



## XVII<sup>th</sup> World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)  
Québec City, Canada June 13-17, 2010



### DEVELOPMENT AND COMMERCIALIZATION OF EMERGING INFRARED RADIATION FOOD PROCESSING TECHNOLOGIES

ZHONGLI PAN<sup>\*1,2</sup>, GRIFFITHS G. ATUNGULU<sup>2</sup>, GOKHAN BINGOL<sup>1</sup>, TARA MCHUGH<sup>1</sup>, JIHONG YANG<sup>2</sup>

<sup>1</sup> Processed Foods Research Unit, USDA-ARS West Regional Research Center, 800 Buchanan Street Albany, California 94710-1105, USA, \*Email of corresponding author: zhongli.pan@ars.usda.gov

<sup>2</sup> Department of Biological and Agricultural Engineering, University of California, Davis, One Shields Avenue, Davis, California 95616, USA

#### CSBE101206 – Presented at Section VI: Postharvest Technology and Process Engineering Conference

**ABSTRACT** In order to demonstrate a newly developed simultaneous infrared dry-blanching and dehydration (SIRDBD) technology on an industrial scale, a mobile and continuous IR heating system was built and tested to examine its performance for SIRDBD of sliced and diced potatoes. The mobile IR heating equipment had an effective total heating area of 5×15 feet. The IR heating from both top and bottom was provided by catalytic IR emitters using natural gas as energy source. During processing, the products were conveyed using a belt and the total residence time in the IR equipment varied from 224 to 544 s. The result showed that inactivation of polyphenol oxidase (PPO) was achieved when the belt speed was 3.175 ft/min with corresponding residence time of 283 s for 2.89 mm thick potato slices. To achieve full blanching of thicker slices of 6.42 and 9.03 mm, the belt speeds were 2.43 ft/min and 2.739 ft/min, respectively, corresponding to 370 and 328 s residence time. The fully blanched product can also be achieved by using high heat in the early stage with reduced heating time. Using high heat in the very first stages to heat the slices to inactivation temperatures was essential for obtaining high quality blanched product and for less energy consumption. Moisture loss during blanching could be replenished to a certain extent by dipping blanched products in water. The results showed that SIDBD could be an effective and efficient method for processing fruits and vegetables.

**Keywords:** Infrared heating, Food processing, Emerging technologies, Dry blanching, Dehydration, Commercialization.

## 1. INTRODUCTION

In the food industry, blanching has become a very important unit operation prior to freezing, canning, and drying of fruits or vegetables, in order to inactivate enzymes, modify food texture, preserve food color, flavour, and nutritional value, and to remove trapped air. Many of fruit and vegetable products need to be further partially dried to produce the products with desirable quality characteristics. Conventionally, blanching and drying are normally executed in two separate steps by steam or hot water blanching and followed by hot air drying, both of which are related with several disadvantages, such as low energy and processing efficiency, poor finished product quality, and environmental pollution (Bomben, 1977; Vanlaanen, 2003). Specifically, energy conservation and waste reduction requirements have called for an immediate intervention which demands the new blanching and dehydration technologies. Consequently, infrared (IR) based blanching and drying technology has emerged and demonstrated great potential to solve these concerns in the food industry.

IR is an electromagnetic energy and is transmitted as a wave, which penetrates the foods and is then converted to heat. A new processing method using IR has been developed that enables fruits and vegetables to be blanched and dried in one step versus the current two-step process (Pan and McHugh, 2004). Therefore, the process is named as simultaneous infrared dry-blanching and dehydration (SIRDBD). When it was used for processing fruits and vegetables, the SIRDBD resulted in high product quality with better texture and nutritional value than conventionally blanched and/or dried counterparts (Pan and McHugh, 2004). The method is more energy efficient than current methodologies and is also less time-consuming. The IR based blanching does not require the use of steam or water for blanching hence it is named as IR dry-blanching (IRDB). IRDB offers the food industry a novel waste-free, environmentally-friendly technology to accomplish blanching. It is clear that there is a strong interest in implementing the technology even though SIRDBD is still in its infant commercial stage at present.

The mechanism of catalytic IR (CIR) emitter has been illustrated in details in a recent publication (Zhu and Pan, 2009). Primarily the platinum catalyst inside the CIR emitter accelerates the oxidation of natural or propane gas, resulting in medium- and far-infrared energy with peak wavelengths between 3 to 6  $\mu\text{m}$ , which matches reasonably well with the three absorption peaks of water in that wavelength range. Therefore, rapid heating of high-moisture foods has led to the successful demonstrations of blanching and/or dehydration of many fruits and vegetables including pears, carrots, and sweet corn kernels (Pan and McHugh, 2004), onions (Gabel et al., 2006), bananas and strawberries (Pan et al., 2008; Shih et al., 2008), blueberries (Shi et al., 2008a; Shi et al., 2008b), and apples (Zhu and Pan, 2009).

SIRDBD can be achieved in two heating modes, continuous and intermittent heating. During continuous heating, the radiation intensity is maintained constant by retaining a continuous supply of natural gas to the CIR emitter. For quick come-up and moisture removal or enzyme inactivation, continuous heating is advantageous since it delivers a constant high energy to the surface of product (Zhu and Pan, 2009). The relationship between processing parameters and product quality during SIRDBD with continuous and intermittent heating has been investigated (Zhu and Pan, 2009; Zhu et al. 2010). Zhu et al. (2010) have suggested applying intermittent heating, which has been

shown to solve the problem of limited penetration of IR for thick materials. Intermittent heating can be achieved by keeping product temperature constant through turning the natural gas supply on and off. The advantages of intermittent heating have been well recognized in terms of energy savings and improved product quality, since the desired processing temperature can be maintained (Sandu, 1986; Chua and Chou, 2003; Zhu et al., 2010).

In order to demonstrate the advantages of the new SIRDBD processing method and facilitate industrialization and commercialization of the new technology, the objectives of this study were as follows:

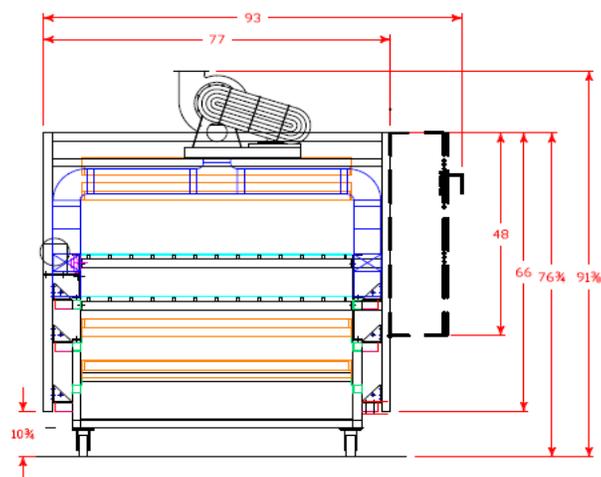
1. To design and build a mobile IR heating equipment for SIRDBD of sliced and diced potatoes.
2. To conduct tests to evaluate its processing performance and product quality.
3. To provide essential information for scale-up of the new processing method and appropriate processing parameters to achieve desirable product quality.

## **2. MATERIALS AND METHODS**

### **2.1. IR HEATING EQUIPMENT**

We worked with Catalytic Infrared Drying Technologies LLC (Independence, KS) and designed a new mobile IR unit for demonstrating on an industrial scale the efficacy of a continuous IR heating system to accomplish SIRDBD of fruits and vegetables. Even though it is a continuous heating system, the arrangement of the emitters has certain capability to simulate intermittent heating. The detailed design drawing of the mobile IR unit is given in Figures 1 and 2.





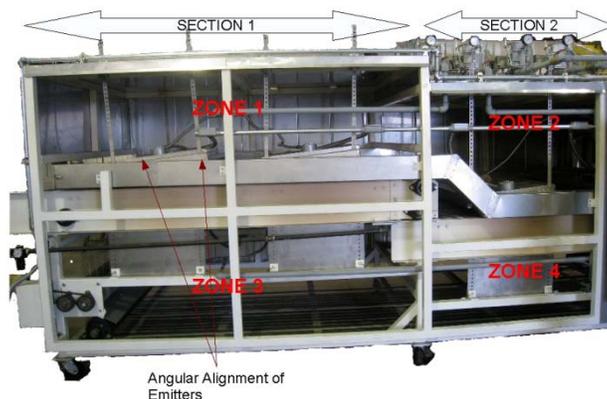
**Figure 2 Design drawing of mobile IR equipment (Rear View)**

The IR heating unit is equipped with an automatically controlled variable speed conveyor belt and catalytic emitters powered with natural gas. The effective heating area is  $1.5 \times 4.5$  m ( $5 \times 15$  feet). The IR intensity or heat delivered to the products can be adjusted by varying the gas supply or by changing the emitter positions. The height, length and width of the new mobile IR equipment are 2, 6 and 2 m (77, 240 and 77 inches) respectively (Figures 1-3). The overall width of the equipment, including the control panel, is 2.4 m (93 inches). The total weight is approximately 2000 kg (4500 lbs).



**Figure 3 Mobile infrared heating equipment for processing vegetables and fruits**

The unit consists of 8 emitters in 4 imaginary zones as shown in Figure 4. Each zone is equipped with 2 emitters. Zones 1 and 3 together and zones 2 and 4 together hereinafter are referred as section 1 and section 2, respectively. Each emitter has a dimension of  $0.6 \times 1.5$  m ( $24 \times 60$  inches). Emitters can be positioned at different distances from the belt to vary IR intensity. The angular alignment of the emitters was for achieving optimized performance of catalytic IR emitters. Unless otherwise stated, during the experiments the distance between the emitters and the belt was 3 inches at the lower end and 5 inches at the higher end. If it is necessary to provide very high heat flux to the product, the distance between the emitters and the product can be adjusted to be even less than 0.05 m (2 inches).



**Figure 4 Side view of inside mobile IR equipment with imaginary zones and imaginary sections**

The unit has four type-J thermocouples (2 on top of zone 1 and 2) for monitoring the air temperature within the unit itself. The IR intensity was varied by changing the natural gas supply. The highest IR intensity was achieved by setting the gas supply valves fully open (100%) which provided energy of 607,714 kJ/h (≈576,000 BTU/h) for the eight emitters. Similarly, the lowest IR intensity was achieved by setting the values at the lowest position (0%) which provided energy of 303,857 kJ/h (≈288,000 BTU/h) for the eight emitters. Setting the controller to 0% at the panel provided 50% actual gas flow to the emitters. Changing the setting from 0% to 100% at the panel changed the actual gas flow from 50% to 100%, respectively. In the current study, we reported the actual gas flow rates rather than the settings at the panel. All electrical components in the IR unit operated at 208V. The IR emitters were only run on natural gas. However, they can be changed to operate with propane. A fan was installed on top of the unit and was used to remove air with high moisture from the heating chamber when it was necessary. It is recommended that the fan should be turned off during blanching to obtain high relative humidity in the chamber to minimize the moisture loss when excessive moisture loss is not desirable.

## 2.2. IR heating equipment Testing

During the tests, the speed of the belt varied from 0.5 m/min (1.654 ft/min) to 1.2m/min (4.017 ft/min). The speed of the belt in the unit was controlled by using a variable speed motor. The relationship between frequency (Hz) of motor and actual speed of the conveyor belt was established and is given the relationship (1):

$$v_b = 0.1551 \times f + 0.9996 \quad (1)$$

where,  $v_b$  is the speed of belt (ft/min) and  $f$  is the frequency (Hz) and the correlation coefficient  $r^2$  was 0.9996. The belt specifications were thus: flat flex 42"×0.062"×60" wide 25 sp, sle, ss. The stainless steel belt had a mesh opening of 2 ¼"×¼".

## 2.3. DRY-BLANCHING AND DEHYDRATION TESTS

Russet potatoes were purchased from a local grocery store in Independence, Kansas. Potato slices with three different thicknesses (2.89±0.34, 6.42±0.36 and 9.03±0.32 mm) were used for performing the tests. Diced potatoes with dimension of 9.5×8.3 mm were also tested. The following procedure was adopted to measure the moisture content of

potatoes: Potatoes which were brought from the processing facility in frozen state were allowed to thaw in plastic pouches. The whole content of plastic pouches was dumped into a blender and was ground. At least 10 g of ground sample was put into metallic dishes which were placed into a vacuum oven at 70°C for 24 hours. Experiments were in triplicate and average values are reported. Initial moisture content of potatoes was 81.21±2.21% on wet basis. We measured enzymatic activities, quality, surface and center temperatures and final moisture content of the samples. The load rates of potato slices varied from 2.10 to 6.42 kg/m<sup>2</sup> for 2.89 and 9.02 mm thick samples, respectively. The relationship between loading rate and slice thickness was established as:

$$LR = 0.7089 \times Th + 0.1468 \quad (2)$$

where, *LR* is the loading rate (kg/m<sup>2</sup>) and *Th* is the product thickness (mm) and the correlation coefficient *r*<sup>2</sup> was 0.9933. In order to assess the optimal processing conditions to achieve blanched products, tests under different conditions were conducted (Table 1).

**Table 1. Test conditions for dry-blanching and dehydration of potato slices**

Test condition	Gas supply		Conveyor speed m/min (ft/min)	Fan	Residence time (seconds)	
	Section 1	Section 2			Exposure to IR	Total
1	100%	OFF	0.5 (1.7)	ON	272	544
2	100%	OFF	1.0 (3.2)	OFF	141.5	283
3	100%	OFF	0.7 (2.4)	OFF	185	370
4	100%	50%	1.1 (3.5)	OFF	256	256
5	100%	OFF	0.8 (2.7)	OFF	164	328
6	100%	50%	1.2 (4.0)	OFF	224	224

For all these tests, the distance between the bottom/top emitters and conveyor belt were 3 inches at low side of the emitter to 5 inches at high side of the emitters. Direct exposure to IR residence time is the time that the potato slices were directly passing through the top/bottom heating section whereas the total residence time is the time that the potato slices remained in the unit. This means that in the case of tests with Section 2 off, the potato slices only experienced heating in Section 1. However, the total residence time count is based on the total time for samples to go through both Section 1 and 2.

To determine the final temperature of the product exiting the IR equipment, we measured the surface and center temperatures of the food products using a hand-held

infrared thermometer and type-K thermocouple, respectively. To monitor the temperature change during the entire residence time within the unit, the center and surface temperatures of slices were measured and recorded using type-K thermocouple and Omega HH147 Data Logger Thermometer (Omega, Connecticut, USA). The temperature data provide important information for avoiding over and under heating of the products, calculating enzyme inactivation, and improving the design of IR heating equipment and configuration of the emitters.

## **2.4. Test Procedures of polyphenol oxidase and peroxidase enzymes**

### **2.4.1. Testing peroxidase enzyme activity**

Residual peroxidase enzyme after dry-blanching of the products was conducted (Miller, 1998 and Nielsen, 1998). The detailed procedures involved preparation of 0.5% Guaiacol solution, preparation of 0.08% Hydrogen Peroxide, sample preparation and testing. In preparation of 0.5% Guaiacol solution, 125 ml distilled water was poured into a clean 250 ml brown glass storage bottle and 125 ml isopropyl alcohol added to the bottle. A sample volume of 1.3 ml concentrated Guaiacol was added to the bottle. The bottle cap was replaced and storage glass inverted several times to mix the solution thoroughly. In preparation of 0.08% Hydrogen Peroxide, we used a brown glass storage bottle containing 250 ml distilled water into which 0.7 ml of 30% Hydrogen Peroxide was added and the bottle cap replaced. After preparing the reagents, 7 ounces of product material was put in blender and 600 ml of water added. The blender was run for 1 minute to produce the puree. A fine mesh silk filter (0.15×0.15 m (6"× 6") square) was used to strain 5-6 ml of the blended sample. The procedure was repeated to strain about 50 ml of the sample into the same container. Then 2.0 ml each of this strained sample were transferred into two 25 ml Nalgene fermentation tubes. One of the tubes was identified as the blank and 21 ml water added to this tube. In the second tube (reaction tube), 20 ml water was added. Approximately 1 ml (1 eye-dropper) of 0.5% Guaiacol was added to both tubes. Approximately 1 ml (1 eye-dropper) of 0.08% Hydrogen Peroxide was added in the reaction tube. The tubes were covered at the top and inverted three times to blend the mixtures. We observed and noted the time any color change occurred in the "reaction" and control tubes. Any color change in the reaction tube was considered a positive test (i.e. inadequate blanching of the product). If no color change developed in 3.5 min, the test was considered negative, and the product adequately blanched. If color develops after 3.5 min the test was still considered negative.

### **2.4.2. Testing polyphenol oxidase enzyme activity**

The indicator enzyme in potato blanching is polyphenol oxidase (PPO). The procedures for testing the residual PPO were provided by Deb Dihel (Director R&D, Product Development, ConAgra Foods). It is known that if PPO is not inactivated, browning reactions take place within 30-60 minutes. Thus after IR dry-blanching, the color change of potatoes was visually examined.

## **3. RESULTS AND DISCUSSION**

### 3.1. IR equipment performance

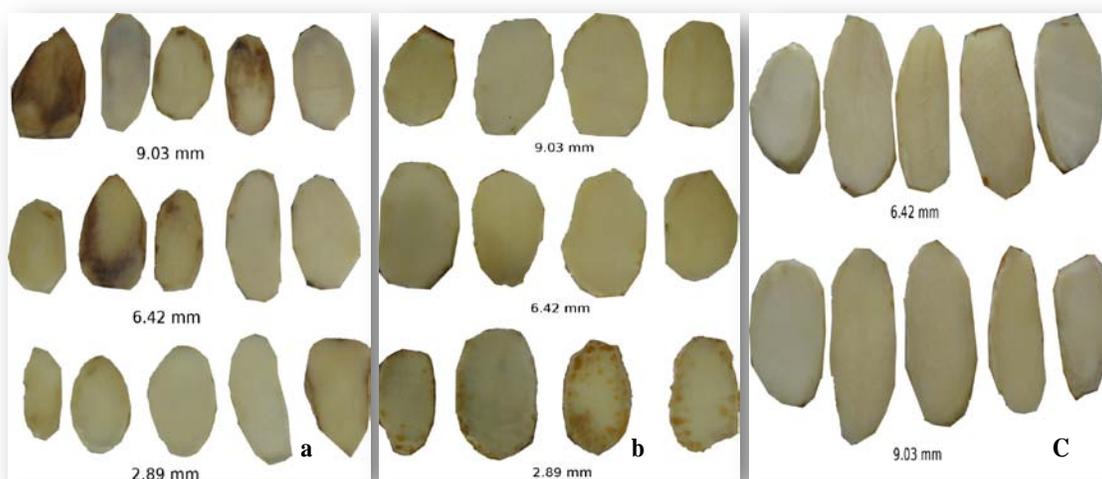
The test results under different equipment settings and operation conditions are given in Table 3. In general, the weight reduction increased with the decrease of thickness which ranged from 10 to 54%. However, for some tests, the surface temperatures of the products increased with the increase of product thickness which could be due to cooling effect on thin slices at the exiting point when the temperatures were measured. The highest weight reduction occurred for Test 1 when the fan was on and heating time was relatively long. During our experiments we observed that the best condition for blanching of 2.89 mm thick samples was Test 2 with desired product and short heating time as can be seen from Figure (a).

**Table 2. Final moisture content, percentage weight reduction and surface temperature of potato slices**

Test condition*	Slice thickness (mm)	Final moisture content (%MC)	Weight reduction (%)	Temperature (°C)
<b>Test 1</b>	2.89±0.34	59.52	53.57	52.82±5.09
	6.42±0.36	74.81	25.38	55.78±1.99
	9.03±0.32	77.00	18.29	57.22±1.49
<b>Test 2</b>	2.89±0.34	73.29	29.63	48.50±3.77
	6.42±0.36	78.17	13.91	51.65±0.71
	9.03±0.32	79.34	9.04	56.62±2.69
<b>Test 3</b>	2.89±0.34	62.42	50.00	49.73±2.34
	6.42±0.36	76.57	19.79	51.05±2.09
	9.03±0.32	78.31	13.38	52.25±0.96
<b>Test 4</b>	2.89±0.34	69.93	37.50	93.80±3.11

	6.42±0.36	76.56	19.83	90.60±2.99
	9.03±0.32	77.67	15.85	90.55±2.45
	2.89±0.34	64.85	46.54	42.13±1.81
<b>Test 5</b>	6.42±0.36	77.65	15.93	53.03±3.09
	9.03±0.32	79.05	10.29	53.73±2.58
	2.89±0.34	66.97	43.10	99.15±0.21
<b>Test 6</b>	6.42±0.36	76.75	19.20	92.87±5.96
	9.03±0.32	78.42	12.94	78.88±1.42

\* Table 1 summarizes the test conditions for dry-blanching and dehydration potato slices

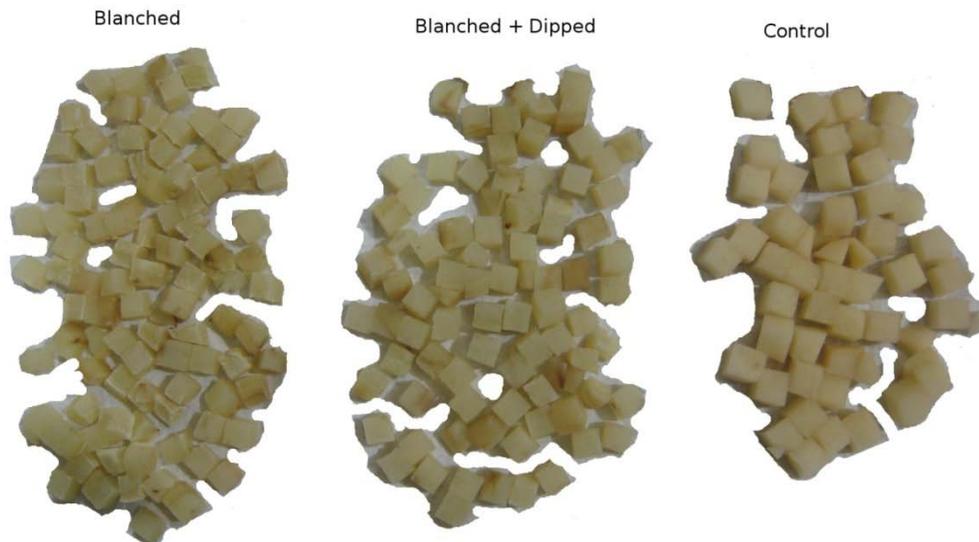


**Figure 5: Images of potato slices of different thicknesses: a: 1 hour after blanching (Test 2); b: 45 minutes after IR blanching (Test 3); c: 30 minutes after blanching (Test 4).**

After exiting the blancher no significant color change of potato slices were observed. However, it is seen from Figure 5(a) that the color change in 9.03 and 6.42 mm thick samples was significant. This could be due to the fact the temperature profile during IR

blanching of thicker samples in Test 2 was not enough to inactivate PPO enzyme within the center of the thick slices. However, for 2.89 mm thick samples it can be assumed that PPO was inactivated since no browning reactions occurred. Both Test 3 and 4 had similar effect on PPO inactivation and were suitable for blanching of 6.42 and 9.03 mm thick samples (Figs 5(b) and 5(c)). But the 2.89 mm samples had charred zones. The Test 3 used much less heating time (185 seconds) compared to Test 4 (256 seconds). The shorter heating time of Test 3 also means less energy consumption. It was also observed that Test 5, which had less residence time than Test 3, therefore less energy consumption, also inactivated the PPO in potato slices thus it is recommended for dry-blanching of 6.42 and 9.03 mm thick samples.

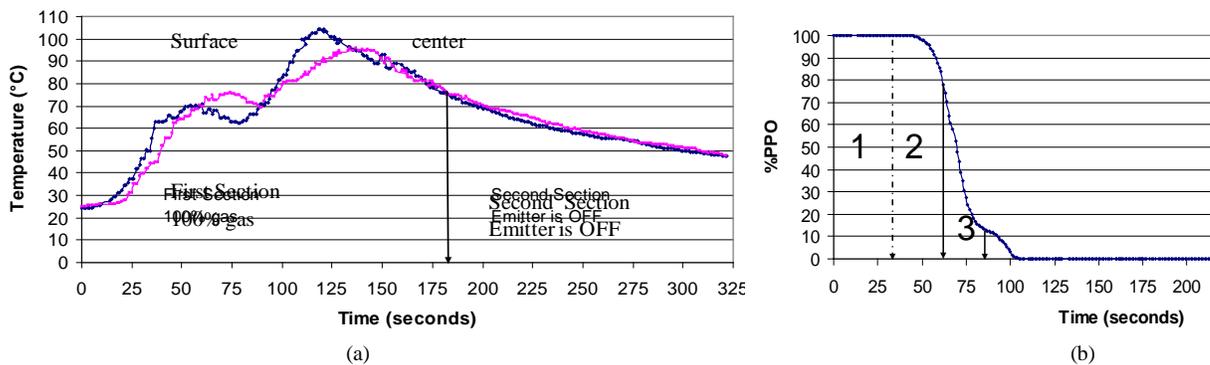
In case of diced potatoes, it was noted that after 4 minutes exposure to IR radiation, the weight of diced potatoes reduced by 51.06% and the moisture content decreased to 66.31%. In order to regain the moisture loss caused by infrared dry-blanching, diced potatoes were dipped into water for 1 minute after blanching and the moisture content was increased to 70.2%. After 30 minutes slight browning reaction took place in control samples; however, there was no observed browning for blanched samples (Figure 6). It is notable that dipping after blanching improved the final appearance of diced potatoes. The blanching time should be much shorter if the configuration of emitters is optimized.



**Figure 6. Diced potatoes 30 minutes after dry-blanching**

### **3.2. Temperature profiles and theoretical inactivation of polyphenol oxidase (PPO)**

Heating profile of 6.42 and 9.03 mm thick potato slices were measured during infrared dry-blanching process. For the 6.42 mm slices the conditions of Test 5 and 6 were used.

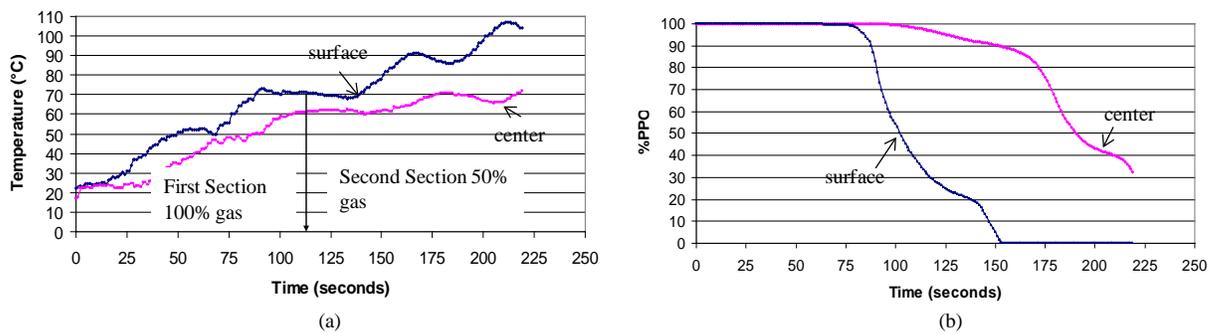


**Figure 7. (a): Temperature profile and (b): percentage of remaining PPO for 6.42 mm thick slices at 0.8 m/min (2.739 ft/min) belt speed and emitters on OFF mode in Section 2 (Test 5).**

For Test #5, during IR heating the surface temperature of potato slices rose more rapidly than the center temperature. However, after exiting the region of the first emitter (after 50 seconds in Figure 7 (a)) of zone 1 and 3, the surface temperature decreased due to evaporative cooling and no emitters above or below the products and center temperature remained almost constant. Upon entering the region with the second emitter in Section 1 (zone 1 and 3) the surface and center temperature of potato slices continued to rise albeit not significant as in the case of the region with the first emitter. The temperature of the slices in the Section 2 started to decrease until exiting the unit. Although there was no heating in Section 2, the section still prevented the product from rapid cooling.

To estimate the PPO activities, the decimal reduction time (D-value) of 5 minutes at 65°C with a thermal resistance constant (z-value) of 8°C was used (Anthon and Barret, 2002). It is seen from Figure 7(b) that the inactivation of PPO started when the center temperature of slices reached very close to 65°C which corresponded with the location of products exiting the first top and bottom emitters in zone 1 and 3. This shows that the significant temperature increase in the first top and bottom emitters in Zone 1 and 3 triggered the inactivation of PPO. In the area of the Fig. 7(b) labelled as number 3, the slices were traveling between the first and the second emitters in section 1. Upon entering the second top and bottom emitters in section 1, little amount of PPO was left to be inactivated. Thus, the result shows that before exiting the second top and bottom emitters in section 1, PPO was completely inactivated.

The same experiment was also repeated with a slightly higher residence time for potato slices having 9.03 mm thickness. Similar temperature profile and inactivation kinetics were obtained.



**Figure 8. (a): Temperature profile and (b): percentage of remaining PPO for 6.42 mm thick slices at 1.2 m/min (4.017 ft/min) belt speed and 50% natural gas flow in Section 2 (Test 6).**

To compare the difference between Test #5 and #6, Figure 8(a) shows that the temperature profile of Test #6 was very similar to the Test #5 (Figure 7(a)) in Section 1, but the temperature increase was slower because the speed of conveyor belt was almost 1.5 times faster. In Section 2, because the emitter was on (at low intensity with 10.55 kW of heat flux per emitter), the temperature of potato slices continued to increase. However, the significant difference between the surface and center temperatures was not expected. This might be due to the fact that the thermocouple tip protruded outside the surface of potato slice and was exposed to the IR heat directly. The PPO inactivation started when the surface temperature of slices reached above 65°C upon exiting the second top and bottom emitters in Zone 1 and 3, whereas center temperature of slices reached above 65°C upon exiting the first top and bottom emitters in zone 2 and 4 (first top and bottom emitter in Section 2). When complete inactivation of PPO was achieved at the surface, about 30% PPO still remained at the center region. We observed that in order to quickly heat up the product to inactivation temperatures, it is necessary to use high IR intensity in the initial stage.

### 3.7. Energy Consideration

In order to avoid unnecessary energy use and to obtain high quality of either blanched or partially or fully dehydrated products, specific adjustment of the equipment setting based on each product are necessary. For instance, moisture loss can be controlled by optimizing the processing conditions, such as emitter configuration, amount of natural gas to the emitters, belt speed and dipping in water after blanching to replenish the lost moisture.

To perform an energy analysis of the processing system, the following considerations were made: energy loss by natural gas to infrared conversion was based on the conversion rate for natural gas to infrared radiation of approximately 80%; it was assumed that heat losses are by natural convection and radiation; the face-material of the equipment was polished stainless steel; and the temperatures of the walls of the building surrounding the equipment were assumed to be the same with the ambient temperature (20°C). Summarized energy analysis results for a continuous process (Test 2) with total processing time of 283 s and 4 running emitters during infrared dry blanching of potato

are presented in Table 7 (natural gas supply at section 1 was set at 100% and at section 2 the emitter were turned off; the conveyor speed was set at 1 m/min (3.175 ft/min); the fan was set at off mode; the exposure time to IR was 141.5 s and the total product residence time in the unit was 283 s).

**Table 7. Summarized data of energy analysis for a selected condition (Test 2).**

<b>Parameter</b>	<b>Amount**</b>
Power consumption	42.2 kW
Energy losses	
gas to IR	- Loss due to conversion of natural 4777.3 kJ
	- Energy loss by natural convection 1074.4 kJ
	- Energy loss by radiation 140 kJ
Total energy loss	5986.7 kJ
Operation efficiency	74.9%
Total natural gas consumption	0.64 m <sup>3</sup>
Cost per lb of potato	0.9 c/lb

\*Selected test conditions for potato processing are thus: Gas supply at section 1 equals 100% and at section 2 is off; Conveyor speed is set at 3.175 ft/min; Fan is set at off mode; The exposure time to IR is 141.5 s and total product residence time in unit 283 s.

\*\* The calculations are based on a continuous process with the total processing time of 283 seconds and 4 running emitters.

#### **4. CONCLUSIONS**

Based on the experimental results, IR heating can be used for achieving simultaneous dry blanching and dehydration of sliced or diced potatoes through the use of

appropriate equipment settings and operating conditions. The inactivation of PPO was achieved when one emitter in Section 1 was on and the belt speed was 1 m/min (3.175 ft/min) for the 2.89 mm thick potato slices corresponding to residence time of 283 s. However, to achieve full blanching of thicker slices such as 6.42 and 9.03 mm the belt speed was lowered to 0.7 m/min (2.43 ft/min) or to 0.8 m/min (2.739 ft/min), corresponding to 370 and 328 s residence time, respectively. Or the belt speed can be increased to 1.1 m/min (3.514 ft/min) or 256 s residence time when the emitters in the second section of the equipment were run in lowest heating level. The weight loss varied from 29.63% for 2.89 mm thick samples to 13.38% for 9.03 mm thick slices. Using high heat in the very first stages to heat the slices to inactivation temperatures was essential for obtaining high quality blanched product and for less energy consumption. The moisture loss during the blanching and dehydration can be controlled by selecting appropriate processing conditions or by replenishing the lost water of the blanched products through dipping in water or by spraying water onto the product. The optimized equipment settings and operational conditions need to be determined based on each specific product and the quality requirements of the final product.

## References

- Anthon and Barret, 2002. Kinetic Parameters for the Thermal Inactivation of Quality-Related Enzymes in Carrots and Potatoes. *Journal of Agricultural and Food Chemistry*, 50, 4119-4125
- Bomben, J. L. 1977. Effluent generation, energy use and cost of blanching. *Journal of food process engineering*. 1 (4): 329-341.
- Chua, K. J. and Chou, S. K. 2003. Low-cost drying methods for developing countries. *Trends in food science and technology*, 14 (12): 519-528.
- Gabel, M., Pan, Z., Amaratunga, K. S. P., Harris, L. and Thompson, J. F. (2006) Catalytic infrared dehydration of onions. *Journal of Food Science*, 71(9): 351-358.
- Miller, D. D. (1998) 'Food Chemistry: A laboratory manual'. (John Wiley & Sons. Inc.: New York, USA).
- Nielsen, S. S. (ed.) (1998) 'Food Analysis' 2nd Ed. (Aspen Publishers, Inc.: Gaithersburg, Maryland, USA).
- Pan, Z. and McHugh, T. H. 2004. In U.S. Patent Application. 20060034981. Filed 8/13/2004, published 2/16/2006.
- Pan, Z., C. Shih, T.H. McHugh and E. Hirschberg. 2008. Study of banana dehydration using sequential infrared radiation heating and freeze-drying. *LWT - Food Science and Technology*. 41:1944-1951.
- Sandu, C. 1986. Infrared radiative drying in food engineering: a process analysis. *Biotechnology progress*; 2(3): 109-119.
- Shi, J., Pan, Z., McHugh, T. H., Wood, D., Hirschberg, E. and Olson, D. 2008a. Drying and quality characteristics of fresh and sugar-infused blueberries dried with

- infrared radiation heating. *LWT – Food Science and Technology*, 41(10):1962-1972.
- Shi, J., Z Pan, T.H. McHugh, D. Wood, Y. Zhu, R.J. Avena-Bustillos, E. Hirschberg. 2008b. Effect of berry size and sodium hydroxide pretreatment on the drying characteristics of blueberries under infrared radiation heating. *Journal of Food Science*. 73(6):E259-E265.
- Shih, C., Z. Pan, T.H. McHugh, D. Wood and E. Hirschberg. 2008. Sequential infrared radiation and freeze-drying method for producing crispy strawberries. *Transactions of the ASABE*. 51(1): 205-216.
- Vanlaanen, P. 2003. Freezing fruits and vegetables. Texas Agricultural Extension Service: L-2215.
- Zhu, Y. and Z. Pan. 2009. Processing and quality characteristics of apple slices under simultaneous infrared dry-blanching and dehydration with continuous heating. *Journal of Food Engineering*. 90(4):441-452.
- Zhu, Y. and Z. Pan., T. H. McHugh, and D. M. Barrett. 2010. Processing and quality characteristics of apple slices processed under simultaneous infrared dry-blanching and dehydration with intermittent heating. *Journal of Food Engineering*, 97(1), 8-16.