Introduction of a New Ultrasound and Infrared Assisted Conductive Hydro-Dryer

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Written for presentation at the CSBE/SCGAB 2018 Annual Conference
University of Guelph, Guelph, ON
22-25 July 2018

ABSTRACT Conductive hydro-drying also was known as Refractance Window (RW) drying is a relatively new drying technology, which uses hot water at 90-95 °C as a means to carry thermal energy to the moist materials that are placed on a semi-transparent Mylar plastic sheet which floats over circulating hot water. Unused thermal energy in the hot water is recycled by its circulation which results in a very energy efficient process. The product temperature during the process is usually between 70 °C and 80 °C.

Numerous studies on RW technology have shown a high retention of heat sensitive quality parameters (vitamins, antioxidants and color) with better energy efficiency as compared to freeze drying as well as many other conventional drying methods.

Early understandings of heat transfer in RW drying had concluded that thermal radiation from hot water was the main heat transfer mechanism but recently a conjugate heat and mass transfer model showed that a major portion of thermal energy is transferred via conduction that is why some of the researchers proposed the term “conductive hydro-drying” for the name of this technology.

Increasing the product thickness or reducing the hot water temperature will drastically reduce the drying rate in RW dryer; in order to minimize such limitations, a combination of ultrasound and infrared with RW technology was created. Ultrasound and Infrared Assisted Conductive Hydro-Dryer is a
patented new drying method which aims to maintain or increase the drying speed while reducing the hot water temperature or increasing the drying material thickness.

**Keywords:** Refractance Window drying, ultrasound, infrared, energy efficiency, heat sensitive quality parameters.

**INTRODUCTION**

Dried food materials including vegetables, fruits and other food ingredients have a wide range of uses in the food industry and prepared foods. In the quality aspects, maintenance of sensitive and important quality attributes such as aroma, color, and nutrients has always been a challenge in developing drying methods to preserve heat sensitive ingredients in fruits and vegetables. On the other hand, increasing consumer awareness and demand for high-quality dehydrated foods stimulates efforts toward development of improved and innovative drying technologies (Baeghbali, 2012; Nindo, Feng, et al, 2003).

In the energy aspects, statistics show that thermal drying operations consume up to 25% of the national industrial energy in the developed countries. For example, the energy consumption of drying in 2012 for the US, UK and France were 1600×109, 128×109, 168×109 MJ/year, respectively. With the rapid industrialization of emerging global economies, the cost of energy consumed for thermal drying and the resulting adverse environmental impact of the greenhouse gas emissions related to thermal drying is increasing (Law and Mujumdar, 2012).

![Figure 1. Classification of drying methods (Vega-Mercado, Marcela Góngora-Nieto, & Barbosa-Cánovas, 2001).](image-url)
Figure 1 shows a diagram of the classification of drying methods as they evolved in food industries, where novel drying technologies can be classified as 4th generation drying methods.

**REFRACTANCE WINDOW DRYER** Refractance Window (RW) is a relatively new film drying technology which is characterized by maintaining a relatively low temperature inside the food and drying the food in shorter drying times compared to conventional drying methods as well as freeze-drying (Nindo, Sun, et al., 2003). Studies have shown that for drying a similar amount of product, the cost of the RW equipment is about one-third of the cost of a freeze-dryer (FD). In terms of the energy consumption, RW is less energy intensive and consumes less than 50% of the energy consumption of a FD (Nindo and Tang, 2007).

Figure 2 shows a schematic of Refractance Window concept. When there is some hot water in an open container, the heat is transferred from the hot water to the surroundings via conduction, convection, radiation and evaporation (Figure 2a); when a thin transparent plastic membrane which is impermeable to water and steam is placed over the hot water, the evaporation is stopped and the radiation is reflected back in to the water (Figure 2b); when a moist material is placed over the membrane, the wet interface will create a “window” that allows heat transfer through the membrane (Figure 2c); finally when the product is dried, heat transfer to the dried material is dramatically reduced and the drying process is finished (Figure 2d) (Baeghbali, et al., 2010). RW drying system utilizes circulating water at 90 to 95°C as a means to carry thermal energy to materials to be dehydrated (Figure 2 and Figure 3). As the product does not have direct contact with the heat transfer medium during Refractance window dehydration, no cross-contamination occurs (Moses, et al., 2014). Evaporation capacity up to 10 kg m$^{-2}$ h$^{-1}$ shows that RW is a very efficient drying process (Zotarelli, et al., 2015).

The unused heat in the circulating water is recycled. The actual product temperature is usually about 70°C. Studies on RW technology have shown a high retention of product quality (color, vitamins and antioxidants) as compared to other conventional methods of drying, including freeze-drying (Abonyi et al., 2002; Baeghbali, et al., 2016; Nindo and Tang, 2007).

**Heat transfer Mechanism** Thermal energy from circulating hot water is transferred to the wet product via a plastic interface that is relatively transparent to infrared radiation. The actual product temperature is usually below 70°C. The heated water is recycled and reused, thereby improving the thermal efficiency of the system. During RW drying, the three modes of heat transfer, namely conduction, convection, and radiation are active. The plastic conveyor is very thin, it reaches the temperature of hot water flowing beneath it almost immediately. Thermal energy from the hot water is transmitted through the plastic conveyor by conduction and radiation. Thin plastic conveyor with the infrared transmission in the wavelength range that matches the absorption spectrum for water all work together to facilitate rapid drying. Water has high absorption for infrared with wavelengths of 3.0, 4.7, 6.0, and 15.3 µm. The infrared transmission is stronger when the plastic interface is in intimate contact with water on one side and a moist material on the other side. (Nindo and Tang, 2007).

Early understandings suggested that the use of a thin plastic sheet that is transparent to infrared radiation (IR) creates a “window” for thermal radiation from hot water to the wet material. This “window” gradually closes as the material dries out cutting off thermal radiation and prevents the sample to reach hot water temperature. In 2015 a conjugate heat and mass transfer model was developed to simulate the drying of pumpkin slices. Computed results indicated that there was a 5% difference in transmission of IR radiation through the plastic sheet between a dry and wet product. A major portion of thermal energy is transferred via conduction through the plastic sheet. The relatively low sample temperature observed for RW drying of thin samples is attributed to the development of
a dried, thermally resistive layer at the base that prevents heat transfer from the plastic sheet during the later portions of the drying process. For thick-sized samples, the low sample temperature is a result of the development of air spaces between the product and the plastic sheet, which reduces the heat flux from the hot water. As a consequence, the quality of the final product is preserved when compared with other drying techniques. (Baeghbali and Niakousari, 2018; Ortiz-Jerez et al, 2015).

Effect of Air Convection

Effects of natural convection (NC) and forced convection (FC) of air in RW dryer was evaluated during pumpkin drying. Average temperatures of the sample thickness were higher in the runs with natural convection and lower in those with forced convection, which is highly similar to the results of the drying curves. The lowest moisture kinetics were obtained in samples dried with natural-convection, whereas the samples dried with forced-convection exhibited the highest moisture loss values (Ortiz-Jerez and Ochoa-Martinez, 2015).

Figure 2. Refractance Window drying concept (Baeghbali, et al, 2010).
REFRACTANCE WINDOW DRYER PERFORMANCE REVIEW In the following sections, the effect of RW drying on microbial reduction, Vitamin C, anthocyanin and carotene retention and case studies on RW drying of asparagus, paprika, mango and aloe-vera gel as well as energy efficiency of the dryer are briefly reviewed.

Microbial Reduction RW drying of pumpkin puree from 80 to 5% moisture content (wb) was achieved in less than 5 minutes (with water at 95°C). The RW dryer demonstrated 52 to 70% energy efficiency. RW drying of inoculated pumpkin purees resulted in 4.6, 6.1, 6.0, and 5.5 log reductions of total aerobic plate counts (APC), coliforms, *Escherichia coli*, and *Listeria innocua*, respectively (Nindo, Feng, et al., 2003).

Ascorbic Acid Retention Ascorbic acid retention of the strawberry purees (94.0%) after RW drying was comparable to 93.6% in FD (Abonyi et al., 2002). Ascorbic acid retention in strawberry purees dried with RW system (93%) was comparable to FD products (94%) (Sablani, 2006). For asparagus dried using heated air, microwave spouted bed and RW, RW drying resulted in the highest retention of total ascorbic acid (Santos and Silva, 2008).

Anthocyanin Retention 45, 41 and 23% losses in total anthocyanins content were observed in colored potato flakes after FD, drum drying and RW drying, respectively (Nayak, Berrios, Powers, Tang, and Ji, 2011). Haskap-berry puree was dried using an RW dryer and more than 92% of anthocyanins was retained (Celli, et al, 2016). RW dryer produced high-quality pomegranate juice powder with anthocyanins content, anthocyanins color and antioxidant activity equal to or greater than those of the freeze-dried and spray-dried samples (Baeghbali, et al., 2016).

Green Asparagus Drying Green asparagus was dried using tray drying, spouted bed (SB), drying, microwave assisted spouted bed (MWSB), freeze drying and RW drying. Amongst heated air methods, MWSB was the fastest and resulted in higher retention of total antioxidant activity (TAA). TAA and retained ascorbic acid were as follows (Nindo, Sun, et al., 2003):

RW drying>freeze-drying>MWSB>spouted bed drying>tray drying.
**Drying of Strawberry and Carrot** The color of the RW-dried carrot purees was comparable to fresh puree. For RW-dried strawberry purees, the color retention was comparable to FD products (Table 1) (Abonyi et al., 2002).

<table>
<thead>
<tr>
<th>Dryer \ Carotene Loss%</th>
<th>Total carotene</th>
<th>α-carotene</th>
<th>β-carotene</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW Dryer</td>
<td>8.7%</td>
<td>7.4%</td>
<td>9.9%</td>
</tr>
<tr>
<td>Freeze Dryer</td>
<td>4.0%</td>
<td>2.4%</td>
<td>5.4%</td>
</tr>
</tbody>
</table>

**Paprika Drying** Refractance Window drying (RWD) method was employed to dry paprika in comparison with freeze drying, hot-air oven drying, and natural convective drying methods. The freeze-dried and RW-dried paprika showed better reflected color characteristics. There was no significant difference in browning index between freeze-dried and RW-dried samples (Topuz, et al, 2011; Topuz, et al, 2009).

**Mango Drying** Mango powders were obtained using Refractance Window (RW) drying, freeze drying (FD), drum drying (DD), and spray drying (SD). The color of RW-dried mango powder and reconstituted mango puree were comparable to the FD products but were significantly different from DD (darker), and SD (lighter) counterparts. The bulk densities of DD and RW-dried mango powders were higher than FD and SD powders. There were no significant differences between RW and FD powders in terms of solubility and hygroscopicity. The microstructure of RW-dried mango powder was smooth and flaky with uniform thickness (Caparino, et al, 2013; Caparino et al., 2012; Ochoa-Martínez, et al, 2012).

**Aloe-vera Powder** Aloe-vera extract was dried using spray drying (SD), freeze drying (FD), and Refractance Window (RW) drying methods. Solutions prepared from SD aloe had the lowest viscosity, while FD and RW-dried counterparts had higher and nearly equal consistency. The activation energy for network formation of solutions reconstituted from SD powder 23.9±0.1 kJmol⁻¹, which was slightly lower than the 24.6±0.3 and 24.7±0.4 kJmol⁻¹ obtained with FD and RW drying, respectively (Nindo, et al, 2011).

**Energy efficiency** Table 2 show the capacity, typical product temperature and thermal efficiency of RW drying in comparison with other conventional drying technologies. Table 3 show the energy consumption, energy efficiency and equivalent CO₂ emission of RW drying in comparison with other conventional drying technologies.

<table>
<thead>
<tr>
<th>Dryer</th>
<th>Typical capacity (Kg/m³ or m²)</th>
<th>Typical product temperature (°C)</th>
<th>Thermal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary dryer</td>
<td>30-80 m³</td>
<td>~175</td>
<td>25-50</td>
</tr>
<tr>
<td>Spray dryer</td>
<td>1-30 m³</td>
<td>80-120</td>
<td>20-51</td>
</tr>
<tr>
<td>Drum dryer</td>
<td>6-20 m²</td>
<td>120-130</td>
<td>35-78</td>
</tr>
<tr>
<td>RW dryer</td>
<td>1-10 m²</td>
<td>60-70</td>
<td>52-77</td>
</tr>
</tbody>
</table>
Table 3. Comparison of energy consumption, energy efficiency and equivalent CO₂ emission for different drying methods (Baeghbali et al., 2016)

<table>
<thead>
<tr>
<th>Dryer</th>
<th>Calculated energy needed for drying 1kg sample (kWh)</th>
<th>Energy consumption for drying 1kg sample (kWh)</th>
<th>Overall energy efficiency (%)</th>
<th>CO₂ Emission for drying 1kg sample (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze dryer</td>
<td>1.46</td>
<td>130.65±0.82&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.12</td>
<td>104.52</td>
</tr>
<tr>
<td>RW dryer</td>
<td>1.36</td>
<td>4.31±0.82&lt;sup&gt;c&lt;/sup&gt;</td>
<td>31.56</td>
<td>3.45</td>
</tr>
<tr>
<td>Spray dryer</td>
<td>1.42</td>
<td>11.01±0.82&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.92</td>
<td>8.81</td>
</tr>
</tbody>
</table>

<sup>a</sup>Different letters in each column indicate a significant difference (p ≤0.05)

ULTRASOUND ASSISTED DRYING Many studies showed that application of ultrasound in combination with different drying methods can improve the drying rate. Ultrasound waves enhance drying processes because of “heating effects”, “vibration effects”, and “synergistic effects” which in turn causes a temperature increase, turbulence in the air near the drying area which enhances the heat and transfer plus causing a synergistic effect that increases the drying speed (Kowalski and Mierzwa, 2015). Also, there is a “sponge effect” that is due to the quick compressions and expansions in the solid moist material which will facilitate the drying process (de la Fuente-Blanco, et al., 2006).

INFRARED ASSISTED DRYING Similar to the ultrasound application, application of infrared in combination with different drying methods can result in better product quality, shorter drying times and improved energy efficiency. Infrared is easy to operate and can be easily combined with different drying methods to overcome the problem with the low penetration depth of infrared radiation (Riadh et al, 2014).

ULTRASOUND AND INFRARED ASSISTED CONDUCTIVE HYDRO-DRYER Our studies on Refractance Window drying have shown that decreasing the hot water temperature and/or increasing the sample thickness will cause a significant reduction in drying speed (Baeghbali, 2012; Baeghbali et al, 2010; Baeghbali and Niakousari, 2015; Baeghbali et al., 2016). In order to solve this problem, “Ultrasound and Infrared Assisted Conductive Hydro-dryer” (UIACHD) was designed and manufactured for the first time in the department of food science and technology at Shiraz University, Iran. UIACHD is a patented new drying method designed to increase the drying speed in the Refractance Window dryer to provide the possibility of increasing the moist material thickness or reducing the hot water temperature (Baeghbali and Niakousari, 2018).

CONCLUSION Refractance Window is a new drying technique and it is characterized by short drying times, low cost, high energy efficiency and high evaporation capacity. RW dryer can produce high-quality products with heat-sensitive vitamins, phytochemicals content, color and antioxidant activity comparable to freeze-dried products. A conjugate heat and mass transfer model showed that a major portion of thermal energy is transferred via conduction through the plastic sheet.

Our studies have shown that the combination of ultrasound and infrared with “conductive hydro-drying” can improve the performance of the dryer. Further studies on the mechanisms of heat and mass transfer can lead to better understanding and improvement of this technology.
REFERENCES


Baeghbali, V. 2012. Design, manufacture and investigating functionality of Refractance Window System for eliminating moisture of food materials. (M.Sc.), Shiraz University, Shiraz, Iran.


