
<td>34.8</td>
<td>722</td>
</tr>
</tbody>
</table>

³ Blueberry juice used as feedstock.

The other measure of performance used in this study is overall heat transfer coefficient \((U)\), which ranged from 367 to 666 W m\(^{-2}\) C\(^{-1}\) and 619 to 733 W m\(^{-2}\) C\(^{-1}\) for the direct steam injection and for the shell and tube heat exchanger, respectively (Table III). These values generally increased with product flow rate. However, the figures obtained are in the lower range when compared to 1930 W m\(^{-2}\) C\(^{-1}\) reported for a 4-effect, 6-stage orange juice vacuum evaporator investigated by Rao and Vitali (1999). For a thin film scraped surface evaporator (TFSSE), Sangrame et al. (2000) obtained \(U\) values between 477 and 939 W m\(^{-2}\) C\(^{-1}\) while using water as feed, and 626 and 911 W m\(^{-2}\) C\(^{-1}\) with tomato pulp. The corresponding evaporation rates reported for the TFSSE were 14.7–30.7 and 13.2–33.7 kg h\(^{-1}\), respectively. This is an indication that the overall heat transfer coefficient of the RW evaporator is very good when compared to these vacuum systems.

### 5. CONCLUSION

The amount of water evaporated per unit weight of steam consumed ranged from 0.64 and 0.84, and the highest evaporation rate recorded with the direct steam injection method of heating was 211 kg h\(^{-1}\) (31.8 kg h\(^{-1}\) m\(^{-2}\)). After the air volume and flow pattern in the system were improved, the average evaporation capacity increased from an average of 141 to 163 kg h\(^{-1}\) (21.2–24.5 kg h\(^{-1}\) m\(^{-2}\)). Installation of a shell and tube heat exchanger further increased the capacity and steam economy to between 196 and 239 kg h\(^{-1}\) (29.5–36.0 kg h\(^{-1}\) m\(^{-2}\)) and 0.80–0.99, respectively. During the concentration of blueberry puree, blueberry juice and raspberry juice, the average product temperature was 65°C, and 2492–2719 kJ of energy was used per kilogram of water evaporated. The overall heat transfer coefficient for the system increased with increase in circulating water flow rate, product flow rate, and evaporator tilt. Highest values of heat transfer coefficient were 666 W m\(^{-2}\) C\(^{-1}\) with steam injection and 733 W m\(^{-2}\) C\(^{-1}\) with the shell and tube heat exchanger. These were obtained with the evaporator tray inclined at 37° and hot water circulating at 6.8 kg s\(^{-1}\). Given that the Refractance Window® evaporator is much less expensive and operates at normal atmospheric conditions, the results obtained are very good when compared to other evaporators working under similar conditions.

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Table IV. Heat quantities used in calculation of heat transfer during evaporation of blueberry juice (Equations (5) and (6))

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>Feed circulation rate (rpm)</th>
<th>Product heating, (Q_p)</th>
<th>Evaporation Heat, (Q_w)</th>
<th>Heat from steam, (Q_s)</th>
<th>Product heating, (Q_p)</th>
<th>Evaporation Heat, (Q_w)</th>
<th>Heat from steam, (Q_s)</th>
</tr>
</thead>
<tbody>
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<td>116.7</td>
<td>150.0</td>
<td>19.4</td>
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<td>13.3</td>
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<td>156.4</td>
<td>116.3</td>
</tr>
<tr>
<td>30°</td>
<td>169</td>
<td>11.2</td>
<td>96.0</td>
<td>119.8</td>
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<td>7.6</td>
<td>84.9</td>
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<td>147.3</td>
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<tr>
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<td>17.4</td>
<td>152.7</td>
<td>116.0</td>
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<tr>
<td>24°</td>
<td>150</td>
<td>7.3</td>
<td>62.9</td>
<td>98.3</td>
<td>17.0</td>
<td>148.9</td>
<td>114.1</td>
</tr>
</tbody>
</table>

\(^{5}\) Heating rates in kW.

The other measure of performance used in this study is overall heat transfer coefficient \((U)\), which ranged from 367 to 666 W m\(^{-2}\) C\(^{-1}\) and 619 to 733 W m\(^{-2}\) C\(^{-1}\) for the direct steam injection and for the shell and tube heat exchanger, respectively (Table III). These values generally increased with product flow rate. However, the figures obtained are in the lower range when compared to 1930 W m\(^{-2}\) C\(^{-1}\) reported for a 4-effect, 6-stage orange juice vacuum evaporator investigated by Rao and Vitali (1999). For a thin film scraped surface evaporator (TFSSE), Sangrame et al. (2000) obtained \(U\) values between 477 and 939 W m\(^{-2}\) C\(^{-1}\) while using water as feed, and 626 and 911 W m\(^{-2}\) C\(^{-1}\) with tomato pulp. The corresponding evaporation rates reported for the TFSSE were 14.7–30.7 and 13.2–33.7 kg h\(^{-1}\), respectively. This is an indication that the overall heat transfer coefficient of the RW evaporator is very good when compared to these vacuum systems.

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NOMENCLATURE

\(A\) = effective evaporation surface area (m\(^2\))
\(c\) = specific heat capacity (kJ kg\(^{-1}\)°C\(^{-1}\))
\(h\) = heat transfer coefficient (W m\(^{-2}\)°C\(^{-1}\))
\(k\) = thermal conductivity (W m\(^{-1}\)°C\(^{-1}\))
\(m\) = mass flow rate (kg s\(^{-1}\))
\(x\) = total solids content (g g\(^{-1}\) dry wt\(^{-1}\))
\(U\) = overall heat transfer coefficient (W m\(^{-2}\)°C\(^{-1}\))
\(\text{LMTD}\) = logarithmic mean temperature difference (°C)
\(\text{RW}\) = Refractance Window\(^R\)
\(T\) = temperature (°C)
\(Q\) = heat transfer rate (kW)
\(\delta\) = thickness of Mylar\(^R\) plastic sheet (m)
\(l_s\) = latent heat of condensing steam (J kg\(^{-1}\))
\(l_w\) = latent heat of evaporation of water from product (J kg\(^{-1}\))

Subscripts

\(\text{p,in, p,out}\) = product at inlet and outlet of the evaporator
\(w\) = water or vapour
\(s\) = steam

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REFERENCES