CHARACTERIZATION OF BAKED POTATO STRIPS PROCESSED IN A RADIANT WALL OVEN

by

BILAL KIRMACI

(Under the Direction of Rakesh K. Singh)

ABSTRACT

A Radiant Wall Oven (RWO) was used to produce potato strips with lower fat content while maintaining the similar quality to deep-fat fried product. Frozen par-fried potato strips purchased from commercial supplier were sorted and cut to have 5 x 1 x 1 cm^3 dimensions, and baked in a RWO at temperatures of 290 – 365 °C with different processing times. Radiant, natural convective and overall heat transfer coefficients were determined for each RWO treatment by experimentally monitoring temperature and heat flux. Cutting force, puncture force, lightness, chroma and hue, moisture and fat contents of the RWO-baked potato strips were measured and compared to that of deep-fat fried samples (177 °C for 3 min). Correlation between heat transfer parameters and quality characteristics of the samples were also determined. The time-temperature treatment was used to develop a severity parameter to predict the quality characteristics of RWO-baked potato strips. Instrumental and trained panel sensory assessment of texture of the potato strips indicated that RWO-baked strips at 365 °C for 6.5 min had similar texture as deep-fat fried potato strips, yet contained 81.5% less fat. However, those potato strips were lighter and less brown in color, and had 18% more moisture than the deep-fat fried potato strips. Consumer acceptability of RWO-baked potato strips was 65.7% before and 85.7% after revealing the Nutrition Facts. Both were lower than the acceptability of deep-fat fried samples. However, 36.5% of consumers were willing to purchase RWO-baked samples. To reduce the processing time, heating by steam processing for 75 s or 90 s was used prior to potato strips were baked in RWO oven at temperatures of 450 – 550 °C for 1.5 – 3.5 min. Based on the instrumental and sensory analysis, RWO processing at 500 °C for 3 min after steam processing for 90 s resulted in the baked potato strips most similar to the control samples. Finally, a 41-member consumer panel indicated 51.2% acceptability and 35% willingness to purchase the RWO-baked pre-cooked potato strips. Even though RWO-baked potato strips needed improvement, consumers were willing to compromise sensory quality for calorie reduction in potato strips.

INDEX WORDS: Color, Infrared Heating, Potato Strips, Radiant Heat Transfer Coefficient, Radiant Wall Oven, Sensory, Texture

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DEDICATION

To my precious daughter, lovely wife, father, and mother

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CHAPTER 1

INTRODUCTION

French fries are one of the most popular foods in the U.S., as 6.5 million ton frozen French fries were produced annually with a market over $1.6 billion (USDA ERS 2014a; USDA ERS 2014b). In spite of its popularity, French fries are perceived as one of the food products contributing to exceed recommended daily allowances for fat. Fast food consumption including French fries is related to poorer diet and one of the causes of rising obesity rates in the U.S (Pereira and others 2005; Moore and others 2009). Therefore, one of the focuses of the food industry is fat reduction in French fries.

Potato fries are conventionally cooked in hot oil where heat transfer takes place between the oil and fries. Heat is generally transferred as a means of conduction, convection and radiation. Infrared (IR) radiation supplies high heat to product by electromagnetic energy without requiring any medium. Radiant Wall Oven (RWO) used in this study, a gas-fired infrared (IR) heater, consists of an elliptical tube stainless alloy that emits IR radiation with a wavelength range of 3 – 6 μm to the product. Having lower penetration depth of IR radiation, surface of the product gets heated rapidly. This will result in crust and color formation on the surface.

The scope of this research covers the production of reduced-fat potato strips in RWO without compromising the quality. The objectives of this research are as follows:

1. Experimentally determine the overall heat transfer coefficient of RWO processing during baking of potato strips.

2. Study the effect of this process on instrumental and sensory quality characteristics of the baked potato strips with respect to deep-fat fried samples.

3. Evaluate the relationship between heat transfer parameters and the color and texture of the potato strips.

4. Instrumentally measure and compare color and texture of RWO baked, conventional oven baked and deep-fat fried potato strips.

5. Evaluate and compare consumer acceptability and willingness to purchase of RWO baked potato strips to deep-fat fried and conventional oven baked samples.

6. Investigate the quality characteristics of RWO processed pre-cooked potato strips by both instrumental and sensory analysis in comparison with deep-fat fried counterparts.

7. Determine consumer acceptability of the selected RWO processed pre-cooked potato strips based on instrumental and sensory analysis.

This work consists of six chapters. Introduction, the first chapter, is followed by the comprehensive literature review on production and quality of French fries, mechanism and reduction of fat uptake, basic principles and novel applications of IR heating. In the third chapter, frozen par-fried potato strips were baked in a RWO at 12 different time-temperature combinations to achieve the objectives #1, #2, and #3. Assessed instrumental and sensory quality characteristics of RWO baked potato strips were compared to that of deep-fat fried potato strips. Furthermore, overall, radiant and convective heat transfer coefficients were calculated from heat flux and monitored temperatures of the product at the surface and center, surrounding air around the product and wall temperature of the RWO. Relationship between heat transfer coefficients and texture was also evaluated.

Consumer acceptability of the best RWO treatment is discussed in Chapter 4. Moreover, the objectives #4 and #5 were investigated in the Chapter 4. In addition to consumer acceptability, willingness to purchase of the deep-fat fried, conventionally and RWO baked potato strips were also studied. Moreover, instrumental quality characteristics of those samples were determined and compared against each other in terms of moisture and fat content, shrinkage, color and texture.

In Chapter 5, alternative heating method applied to the potato strips prior to RWO baking. Saturated steam was used to pre-cook the potato strips for 75 s or 90 s, and then, they were baked in the RWO at six different time-temperature combinations. Instrumental and sensory quality characteristics of the RWO-baked pre-cooked potato strips were determined. Furthermore, consumer acceptability of the best RWO treatment was also determined by sensory analysis. The scope of this chapter was to complete objectives #6 and #7.

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CHAPTER 2

LITERATURE REVIEW

French Fry Production

Potato, *Solanum tuberosum*, is considered a staple food around the world. The total potato production was over 368 million ton in the world in 2013 (FAOSTAT 2014). The large producers of the potato crop are China (24%), India (12%), Russia (8%), Ukraine (6%), and U.S. (5%) (FAOSTAT 2014). Potato production in the U.S. was forecasted almost 20 million ton in 2013 (USDA NASS 2014). Raw Russet Burbank potatoes consist of 78.6% water, 18.1% carbohydrate, 2.1% protein and 0.1% fat (USDA ARS 2014). Almost one-third of the harvested potato crop in the U.S. was utilized as Frozen fries in 2012/2013 (Figure 2.1, USDA ERS 2014a) with a total trade over $1.6 billion (USDA ERS 2014b).

Raw Idaho® potatoes meet requirement of American Heart Association's criteria for foods low in saturated fat and cholesterol (The Idaho Potato Commission 2014). However, when potato strips are deep-fried, they play significant role in calorie supply due to their fat content. The fat content of French fries available at quick service restaurants is given Table 2.1 which ranges from 12.5 – 15.5% wet weight basis (USDA ARS 2014). Because of health issues, consumers are becoming more interested in the nutritional value of the fast food products within the past two years, according to 87% of fast food operators (NRA 2014). Lowering fat intake has been advised as it decreases cardiovascular risk on short-term, although long term effects were not known (Rees and others 2013). Furthermore, lowering energy intake by fat reduction was found to be associated with lower body weight (Hooper and others 2012).

One of the focus of the food industry is fat reduction. "Reduced-fat" claim was defined as at least 25% less fat per reference amount customarily consumed (RACC) than an appropriate reference food, or for meals and main dishes, at least 25% less fat per 100g (FDA 2013). Furthermore, it was also stated that reference food may not be "Low Fat". Kraak and others (2011) analyzed the progress of the food industry. They have concluded that while production companies made moderate progress for healthier foods, fast-food companies had limited progress to offer healthier foods on their menus, as suggested by Institute of Medicine (IOM). Recent efforts to reduce the fat content of the French fries are given in Table 2.2.

Fat Uptake Mechanism

Frying is responsible for almost all of the fat content of the French fries, except originally found in the cell structure of the potato. When surface temperature of the French fries reaches to 100 °C during frying, water around the surface begins to evaporate. As the surface dries out, boundary of evaporating water shifts toward the center of potato strips causing crust formation (van Loon and others 2007). Migration of water vapor from core makes the crust porous (Mellema 2003). Even though, void space constitutes most of the (~80%) volume of the crust (Lima and Singh 2001), only about 20% of the adsorbed fat is found in the pores at the end of frying (Moreira and others 1997). When the product is removed from the fryer, evaporation of water stops and condensation of the water vapor starts inside the French fries forming the vacuum. Many studies (Moreira and others 1997; Aguilera and Gloria-Hernandez 2000; Moreno and others 2010) argue that most of the oil adsorption in French fries happens during the cooling of the fried samples due to condensation of the water vapor inside the core and capillary suctions. Ufheil and Escher (1996) added dye tracer to the oil and reported that most of the fat uptake occurred at the end of frying. They concluded that fat uptake is a surface phenomenon involving a balance between oil adhesion to surface and drainage immediately after the product removed from the fryer. Moreover, Weaver and Huxsoll (1970) reported 25% oil reduction by just draining potato strips with a paper towel. However, fat uptake mechanism in the potato chips is mainly due to capillary action because of having very low moisture content, i.e., vapor migration stops at some point of the frying process, with respect to potato strips (Mellema 2003). In addition to condensation and capillary forces, pore sizes, surface irregularity, permeability, crust structure, wetting properties and hydrophobicity also plays role in oil adsorption (Moreno and others 2010).

Fat Uptake Reduction

As amount of fat in the diet became a concern, efforts to reduce the oil content of the fried potato strips have been started (Gamble and Rice 1988). There has been broad interest on research for reduction of fat content of French fries. The efforts to reduce fat content of the French fries can be categorized as modification of the raw material or the process. Gamble and Rice (1988) discovered that oil uptake is related to the surface area and thickness of the potato chips to be fried. They concluded that the thicker the potato strips the lesser the oil content of the product. In another research, Tajner-Czopek and others (2008) reported that thicker potato strips had significantly higher fat content than thinner potato strips. However, both types of potato strips were not treated in the similar manner. They increased the frying time for thicker potato strips to achieve products with proper texture. Longer frying times resulted in more water evaporation, thus more pores were formed (Mehta and Swinburn 2001; Romani and others 2009). Therefore, fat content of the product on wet weight basis also increased with increased frying times.

Rommens and others (2010) reported that potato strips made from the outer sides adsorbed less oil than those from inner sides of the same potato, as relatively large parenchyma cells found in the central pith region of the tuber. Furthermore, outer strips had less moisture and more solids than inner strips. However, frying only outer parts of the potatoes and storing the rest for other purposes, such as canning as suggested by the authors, is not practical due to low demand of those products (USDA ERS 2014a).

Coatings and batters are used to reduce the fat content of the French fries (Mellema 2003), and there are some commercial applications of this method as well (Baertlein 2011; Strom 2013). Lisińska and others (2007) investigated that concept from raw material point of view. They used hemicellulytic and pectolytic enzymes to destruct the cell walls of the potato strips to lower the fat adsorption during frying. Weakened cell walls due to activity of enzymes caused starch release. An impermeable layer, formed when released starch encountered with hot oil during frying, significantly reduced the oil uptake by limiting the fat penetration through the inside of the potato strips. Moreover, it was reported that fat reduction after pre-treatment with hemicellulytic and pectolytic enzymes in the Innowator variety was higher when compared to the Santana variety. It should be noted that the former variety had lower dry matter than the latter.

Blanching is another important unit operation of French fries production. In general, blanching is a single or multi stage procedure with hot water at temperature 60 – 100 °C or steam depending on the desired product quality (Sanz and others 2007; Tajner-Czopek and others 2008). The main purposes of blanching potato strips are (i) to inactivate the enzyme activity, (ii) to condition the potato strips by leaching out the reducing sugar that controls the color after frying, (iii) to reduce the fat adsorption during frying by forming a surface barrier through the gelatinization of the surface layer of starches (Weaver and others 1975). High temperature short time blanching inactivates enzymes, such as polyphenol oxidase, and low temperature long time blanching controls the reducing sugar content of the potato strips (Sanz and others 2007). Pre-drying, and removing the excess amount of moisture gained during blanching of potato strips prior to par-frying is also important in reducing the oil uptake. The purpose of pre-drying is to reduce the frying time and degradation of oil, thus, reducing the fat uptake during frying. Tajner-Czopek and others (2008) compared convective pre-drying of blanched potato strips to vacuum-microwave (VM) pre-drying. They reported that hot dry air at 75 °C for 10 – 15 min was required to increase the dry matter of blanched potato strips to 25%. Moreover, VM processing for 6 min was enough to achieve the same level of dry matter in the potato strips. Besides shortening the processing time, deep-fat fried VM processed potato strips adsorbed less fat than the fried hot dry air processed potato strips.

Ahmad Tarmizi and Niranjan (2013) compared the effect of air and vacuum drainage on the oil content of the potato chips and French fries. They concluded that oil content of the French fries drained under vacuum or atmospheric pressure was not significantly different, even though vacuum drained potato chips had 38% less oil than potato chips that were drained under atmospheric pressure. It was stated that vacuum drainage reduced the fat content of the potato chips when there was moisture evaporation from the product. However, net moisture evaporation ceased during vacuum draining of potato strips.

Quality of French Fry

Quality, a term, can be regarded as an absence of defects or a degree of excellence (Shewfelt 1999). Kramer and Twigg (1970) defined the quality as: *"composite of those characteristics that differentiate individual units of a product, and have significance in* *determining the degree of acceptability of that unit by the buyer.”* Quality of the potato strips includes moisture content, color, texture and flavor, as well as the fat content (Pedreschi 2009).

Texture

Texture of the French fries is one of the most important quality aspects that leads to its popularity among consumers, besides color. Non-uniform texture of the French fries can be described as a mealy like baked potato core is wrapped with a porous, crisp and oily crust (Weaver and others 1975; Miranda and Aguilera 2006; Pedreschi 2009). French fry texture is formed during frying. Porous crust formation was described in the previous section. Briefly, the removal of water from surface and under surface forms the crust, and movement of pressurized water vapor from inside to outside causes porosity in the crust. Lima and Singh (2001) emphasized that most of the (~80%) volume of the crust consists of void space. That leads crispiness of the French fries, related to numerous fractures when the porous and low moist crust is being deformed. On the other hand, gelatinized starch and disintegrated lamella between cells yield the soft and cooked potato texture, i.e. mealy texture, in the core (Miranda and Aguilera 2006).

Studies that assessed the texture of the French fries are given in Table 2.3. In regards to texture of French fries, cutting force, hardness, puncture force and crispiness are evaluated instrumentally. Cutting force is defined as the required maximum force to cut the French fries by knife blade probes. Puncture test is the penetration of the 1 – 3 mm diameter puncture probe into the product. This test can give information about springiness of the product: the slope of initial linear increase in force, toughness of the crust: the maximum force to penetrate the probe, and softness of the core: the constant force registered at the center (Pedreschi and others 2001). Kramer shear or knife blade shear tests are used to determine the hardness of the potato strips.

Walter Jr. and others (2002) studied the texture of the restructured sweet potato French fries by instrumental texture profile analysis, three-point bending force, Kramer shear force, and puncture force. Among those tests, precision of the Kramer shear force was reported as the highest by having the least coefficient of variation.

Vincent (1998) stated that many small fracture events might have surpassed the large facture events during deformation of crispy crust. Sound emission, which occurred during those mechanical failure events, played important role on the sensory perception of crispiness (Vickers and Bourne 1976). Therefore, crispiness of French fries can be evaluated by mechanical and acoustic measurements such as frequency and intensity of the force and sound (Vincent 1998; Sanz and others 2007). Besides, linear distance is also used to evaluate the crispiness of the food products (Kitchen 2013). The linear distance is the length of force-deformation curve, i.e. imaginary line that connects all data points. Longer linear distance due to jagged response of the force corresponds to the crispier and more brittle texture (Varela and others 2006).

Sanz and others (2007) evaluated the effect of pre-drying and final frying times on the crispiness of French fries by fracture and acoustic measurements in terms of number of peak force and sound higher than a certain threshold. They noted that effect of pre-drying on the crispiness of the French fries can be explained by moisture content of the crust instead of entire product.

Van Loon and others (2007) investigated effect of pre-drying and par-frying conditions on the crispiness of the French fries by counting number of peaks in the force-deformation curve for each treatment. They have reported that pre-drying the blanched potato strips to 10% - 15% weight loss increased crispiness. In contrast, crispiness was reduced when weight of the potato strips decreased by 20% at the end of pre-drying. They also noted that par-frying of potato strips at 180 °C resulted in crispier products than par-frying of potato strips at 160 or 170 °C. They concluded that number of peaks in the force-deformation curve was well correlated with the crispiness evaluated by sensory analysis.

One of the most important factors that influence the texture of the French fries is dry matter. In general, potatoes having higher dry matter, specific gravity, and starch content are selected for frying (Miranda and Aguilera 2006). Specific gravity differs not only between tubers of same plant, but also strips taken from different parts of the same tuber (Liu and others 2009). Inner pith area of the potato tuber containing large parenchyma cell, in which more water and less starch are found, has lower specific gravity than outer cortex area (Rommens and others 2010). Therefore, there is variation in the texture of the French fries naturally due to heterogeneity of the tuber. Lisiñska (1989) stated that Russet Burbank variety potatoes had specific gravity of 1.1 – 1.115 and over 25% dry matter, yet resulted in the highest yield of French fries with 55.7 – 56.9% among the three different potato varieties.

Using firming agents during blanching, such as calcium salts, improve the firmness of the potato strips, besides pre-drying. Firming agents are especially needed when steam is used to blanch the potato strips that softens the tissues (Ng and Waldron 1997). Moreover, low temperature blanching promotes the pectin methyl esterase (PME) activity, i.e. hydrolysis of methyl ester bonds in pectin increased. As a result, free carboxylic groups are released and their possible interaction with divalent ions leads increase in firmness (Aguilar and others 1997). In addition to texture, it was reported that PME activity also reduced the fat content of the potato strips due to lowering the porosity (Aguilar and others 1997).

Color

Color and appearance of a product is the first quality parameter that consumers assess (Lawless and Heymann 2010b). Color can be defined as the perception of light-object interaction in the brain. When light encounters surface of an object, it is refracted, reflected, absorbed or transmitted. Cones, found in the human eye, are responsible for color perception at higher light levels and sensitive to red, green and blue light (Barrett and others 2010). Color is instrumentally measured with colorimeters and its quantification is defined by three dimensional CIE (International Commission on Illumination) color spaces. For instance, in the CIE L*C*h color space, color is defined as lightness (L*), hue angle, and chroma. Lightness shows the light reflection from the object, where 0 and 100 corresponds to pure black and pure white, respectively. (Barrett and others 2010). Hue angle of 0 °, 90 °, 180 ° and 270 ° represents the red-purple, yellow, bluish-green, and blue, respectively (McGuire 1992). Chroma is the saturation or intensity of the color, i.e., brightness (Barrett and others 2010). Shewfelt (1993) emphasizes the importance of relevancy of color evaluation to human perception rather than directly reporting Lab results, which is defined as machine language of color.

Light golden brown color of the French fries was a result of the reaction between reducing sugars and amino acids during frying, known as Maillard reaction (Márquez and Añón 1986). High correlation between color parameters (L* and a*) and acrylamide, a carcinogenic compound that mainly formed via Maillard reaction, content of the French fries was reported (Pedreschi and others 2006; Keramat and others 2011). Maillard reaction not only improves the color, but also contributes to the frying flavor in the crust during frying (Gillatt 2001). When not limited by lowering reducing sugar or asparagine content of the raw potato, this reaction will cause excessive darkening, off-flavor and acrylamide formation (Lisiñska 1989; Sahin 2000; Pedreschi and others 2006).

One of the methods to prevent excessive Maillard reaction is controlling the reducing sugar content of potato. During the chilled storage of potatoes, starches break down and form reducing sugars. This can be controlled by two-stage conditioning of potatoes prior to processing. Initially, potatoes are pre-conditioned by storing at 12 – 15.5 °C for as long as 6 weeks, followed by second storage for 5-6 weeks at 20 – 30 °C and 85 – 90% relative humidity prior to processing (Pinhero and others 2009). It should be noted that storage of potatoes at 20 °C causes excessive greening of tuber leading to color defect on the potato strips, although greening was not noticed at 5 °C storage (Salunkhe and others 1989). Besides conditioning, blanching is also used to reduce sugar content of the potato strips (Weaver and others 1975). Color analysis of deep-fat fried potato strips are given in Table 2.4. As it seen from the table, different lightness, a* and b* of fried potato strips were reported for the same frying conditions. Thus, color of the potato strips does not depend on only frying time and temperature, but also potato variety, conditioning prior to frying, dimensions of the French fries, blanching time and nature of the oil used (Sahin 2000).

Shrinkage

Shrinkage in the fried product is observed due to removal of bound water (Yamsaengsung and Moreira 2002a). From shrinkage point of view, frying can be separated into three regions: (*i*) initial shrinkage or volume loss stage, (*ii*) recovery stage, and (*iii*) constant stage (Taiwo and Baik 2007; Andrés and others 2013). In the first region, where product at frozen, or chilled or room temperature is introduced to hot oil causing shrinkage due to water loss. In the recovery stage, when frying times are longer (say, over 3 min), volume of the product expands with respect to initial shrinkage. That is due to excessive pressure built inside the product and some oil replacement of void spaces. While diameter of the fried tortilla chips shrunk, expansion in thickness was observed due to puffing (Yamsaengsung and Moreira 2002b). In the last region, constant stage, shrinkage is ceased due to hardened crust preventing further volume change, in spite of ongoing moisture loss. Andrés and others (2013) verified the aforementioned three shrinkage stages by plotting volume change with respect water loss during frying. It should be noted that internal porosity increased during recovery and constant stage, as moisture vapor migrates from inside core through the crust (Andrés and others 2013).

Volume change in deep-fat fried un-pretreated, blanched and frozen pre-fried potato strips, having .9 x .9 x 3 cm^3dimensions, at 180 °C for 4 min were reported as 36%, 30%, and 10%, respectively (Andrés and others 2013). In the case of deep-fat fried sweet potato chips, which have 3.5 cm diameter and 1 cm thickness, deep-fat fried at 170 °C for 3 min, shrinkage in fried frozen potato chips was 10% and 18% in diameter and thickness, respectively (Taiwo and Baik 2007).

Sensory Analysis

Sensory analysis of a product can be either analytical or affective. Descriptive sensory analysis, an analytical test, requires that the panelists should be trained to increase the precision and accuracy in the evaluation of the same product among panelists. While training of panelists might take two weeks to six months, familiarization of terminology is needed in experienced panel in one or two sessions (Barrett and others 2010). Moreover, human subjects should be selected from the individuals who are the current consumer or potential future consumer of the tested food product, and like the product (Lawless and Heymann 2010c). Product screening is also an important step prior to sensory analysis to use sensory resources effectively (Stone and others 2012).

Just about right scale, generally used in affective testing, combines the intensity and hedonic judgments (Lawless and Heymann 2010a). Participation of at least 40 panelists is recommended for sensory acceptance tests when conducted in a laboratory environment (Stone and others 2012). However, Chan and others (2013) investigated validity of photography usage to report consumer preference on meat doneness by a 10-member panel. The panelists asked to rate the meat doneness on the JAR scale. They concluded that photography usage to report consumer preference was valid.

Consumer, who will consume the food product, oriented quality analysis is also beneficial to characterize the product, in addition to product oriented quality measurements such as color, texture and fat content determination instrumentally (Shewfelt 1999). Consumer acceptability/preference, or any affective analysis, can be inferred from neither descriptive sensory analysis nor instrumental analysis. Thus, a thorough quality analysis of a specific product requires affective consumer evaluation. Nine-point hedonic scale has been widely used with a considerable success to determine the consumer acceptability (Barrett and others 2010; Stone and others 2012). However, it has been criticized for unequal intervals, lacking of end effects due to consumers tendency, and, reporting the means as acceptability of a product without taking into account unacceptable scores (Dubost and others 2003). Shewfelt (1999) suggested using a three-point acceptability scale to determine consumer acceptability by reporting the frequency of each response. Sensory assessment of French fries has included evaluation of overall appearance, acceptability, flavor, texture, and oily mouthfeel (Lloyd and others 2004), color and taste (Bingol and others 2012), intensity of blush, crispiness, mealiness, and oiliness (Tajner-Czopek and others 2008; Rommens and others 2010).

Infrared (IR) Heating

Heating is used to cook or warm the food before eating. Hence, texture of the food is altered, the flavor is promoted, color is changed and shelf life of the product is extended. Heat is transferred in three different ways: conduction, convection and radiation. Both conduction and convection require a medium to transfer the heat, but radiation can occur even in vacuum. Physical contact is needed for conduction, as heat is transferred by lattice vibration and/or particle collision (Wang and Sun 2012). In convection, heat is transferred by the natural or forced movement of the fluid (air, oil, etc.) around the product. However in radiative heating, like radio frequency (RF) and microwave heating, heat is transferred by the electromagnetic waves. Furthermore, wavelength and frequency of the electromagnetic waves determine the category of heating. For instance, the higher wavelengths (1 m to 100 km) of electromagnetic waves occur in RF, and the lower wavelengths (0.78 to 1000 μm) are in the infrared (IR) heating range. Having short wavelength, energy do not penetrate deep into the food in IR heating. This allows IR heating to be used as surface heat treatment. Penetration depths measured during IR heating are given in Table 2.5. Sakai and others (1993) modeled the IR heating to predict the temperature profile. They reported that there is no effect of penetration depth of far-IR energy on the temperature distribution in the food.

Basic Principles of IR Heating

The IR portion of the electromagnetic spectrum lies in the range of 0.78 to 1000 μm. IR region is divided into three sub-regions: Near-Infrared (NIR; 0.75 – 1.4 μm), Mid-Infrared (MIR;

1.4 – 3 μm) and Far-Infrared (FIR; 3 – 1000 μm) (Krishnamurthy and others 2008). When emitted IR electromagnetic wave incidents upon a surface, it is absorbed, reflected and transmitted. While most solids do not transmit the IR energy wave, fraction of transmitted depends on the thickness of the liquid. On the other hand, gases reflect very little and non-polar symmetrical molecules, such as O_2, H_2, N_2 and dry air, transmit the IR electromagnetic waves (Pitts and Sissom 1977). Fraction of absorbed, reflected and transmitted radiant energy is called as absorptivity (α), reflectivity (ρ) and transmissivity (τ), respectively. Moreover, the relationship between them as follows (Pitts and Sissom 1977):

$$\alpha + \rho + \tau = 1 \quad (1)$$

Sakai and Hanzawa (1994) reported that main food constituents such as starches, proteins and water absorb FIR electromagnetic energy with wavelength of 2.5 μm and longer. When a food surface is exposed to IR electromagnetic energy, the absorbed IR energy induces changes in vibrational state of the molecules. For example, when water molecules absorb the IR energy, symmetrical stretching, antisymmetric stretching and symmetrical deformation vibrations occur and lead to heating (Sakai and Hanzawa 1994).

Blackbody is defined as ideal emitter which emits all of its energy and has ideal surface to absorb the all incident thermal radiation. Emissive power of a blackbody at a specific temperature, T (K) is defined by the Stefan-Boltzmann law (Pitts and Sissom 1977):

$$E_b = \sigma \times (T)^4 \quad (2)$$

It shows that total emissive power is proportional to the fourth power of absolute surface temperature of emitter source. Emitted radiation energy was proportional to the Stefan-Boltzmann constant (σ), 5.67 x 10 $^{-8}$ W/m^{2}K^4. Furthermore, any surface having higher temperature than 0 K emits IR energy according to Stefan-Boltzmann law.

Different amounts of radiated energy is emitted at different wavelengths from a surface. Spectral emissive power distribution of blackbody ($E_{b,\lambda}$) is defined as a function of temperature (T) and wavelength (λ) by Planck's law (Pitts and Sissom 1977; Krishnamurthy and others 2008; Ibarz and Barbosa-Cánovas 2002):

$$E_{b,\lambda}(T,\lambda) = \frac{C_1 \times \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1} \tag{3}$$

where,

$C_1 = 2\pi c^2 \mathrm{h} = 3.742 \times 10^8 \ W \times \mu m^4/m^2$

$C_2 = hc/k = 1.4387 \times 10^4 \ \mu m.K$

where, h is the Planck's constant (6.626 x 10^{-34} J.s), k is the Boltzmann's constant (5.670 x10^{-8} W/m^2.K^4) and c is the speed of light (3 x 10^8 m/s). When spectral emissive power distribution is plotted against wavelength for a source at different temperatures, higher source temperatures result in higher emissive power with increase in the total number of shorter wavelengths. Wien's displacement law describes the peak wavelength (λ_{max}, µm) at which maximum radiation energy is emitted (Pitts and Sissom 1977):

$$\lambda_{max} = \frac{2898}{T} \tag{4}$$

It indicates that maximum thermal radiation is emitted at lower wavelengths due to increase in the source temperature. The frequency of the electromagnetic waves (v, Hz) at peak wavelength can be found from the propagation velocity of electromagnetic waves in vacuum (Pitts and Sissom 1977):

$$c = \lambda_{max} \times v \tag{5}$$

The wavelength of IR energy is inversely varies with its frequency.

Total emissive power of a real surface is lower than that of a blackbody at the same temperature. Total emissivity (ε) is defined as the ratio of the former to the latter at exactly same temperature. As this ratio is not constant for different wavelengths of thermal radiation, gray body having constant emissivity is defined by idealization. Emissivity is a number from zero to one. Moreover, Kirchhoff's law states that monochromatic emissivity and monochromatic absorptivity of a body is the same at a given temperature for specific wavelength (Pitts and Sissom 1977).

Any surface having a temperature above 0 K emits electromagnetic waves according to Stefan-Boltzmann law. Therefore, product being heated during IR heating also emits IR energy to its surroundings. Geometry of the two bodies, i.e. emitter and product, influence this radiant exchange. View factor between two surfaces, also known as configuration factor, defined as fraction of the total energy emitted by a surface, which strikes the other surface directly (Pitts and Sissom 1977; Ibarz and Barbosa-Cánovas 2002). When this phenomena taken into account, heat transfer during the IR heating can be formulized (Pitts and Sissom 1977; Baik and others 2000):

$$q_{source \to product} = \frac{\sigma \times ({T_{source}}^4 - {T_{product}}^4)}{\left(\frac{1-\varepsilon_{source}}{\varepsilon_{source} \times A_{source}}\right) + \left(\frac{1}{F \times A_{source}}\right) + \left(\frac{1-\varepsilon_{product}}{\varepsilon_{product} \times A_{product}}\right)} \quad (6)$$

It is important to note that, if both emitter and product are infinite blackbodies, the transferred heat depends on only Stefan-Boltzmann's law and area of the emitter (A). Moreover, view factors (F) for the bodies with various geometric shapes can be determined from the charts given by (Pitts and Sissom 1977).

Heat transfer by radiation is sometimes expressed using the radiant heat transfer coefficient (h_R), as similar to conduction and convection (Baik and others 1999; Ibarz and Barbosa-Cánovas 2002):

$$q_{source \to product} = h_R \times A \times (T_{source} - T_{product}) \quad (7)$$

where, it is proportional to the area of the emitter (A) and driving force for the heat transfer. As mentioned above, heat transfer by radiation is defined by Stefan-Boltzmann's law. When equation 6 and 7 equal to each other, radiant heat transfer can be re-written as:

$$h_R = \frac{\dfrac{\sigma \times \left(T_{wall}{}^2 + T_{surface}{}^2\right) \times \left(T_{wall} + T_{surface}\right)}{\left(\frac{1-\varepsilon_{wall}}{\varepsilon_{wall} \times A_{wall}}\right) + \left(\frac{1}{F \times A_{wall}}\right) + \left(\frac{1-\varepsilon_{product}}{\varepsilon_{product} \times A_{product}}\right)}}{A_{product}} \quad (8)$$

Applications of IR Heating in Food Processing

Earlier IR applications were mainly focused on the drying and baking of food products, as reviewed by Ginzburg (1969). More recently, IR heating has also been used in blanching, thawing, pasteurization and other miscellaneous food processing operations such as, roasting, cooking and frying. In general, FIR heating was seen more applicable to food processing, since incident IR radiation was absorbed by food constituents, such as water, protein, fat and etc., in that region, i.e. $\lambda > 3$ µm (Sandu 1986). The literature on usage of IR heating in food processing has been reviewed by many researchers (Sakai and Hanzawa 1994; Skjöldebrand 2002; Krishnamurthy and others 2008; Sakai and Mao 2012; Rastogi 2011). The recent reviews have been focused on the opportunities of IR heating in food processing and its limitations, effect of IR heating on the quality of food product and IR heating equipment. Since all of the IR applications in food processing are not within the scope of this research, only literature related to French fry production and frying has been discussed below.

IR Blanching

IR blanching does not require any medium for heat transfer, i.e. water medium, and is one of the dry-blanching methods. Besides blanching, IR blanching removes moisture from the products (Pan and McHugh 2006). Weaver and Huxsoll (1970) applied gas-fired IR burners at 899 – 927 °C for 2 – 6 min for pre-drying of four sides of blanched or un-blanched potato strips prior to par-frying. Potato strips were placed 22.9 – 25.4 cm under the IR burners. It was indicated that IR heating significantly reduced the oil content and limpness of the potato strips. They also investigated effect of IR heating for 4 min on the limpness of the blanched potato strips. IR heating prior to par-frying reduced the limpness of the blanched potato strips over 50%.

Bingol and others (2012) used catalytic infrared heater to dry blanch the potato strips at a heating flux of 11,080W/m^2 for 30 – 180 s. IR treated potato strips were reported to absorb less fat than un-blanched samples after frying for 7 min, even though there was no significant difference in fat content of the both samples after frying for 3 min. Despite the 30 – 37.5% fat reduction, sensory evaluation showed that panelists preferred some of the IR dry-blanched French fries in terms of texture, color and appearance. When IR dry-blanched French fries were compared to water blanched (Bingol and others 2014), dry-blanched potato strips were darker and had 3–20% less fat and 20% less moisture than water-blanched.

IR Frying

Dagerskog (1979) noted that the first known attempt, published in English, to use IR heating as a frying process was made in 1976 by Bolshakov and others. They designed two-stage frying process for baking lean pork meat after analyzing its transmittance spectrograms. Maximum transmission of IR electromagnetic waves occurred in the region of 1.2 µm. Surface heating was targeted in the first stage by FIR heating (λ_{max} at 3.5-3.8 µm) and second stage was focused on internal (deep) heating by NIR heating (λ_{max} at 1.04 µm). IR heated lean pork meat had higher moisture content and sensory quality than the conventionally produced pork meat.

Dagerskog (1979) investigated frying of pork and beef slices solely by either NIR heating with maximum emissive power at 1.2 µm or FIR heating with maximum emissive power at 3.0

µm. It was reported that rate of heating was dependent on product thickness and IR flux rather than temperature of surrounding air and IR heating region, i.e. NIR or FIR region. This was due to high reflection of the IR electromagnetic waves, although increase in both penetration capability and reflectivity was reported as the wavelength of the IR radiation decreased.

IR frying paired with microwave heating was developed to produce low calorie potato chips in a three-stage process (August 1991). The developed equipment included ceramic panels, placed 5 cm above the potato chips, using 480 volts for preferably 1 min to pre-cook the external surface of the samples, then microwave heating at 2450 MHz for preferably 1-2 min used for internal cooking. As a last stage, similar ceramic panels placed 20 cm above the potatoes used to brown the product for preferably 1 min. The design also includes packaging of potato chips under the ultraviolet radiation to increase the shelf life. It was reported that IR fried potato chips has similar surface texture as conventionally produced counterparts.

Recently, Lloyd (2003) developed controlled dynamic radiant (CDR) heated oven, an IR based oven. Five pairs, one above and one below the belt, of 500 W quartz halogen emitters were placed with increased spacing along the belt length. A parabolic shaped reflector with polished surface was placed back of the emitters. They investigated CDR-heated oven to finish fry the par-fried French fries as an alternative to immersion frying. It was reported that heat flux of the CDR-heated oven was similar to that of immersion frying. The obtained maximum heat flux of the CDR-heated oven was 54 kW/m^2. They achieved 32% fat reduction in CDR processed potato strips when compared to fried counterparts with similar overall acceptability. Moreover, CDR processed potato strips were lighter and less uniform in color, harder in texture, and had lower moisture content than immersion fried potato strips.

Melito and Farkas (2012) used the same oven with slight adjustments to process par-fried wheat donuts as an alternative to immersion frying. The heat flux during IR frying of donuts was reported as 13.1 – 24.3 kW/m^2. IR treated wheat donuts were the most similar to the control in terms of instrumental quality parameters, when the emitters were placed 60 mm or with a height gradient from 70 mm to 50 mm above the belt. It was reported that IR treated par-fried wheat donuts had 9 – 28% less fat, darker color and harder texture than the fully fried samples. However, both IR heated and fully fried donuts had similar overall consumer acceptability.

Pilot scale of the CDR-heated oven, Fryless 100 K, was developed with ten pairs of 500 W halogen emitters with adjustable distance from the belt, 5 – 15 cm (Nelson III and others 2013). The power of the pilot scale oven could be up to 10 kW. Adjustable power and distance can form product specific heating zones for better process control. They reported that IR treated chicken patties had 16% less oil and darker color than immersion fried counterparts. Moreover, flavor and less oily mouthfeel attributes of IR treated chicken patties were preferred by consumers, yet overall preference of both of the samples was not different.

The commercial hot air-frying equipments, based on combination of convective and infrared heating, were introduced a couple of decades ago (Artt 2004; QNC Inc 2014). Recently, the design of air-fryers was developed by spraying of oil during the process (McFadden 2008), and variety of kitchen size air fryers were introduced (Bates and Poulter 2010). Even though there is not any literature on the IR based air-fryers, a few studies have been done on convective heating based air-fryers (Andrés and others 2013; Heredia and others 2014). Heredia and others (2014) investigated and compared quality changes in the hot air-fried French fries and deep-fat fried in terms of color and texture, while citing hot air-fried ones had 80% less oil in a separate study. They observed increase in a* and b* of French fries produced by both methods, however increase in a* of the deep-fat fried sample was significantly higher than the other. Texture change was also similar as both of the fries softened first due to gelatinization and then hardened due to crust formation. But, that change was slower in hot air-frying.

Use of Radiant Wall Oven in Food Processing

RWO (Pyramid Food Processing Equipment Manufacturing, Tewksbury, MA), a gas fired IR heater, includes stainless alloy elliptical tube bisected by a perforated belt with a width of 30 cm. The length of the RWO is 113 cm from both ends including the entrance and exit zones. Temperature of the RWO is controlled automatically by adjusting the gas flow. There has not been much research on the RWO. Galindo and others (2005) investigated tissue damage in IR heated carrots after water blanching in RWO at 583 °C for 7 s. It was noted that IR electromagnetic waves caused tissue damage in the carrot was limited to 0.5 mm from the surface. Hence, it showed that FIR heating is a surface heating phenomenon. Furthermore, tissue strength of the IR treated carrots was higher than the water treated samples.

Islam (1998) investigated effect of RWO on the shelf life extension and pathogen reduction of fresh chicken meat. Surface pasteurization of whole broiler in RWO at 649 °C for 5 s achieved 1.23 – 1.73 log reduction in total plate count. When raw chicken drumsticks were processed in RWO at 788 °C for 3 s, total plate count was reduced by 2-3 log leading to almost four weeks of shelf life at 0 °C. RWO processing of 1,000 CFU inoculated raw chicken drumsticks at 788 °C for 3 s was enough to detect no viable CFU of *Salmonella typhimurium* or *Campylobacter jejuni*.

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Table 2.1: Fat and moisture content of French fries available at quick serve restaurants (USDA ARS 2014)

	Fat % (wwb)	Moisture % (wwb)
Wendy’s	14.10	40.62
Burger King	12.48	43.95
McDonald’s	15.47	36.63
Appleebee’s	13.17	41.29
Denny’s	14.13	46.05
T.G.I. Friday’s	14.82	42.23

wwb: wet weight basis

Table 2.2: Percent oil reduction in French fries

Potato variety	Size	Unit Operation	Suggested intervention	Oil reduction (%)	Reference
-	10 x .95 x .95 cm^3	Final frying	IR heating prior to final frying	0 – 28.5%	(Weaver and Huxsoll 1970)
Record	Potato slice with .09 cm thickness Potato slice with .16 cm thickness	Raw Material	Larger sized potato slice used	42%[*]	(Gamble and Rice 1988)
Russet Burbank	10 x .95 x .95 cm^3	Final frying	Final frying replaced with IR heating	32%	(Lloyd and others 2004)
Innowator Santana	6 x 1 x 1 cm^3	Raw material	Pectolytic and hemicellulytic enzymes used	22% 8%	(Lisińska and others 2007)
Santana	6–7 x .8 x .8 cm^3 6–7 x 1 x 1 cm^3	Raw Material Pre-drying	Different French fries size Vacuum-microwave used	12-20%[‡] 0-22%	(Tajner-Czopek and others 2008)
Russet Burbank	10 x .7 x .7 cm^3 Potato rings with 0.7 cm thickness	Raw material	Strips were taken from outer part of the potatoes	28% 22%	(Rommens and others 2010)
Russet Burbank	.94 x .94 cm^2	Blanching	Blanching done with IR heating	30-37.5%[†]	(Bingol and others 2012)
-	.7 x 4 x 4 cm^3 potato slabs	Pre-treatment	Ultrasound-assisted osmotic dehydration prior to frying	12.5%	(Karizaki and others 2013)
Maris Piper	Potato slices with 45 mm in diameter, 2.5 mm thickness 5-7 cm length strips	Post-frying	Oil drainage by vacuum	38% None	(Ahmad Tarmizi and Niranjan 2013)
Russet Burbank	9–11 x.94 x .94 cm^3	Blanching	Blanching done with IR heating	3-20%	(Bingol and others 2014)

[*] Thicker potato slices had 42% less fat than thinner slices.

[†] with respect to deep-fat fried un-blanched potato strips

[‡] Smaller size French fries, fried for 4 min, had lower fat content than larger size counterparts, fried for 5 min.

Table 2.3: Texture assessment of French fries (FF)

Product and size	Equipment	Probe	Test crosshead speed	Measured attribute	Reference
One FF strip with 10 x 1 x 1 cm^3 dimensions	Texture Analyzer TA-XT2, Stable Micro Systems Ltd.,	2 mm diameter metal rod puncture probe	2 mm/s	Springiness, Rupture force, core force	(Pedreschi and others 2001)
One restructured sweet potato FF strip with 9 x .9 x .9 cm^3	Texture Analyzer TA-XT2, Stable Micro Systems Ltd.,	Cylindrical flat-end punch with 1 mm diameter probe Three-point bending accessory Kramer shear cell Parallel plates	1.6 mm/s (5 s delay between cycles)	Peak force (for puncture, three-point bending and Kramer shear test) Instrumental Texture Profile Analysis	(Walter Jr and others 2002)
One FF strip with 10 x .95 x .95 cm^3 dimensions	Texture Analyzer TA-XT2i, Stable Micro Systems Ltd.,	Single flat-end stainless steel probe with 1 mm in diameter Five-blade Kramer shear cell	1.6 mm/s	Puncture force Kramer shear	(Lloyd and others 2004)
One FF strip with 1.1 x 1.1 cm^2 dimensions	Texture Analyzer TA-XT2i, Stable Micro Systems Ltd., Acoustic sensor	15 mm-wide aluminum probe with a 30° cutting angle	40 mm/s	Crispiness	(Sanz and others 2007)
20 FF strips with each having 6 x 1 x 1 cm^3	Instron 5544, Instron Corp.	Rectangular attachment	4.2 mm/ s	Maximum shear force, F_{max}	(Lisińska and others 2007)
One FF strip with 6–7 x .8 x .8 cm^3 and 6–7 x 1 x 1 cm^3	Instron 5544, Instron Corp.	QTS-25 SB cutting attachment	4.2 mm/s	Cutting force, F_{max}	(Tajner-Czopek and others 2008)
Five FF strips with each having 7 x .85 x .85 cm^3 dimensions	Texture Analyzer TA-XT2i, Stable Micro Systems Ltd.,	9 mm-wide aluminum probe with a 30° cutting angle	10 mm/s	Cutting force, F_{max}	(Tuta and others 2010)

Table 2.4: Color analysis of French fries

Processing	Variety	Equipment	Lightness	Hue °	a*	b*	Reference
Deep-fat frying at 172 °C for 3.5 min	Russet Burbank	Digital camera (MVC-CD400, Sony, Tokyo, Japan)	183.7†	-	-	172†	(Lloyd and others 2004)
Deep-fat frying at 180 °C 4 min	Santana	Chroma meter (CR-200, Minolta Ltd, USA)	46.19 ± 2.25	-	4.84 ± 0.82	23.37 ± 1.63	(Tajner-Czopek and others 2008)
Deep-fat frying at 180 °C 5 min			41.93 ± 1.88	-	13.64 ± 0.73	23.54 ± 2.09	
Deep-fat frying at 180 °C for 3 min	-	Digital camera (Powershot A70, Canon, NY, USA)	67.46 ± 1.17	95.80 ± 1.06	-4.72 ± 0.98	-	(Romani and others 2009)
Deep-fat frying at 180 °C for 4.5 min	Lady Olympia	Digital camera (DMCFZ50EGS, Panasonic Japan)	81.8 ± 1.7	-	-18.6 ± 0.6	56.7 ± 4.3	(Tuta and others 2010)
Deep-fat frying at 174 °C for 3 min	Russet Burbank	Chroma meter (CR-200, Minolta Ltd, USA)	59 ± 1‡	-	-0.5 ± 0.5‡	18 ± 0.5‡	(Bingol and others 2012)
Deep-fat frying at 174 °C for 3 min	Russet Burbank	Chroma meter (CR-200, Minolta Ltd, USA)	60‡	-	-1.6‡	15‡	(Bingol and others 2014)

† Lightness: (0 = completely black, 255 = pure white); b*: (0 = blue, 255 = yellow)

‡ Read from the figure

Table 2.5: Penetration depth of electromagnetic waves at different wavelength

	Penetration depth (mm)	Wavelength (μm)	Domain	Author
Apple	152	11 (m)	Radio Frequency	(Wang and others 2003)
	53	328 (mm)	Microwave	
Apple	4.1	1.16	Near-IR	(Ginzburg 1969)
	5.9	1.65	Near-IR	
	7.4	2.36	Mid-IR	
Apple slices	0 – 1	0.4 – 0.6	Visible spectrum	(Peirs and others 2002)
	4 – 5	1	Near-IR	
	1	2	Mid-IR	
Potato	0.57 – 0.66*		Near-IR	(Hashimoto and Kameoka 1997)
	0.24 – 0.54*		Far-IR	
Dough	2.1†	4.65	Far-IR	(van Velzen and others 2003)
	2.5†	5.73	Far-IR	
	4.1†	9.35	Far-IR	

* The depth from surface at which 99% of initial IR energy lost.

† μm

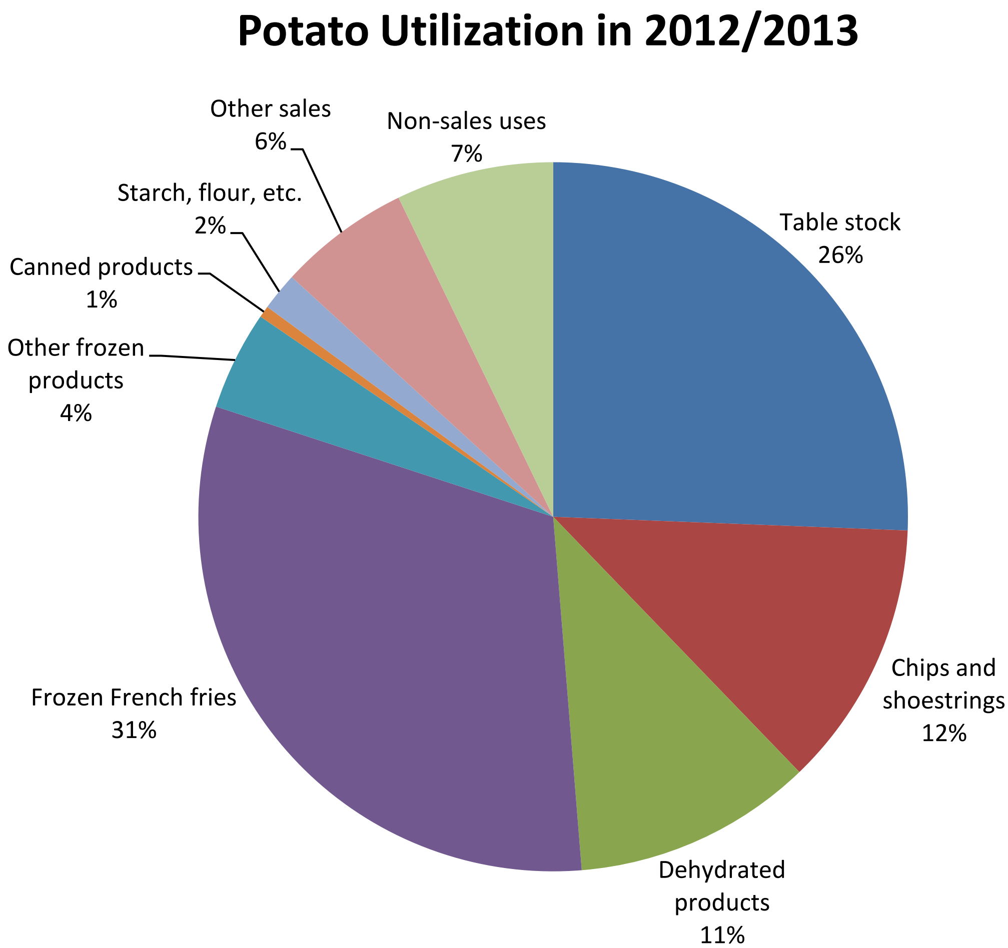

Figure 2.1: Potato crop utilization in 2012/2013 (USDA ERS 2014).

CHAPTER 3

BAKING OF POTATO STRIPS IN A RADIANT WALL OVEN – AN EXPERIMENTAL STUDY OF HEAT TRANSFER COEFFICIENT AND PRODUCT QUALITY[1]

[1]Kirmaci, B. and R.K. Singh. To be submitted to *Journal of Food Science.*

Abstract:

Radiant Wall Oven (RWO) was investigated for baking frozen par-fried potato strips at temperatures of 290 – 365 °C with different processing times to reduce fat content of the final product. Radiant, natural convective and overall heat transfer coefficients were experimentally determined for each RWO treatment by monitoring temperature and heat flux. Product characteristics in terms of cutting force, puncture force, lightness, chroma and hue, moisture and fat content of the RWO baked potato strips were measured and compared to that of deep-fat fried samples (177 °C for 3 min). Correlation between heat transfer parameters and quality characteristics of the samples were also determined. RWO processed potato strips had at least 78% less fat than the deep-fat fried counterparts. RWO baked potato strips at 365 °C for 6.5 min and 340 °C for 7.5 min had similar texture with control. However, moisture content, lightness, chroma and hue of the RWO baked potato strips at 315 °C for 12 min was similar to the fried samples. Two RWO treatments, baking at 315 °C for 12 min and 365 °C for 6.5 min, were further analyzed by sensory analysis. Trained panel verified the results of instrumental analysis of potato strips baked at the latter condition that it had similar texture, in spite of having different color and moisture content. The time-temperature treatment was used to develop a severity parameter which predicted the cutting force, hue and moisture content of RWO baked potato strips.

Keywords: color, infrared heating, potato, radiant heat transfer coefficient, texture

Practical Application:

Radiant Wall Oven, a natural gas fired infrared oven, used to bake potato strips to reduce the fat content of the finished products. Instrumental and sensory assessment of the texture of the potato strips indicated that RWO baked potato strips at 365 °C for 6.5 min had similar texture as deep-fat fried potato strips, yet contained 81.5% less fat. However, those potato strips were lighter and less brown in color, and had 18% more moisture than the deep-fat fried potato strips. After some improvements, RWO baking might be an alternative to deep-fat frying.

Introduction

Potatoes, *Solanum tuberosum*, are available in the market as table stock (unprocessed), frozen par-fried French fries, chips or canned. However, frozen par-fried potato strips (French fries) is the most produced in the U.S. The one-third of the harvested potato crop was processed as frozen potato strips in 2012/2013 (USDA ERS 2014a) with the total trade over $1.6 billion (USDA ERS 2014b). Frozen French fries market has increased dramatically after development of oil blanched, or par-fried French fries (Weaver and others 1975). Par-frying is performed in hot oil at 177 – 190 °C for 1 – 3 min, and fat content of the par-fried potato strips is about 5 – 7% wet basis (Miranda and Aguilera 2006; van Loon and others 2007). After cooling and freezing, the potato strips are distributed to retailers or restaurants. Then, consumers are either advised to final fry the frozen par-fried potato strips in the deep-fat fryer or bake in the conventional oven.

Quality of the potato strips includes oil and moisture content, color, texture and flavor (Pedreschi 2009). Color and appearance of a product is the first quality parameter that consumers assess (Lawless and Heymann 2010). Light golden brown color of the French fries was once thought due to caramelization of sugar; however it has been corrected as Maillard reaction, a reaction between reducing sugar and free amino acid at high temperatures (Weaver and others 1975; Lisiñska 1989). Maillard reaction not only improves the color, but also contributes to the frying flavor in the crust during frying (Gillatt 2001). However, it should be limited by conditioning the potatoes prior to processing or blanching to reduce sugar content of the potatoes (Weaver and others 1975).

Texture of the French fries is one of the most important quality aspects that leads to its popularity among consumers, besides color. French fries have non-uniform texture with a combination of external and internal texture: porous and crisp crust, and moist and soft core

(Pedreschi and others 2001; Weaver and others 1975). French fry texture is formed during frying. When surface temperature reaches to 100 °C, water around the surface begins to evaporate. As the surface dries out, boundary of evaporating water shifts toward the center of potato strips leading to porous crust formation (van Loon and others 2007). Migration of water vapor from core makes the crust porous (Mellema 2003) and creates numerous fractures when the porous and low moisture crust becomes deformed. It has been reported that void space constitutes most of the (~80%) volume of the crust (Lima and Singh 2001) and that leads to crispiness of the French fries. Furthermore, gelatinized starch and disintegrated lamella between cells produce the soft and cooked potato texture, i.e. mealy texture, in the core (Miranda and Aguilera 2006).

Heat is transferred in three different ways: conduction, convection and radiation. In deep-fat frying of potato strips, heat is transferred by convection through hot oil. However, the radiative heat is transferred by the electromagnetic waves. Furthermore, wavelength and frequency of the electromagnetic waves determine the category of the heating. For instance, the higher wavelengths (1 m to 100 km) of electromagnetic waves occur in radiofrequency (RF), and the lower wavelengths (0.78 to 1000 μm) are in the infrared (IR) heating range. Energy does not penetrate deep into the food in IR heating range due to the short wavelength (Sakai and Mao 2012). This allows IR heating to be used as surface heat treatment.

Weaver and Huxsoll (1970) applied gas-fired IR burners for 2 – 6 min for pre-drying of four sides of potato strips prior to par-frying. It was indicated that IR heating reduced the oil content and limpness of the potato strips. Recently, dry-blanching of potato strips using catalytic IR heater was investigated with respect to un-blanched and water blanched potato strips (Bingol and others 2012; Bingol and others 2014). IR treated potato strips were reported to absorb less fat than un-blanched samples after frying for 7 min, even though there was no significant difference in fat content of the both samples after frying for 3 min. Furthermore, dry-blanched potato strips by IR heating had lower fat content than water blanched potato strips after frying at the same temperature for different times.

There has been recent efforts to use IR heating as an alternative to deep-fat frying (Lloyd and others 2004; Melito and Farkas 2012; Nelson III and others 2013). Lloyd and others (2004) suggested Controlled Dynamic Radiant (CDR) processing, an IR based heating by quartz halogen radiant emitters, as a replacement to the deep-fat frying. They achieved 32% fat reduction in CDR processed potato strips when compared to fried counterparts with similar overall acceptability. It was reported that IR treated par-fried wheat donuts had 9-28% less fat with comparable acceptability to the fully fried samples (Melito and Farkas 2012). Nelson III and others (2013) used IR heating equipment having up to 10 kW power with ten different heating zones, each consisting of two halogen emitters from adjustable distances. They reported that IR treated chicken patties had 16% less oil and lighter color than immersion fried counterparts.

Radiant Wall Oven (RWO), a gas-fired IR heater, processing was tested to bake frozen par-fried potato strips instead of deep-fat frying. The RWO is an elliptical tube stainless alloy emits IR radiation to the product in far-infrared (FIR) region. In this study, the wavelength at which maximum emission occurred during RWO processing was 4.54 – 5.15 μm. By having lower penetration depth of IR radiation, surface of the product gets heated rapidly. Hence, the crust is developed at the surface and the color is formed due to non-enzymatic browning. Since heat transfer coefficient is also surface phenomena, its relationship with the quality of the product was also investigated. Heat transfer coefficient can give guidance to scale up or down the equipment and be used to compare similar equipments or processes. We envision that reduced fat potato strips can be produced in RWO without compromising the quality. The objectives of this study were (i) to experimentally determine the overall heat transfer coefficient of RWO processing during baking of potato strips and (ii) to study the effect of this process on instrumental and sensory quality characteristics of the baked potato strips with respect to deep-fat fried samples, and finally (iii) to evaluate the relationship between heat transfer parameters and the color and texture of the potato strips.

Materials and Methods

Sample Preparation

Commercially available 69 packages of 0.9 kg each frozen par-fried regular cut French fries and 4 packages of 0.9 kg each frozen par-fried steak cut French fries were obtained from a national supermarket. Raw materials were stored in a walk-in freezer at -40 °C. Potato strips were sorted and cut to 5 cm in length. For each treatment, 81 potato strips were placed in a Ziploc bag and stored overnight in -20 °C freezer for further processing. Nine potato strips (47.8 ± 0.7 g) were processed for each analysis. To control the temperature of the samples prior to color and texture analysis, processed potato strips were placed on a food warmer for 2 min. The food warmer (Model No: GRFFB, Hatco Corp., Milwaukee, WI) consisted of 500W infrared heat lamp and 250W base heating element. As moisture migration from the inner core to the surface of the potato strip affects the texture (Rovedo and others 1999), any samples that stayed for more than 5 min on the warmer were discarded.

Experimental Design

Radiant Wall Oven (Pyramid Food Processing Equipment Manufacturing, Tewksbury, MA) was used to bake the potato strips at four different temperatures (290, 315, 340, and 365 °C) for three different times (Table 3.1). The temperatures were selected based on the lowest RWO operation temperature and preliminary experiments. As a control treatment, par-fried frozen potato strips were fried in a deep-fat fryer (GE Model 168997, General Electric Company, Fairfield, CT) at 177 °C for 3 minutes with 5 L peanut oil. Fried potato strips were drained on a paper towel and transferred to the food warmer. After 10 h of frying, peanut oil was renewed. Each treatment was replicated three times and the order of treatments was randomized. Upon completion of instrumental analysis, two RWO treatments, which resulted in baked potato strips having the most similar quality to deep-fat fried counterparts, were chosen for further sensory evaluation. Sensory analysis was conducted in duplicate and the order of the treatments was randomized.

Heat Transfer

Radiant, natural convective and overall heat transfer coefficients were determined experimentally for each RWO treatments in triplicate. To determine heat transfer coefficients, heat flux to the potato strips, radiant wall temperature, surface temperature of the product and the temperature of the air surrounding the product were monitored during baking potato strips in RWO.

Temperature of the center of the potato strips and the air surrounding the product were measured by Teflon (Polytetrafluoroethylene - PTFE) coated type T thermocouple (Omega Engineering Inc., Stamford, CT) with portable data logger (RDXL121-D, Omega Engineering Inc., Stamford, CT). Thermocouple was inserted into the product after piercing the potato strips by a hypodermic needle. Surface temperature was determined by thermocouple in the heat flux sensor (HT-50, ITI

Co., Del Mar, CA). Temperature of the wall of the RWO was measured by inconel overbraided Type K thermocouple (XCIB-K-4-6, Omega Engineering Inc., Stamford, CT).

Heat flux towards potato strips in the RWO was determined by heat flux sensor (HT-50, ITI Co., Del Mar, CA) with portable data logger (RDXL121-D, Omega Engineering Inc., Stamford, CT) during RWO processing.

Overall heat transfer coefficient (U_{RWO}) of the RWO was determined by Equation 1 (Baik and others 1999):

$$U_{RWO} = \frac{q"}{(T_{wall} - T_{surface})} \tag{1}$$

where, $q"$, T_{wall}, and $T_{surface}$ are the heat flux through the product (W/m^2), the wall temperature of the RWO and the surface temperature of the potato strip (°C), respectively.

Natural convective heat transfer coefficient (h_{conv}) in the RWO was calculated by Equation 2 (McAdams 1954):

$$h_{conv} = 1.3196 \times \left\{\frac{T_{air} - T_{surface}}{D_{eq}}\right\}^{0.25} \tag{2}$$

where, T_{air} and D_{eq} are the temperature of the surrounding air in the RWO (°C) and the equivalent diameter of the potato strip (0.01667 m), respectively.

Radiant heat transfer coefficient (h_R) of the RWO was calculated by Equation 3 (Baik and others 1999; Ibarz and Barbosa-Cánovas 2002):

$$h_R = U_{RWO} - \frac{h_{conv} \times (T_{air} - T_{surface})}{(T_{wall} - T_{surface})} \tag{3}$$

Moisture and Fat Content

Moisture content of the potato strips was determined by vacuum oven method (AOAC 1995). Immediately after baking/frying, samples were immersed in liquid nitrogen for 20 s. Samples were placed and stored in a freezer at -20 °C for further analysis. About 2 - 3 g homogenized samples were placed in a pre-dried No.1 Whatman Paper and dried in a vacuum oven (Cole-Parmer Instrument Co., Vernon Hills, IL) at below 61 kPa pressure at 70 °C for 24 h.

The fat content of the baked/fried potato strips was measured by the Soxhlet method (AOAC 1995). Dried samples were placed in Soxhlet to extract oil with petroleum ether for 8 h in a Pyrex Distillation Unit. Then, solvent was removed in the vacuum oven at below 61 kPa pressure at 70 °C for 30 min. Fat content was calculated by gravimetrically and reported with respect to dry basis of potato strips.

Texture

Cutting force of the potato strip samples was determined by a Texture Analyzer (TA-XT2i, Stable Micro Systems Ltd., Hamilton, MA) with knife blade attachment with 45° chisel end. Texture Analyzer was calibrated, and pre-test cross-arm speed was set to 1.5 mm/s prior to the test. Speed of the cross arm with knife blade attachment was set to 2 mm/s to halve the five baked potato strips placed adjacent to each other. A 5-kg load cell was used to detect required maximum amount of force to divide the samples into halves, and it was reported as cutting force of the baked/fried samples. Moreover, the linear distance, the length of the imaginary line that connects all data points of force-deformation curve, was calculated. The longer linear distance due to many mechanical failures in the structure when deformed, i.e. jaggedness of the force, relates to crispier texture (Varela and others 2006). In addition to linear distance, number of peaks was also counted, since Van Loon and others (2007) reported that it was correlated well with sensory crispiness. The experiment was repeated nine times per treatment.

Surface of the potato strips was ruptured by the Texture Analyzer with 3 mm puncture probe at 2 mm/s to evaluate the crust. Texture Analyzer was calibrated, and pre-test cross-arm speed was set to 1.5 mm/s prior to the test. Required maximum force to insert the probe into the potato strip

6 mm from the surface was detected by 5-kg load cell and it was reported as puncture force of the baked/fried samples. Moreover, crispiness of the surface was assessed by number of peaks and the linear distance of the force-deformation curve. Total of nine potato strips were ruptured for each treatment, and the experiment conducted in triplicate.

Color

Color of the baked/fried potato strips was determined as lightness (L), chroma (saturation or brightness) and hue angle by the colorimeter (model CR-410, Konica Minolta Sensing Inc., Ramsey, NJ). CIE L*C*h color space, in which chroma and hue angle were derived from a* and b* of CIELAB color space, was used to quantify the color of the potato. Nine potato strip samples were placed adjacent to each other, and color was measured. Colorimeter calibrated with white calibration plate prior to analysis, and averaged three readings for a single measurement. The experiment was replicated nine times for each treatment.

Sensory Analysis

All experiments were done at the sensory laboratory of the Department of Food Science and Technology at The University of Georgia (UGA). White fluorescent lighting was used throughout the evaluation sessions and sensory booths had positive air flow to prevent any aroma circulation from the sample preparation area. Three baked/fried potato strips were placed into a 3 random digit coded paperboard food tray (#25 Southland, The Southern Champion Tray, Chattanooga, TN), and then were served to the panelists immediately. Water at room temperature and unsalted top saltine crackers were used as palate cleansers between samples.

Two RWO treatments that produced baked potato strips with most similar to control samples were selected for sensory analysis among twelve treatments. Color and texture of the RWO baked and deep-fat fried potato strips were evaluated by 10-member trained panel. Permission to carry out sensory analysis for this study was obtained from UGA Institutional Review Board for human subjects. Then, the individuals, who like to eat French fries and not allergic to the ingredients stated on the package of the raw material, were recruited among UGA students and staff. The panelists were familiarized with the color and texture of the French fries at a local fast food restaurant before the sensory analysis.

The panelists evaluated the color and texture of the samples in four sessions using unstructured 150 mm modified just about right (JAR) scale (Figure 3.1). In each evaluation session, the panelists were given one RWO processed pre-cooked potato strip and control samples in pre-determined randomized order. After evaluation, responses were converted to the numbers using a ruler, and least squares mean scores were reported with standard error.

Severity

Severity, described by Heitz and others (1987), was modified for RWO processing to predict the quality attributes of the baked potato strips. Severity of the RWO processing was defined as:

$$Severity = t \times e^{\left(\frac{T_{wall} - T_{surface}}{T_{surface\ mean}}\right)} \tag{4}$$

This was based on the wall set temperature (T_{wall}), corresponding surface temperature of the potato strip ($T_{surface}$), mean surface temperature of the potato strip at all RWO treatments ($T_{surface\ mean}$) and processing time (t) of the RWO processing. Driving force of the heat transfer was normalized by the mean of the surface temperature of potato strips for all RWO treatments. Thus, exponent part of the equation did not have any unit.

Statistical Analysis

Data was analyzed by one-way analysis of variance (ANOVA) and least square means of the RWO treatments were compared to that of control by Dunnett's separation test at 95% confidence level. Heat transfer and sensory analysis data were analyzed using PROC MIXED procedure, as each treatment had its own variation. Correlations between heat transfer coefficients and quality parameters were determined by the Pearson's product moment. Data analysis was done by the statistical software program (SAS® 9.3, SAS Institute Inc., Raleigh, NC). Quality parameters with respect to logarithm of severity were plotted using Microsoft Office Excel® 2007 with linear trend lines (Microsoft Corp., Redmond, WA).

Results and Discussion

RWO processing of potato strips

RWO was successfully utilized to bake frozen par-fried potato strips by exposing infrared energy to the product at far-infrared region. Operating wall temperature fluctuated as the automatic valve controlled the flow of natural gas to control the temperature in the RWO. Mean wall temperatures were 293.7 ± 3.5, 318.4 ± 2.6, 344.0 ± 3.4 and 368.6 ± 4.3 °C for the set point temperatures of 290, 315, 340, and 365 °C. On the other hand, there was some variation (0.1 – 0.5 min) in the processing times due to the motor controlling the conveyor belt. Oil temperature in the deep-fat fryer was 177.5 ± 1.3 °C, and potato strips were manually taken out exactly after frying for 3 min.

RWO had 11.1 cm entrance and exit zone at both ends (Figure 3.2, zone 1 & 4). Temperature monitoring indicated that at 80.8 ± 2.1 cm, temperature of the air surrounding the product started to go down. Furthermore, at 86.0 ± 1.6 cm, temperature of the air surrounding the product were the same as surface temperature of the potato strips. The length of effective heating zone (Figure 3.2, zone 2), from product entrance to RWO till the point where temperature of air surrounding product equals the surface temperature of the product, was 78.9 ± 1.6 cm in RWO. Corresponding heating times for each treatment are given Table 3.2.

Average surface temperatures, heat flux, and overall, radiant and natural convective heat transfer coefficients during RWO treatments are given in Table 3.2. All of these parameters were averaged from the corresponding values within the steady zone (Figure 3.3), where center temperature of the potato strips and air surrounding the potato strips stayed at constant. The highest heat flux, 20.0 ± 0.8 kW/m^2, was observed when potato strips were baked at 365 °C for 6.5 min. In contrast, RWO processing of potato strips at 290 °C for 16.5 min resulted in the lowest heat flux, 10.2 ± 0.8 kW/m^2.

The range of overall and radiant heat transfer coefficient was 61.1 – 81.7 W/m^{2}K and 57.1 – 75.7 W/m^{2}K, respectively. Overall heat transfer coefficient of the all RWO treatments was lower when compared to that of deep-fat frying, reported as 285 W/m^{2}K (Yamsaengsung and Moreira 2002). Like heat flux, the highest and the lowest overall and radiant heat transfer coefficients were observed at high temperature short time and low temperature long time in RWO, respectively. Overall and radiant heat transfer coefficients of RWO treatments within the same temperature were not significantly different from each other. As seen from the Figure 3.3, radiant heat transfer coefficient-time curve is similar to overall heat transfer coefficient-curve. This indicates that heating in RWO was mainly based on the infrared heating. The calculated natural convective heat transfer coefficients in RWO were in the range of 10.24 – 12.15 W/m^{2}K.

The heat flux and overall and radiant heat transfer coefficients of the RWO processing of potato strips at 340 °C for 7.5 min and 365 °C for 9.5 min were not significantly different. However, the latter resulted in the highest surface temperature of potato strips, 133.2 ± 3.4 °C, and the former treatment had the lowest surface temperature of 113.9 ± 3.4 °C. RWO treatments with higher processing times at the same temperature resulted in higher surface temperature except baking of potato strips at 290 °C. It might be related to relatively lower temperature driving force.

Moisture and Fat Content

Moisture content of the all RWO baked and control potato strips was significantly lower than that of frozen par-fried potato strips (Table 3.3). Moisture content of the control treatment was 51.73 ± 1.23% wet basis, and it was not significantly different than that of treatments #2, #3, #6, #9 and #12. It is important to note that processing times of those treatments were the highest within the same temperature, except the treatment #2. However, RWO treatments #1, #4, #5, #7, #8, #10 and #11 resulted in potato strips with significantly higher moisture content than the fried. All of the RWO baked potato strips had significantly less moisture content than the frozen par-fried potato strips, which had moisture content of 72.58 ± 1.23% on a wet basis.

Fat content of the deep-fat fried potato strips, 50.69 ± 0.65% dry basis, were significantly higher than all of the RWO treatments (Table 3.3). RWO treatments resulted in fat reduction by 78.5% – 81.5% in potato strips with respect to control samples. Lloyd and others (2004) reported 32.3% fat reduction in French fries produced by Controlled Dynamic Radiant (CDR) heating. Fat content of the frozen par-fried potato strips was 9.72 ± 0.65 % db. The difference between fat content of the RWO baked and frozen par-fried potato strips was insignificant. Therefore, RWO processing of potato strips did not affect the fat content of the raw material significantly.

Texture

Cutting force of the RWO baked and deep-fat fried potato strips are given in Table 3.4. Only the cutting force of the potato strips that were RWO baked at 340 °C for 7.5 min and at 365 °C for 6.5 min (treatments #7 and #10, respectively) was not significantly different than that of control samples. It should be noted that moisture content of the potato strips baked in those RWO conditions were significantly higher than moisture content of control samples. The results are in agreement with Sanz and others (2007), who concluded that crispiness of the French fries was related to moisture content of the crust instead of entire product. Therefore, crispiness is the property of the crust. The rest of the RWO treatments resulted in significantly higher cutting force than deep-fat frying. The higher cutting force might be explained by case hardening phenomenon. Longer RWO processing within same temperature affected the crust by lowering the moisture content. That's why the required cutting force to cut potato strips that were processed longer in RWO at same temperature were higher.

The comparison of the calculated linear distance from the force-deformation curve of the baked/fried potato strips repeated same results as cutting force. The calculated linear distance of deep-fat fried potato strips was not significantly different than that of treatments #7 and #10. The rest of the RWO treatments had significantly higher calculated linear distance than control due to higher cutting force, i.e. case hardening, instead of fluctuations in the force curve. That was also verified by counting number of peak forces. The number of peak force of the deep-fat fried potato strips (6.33 ± 1.05) was either higher or insignificantly different than that of all RWO baked potato strips, which was in the range of 1.56 – 7.56. Van Loon and others (2007) reported total number of peaks as 50.2 – 56.2 for the potato strips pre-dried or par-fried at various conditions. Dramatically low number of peaks indicated that jaggedness of the force-deformation curve occurred rarely in this study. Therefore, crispiness of the baked/fried potato strips was not assessed by both the number of peaks and the calculated linear distance, in this study.

The required force to puncture RWO baked potato strips by treatments #4, #7 and #10 was not significantly different than required puncture force of the control counterparts (Table 3.4). On the other hand, RWO baked potato strips according to the rest of the treatments required higher force to penetrate the probe through their surface. Results of puncture test were almost same as cutting test, except the treatment #4. Furthermore, similar interpretations were drawn when the calculated linear distance of the jagged puncture force response was analyzed, except the treatments #1 and #12 that were also not significantly different than control. When total number of peak force was counted, control samples had significantly higher number of peak force than RWO treatments except the treatment #3. Mean total number of peak forces of the RWO baked potato strips was in the range of 0 – 0.2 and it was 0.37 ± 0.07 for the control samples. Thus, crispiness was not evaluated from puncture force test, in this study.

Color

Lightness, chroma and hue angle of the RWO baked and deep-fat fried potato strips are given in Table 3.4. In CIE L*C*h color space, hue angle of 0 ° and 90 ° represents the red-purple and yellow color, respectively. Potato strips baked at 365 °C for 9.5 min in RWO (treatment #12) were significantly darker and browner than the control. Whereas, RWO baked potato strips according to treatment #1, #4, #7 and #10 were significantly lighter and closer to yellow than the fried samples. The lightness and hue of RWO baked potato strips according to treatment # 2, #3, #6, #8, #9 and #11 were not significantly different than that of deep-fat fried potato strips. Longer RWO processing times at the same temperature caused potato strips to have lower lightness and hue than shorter processing times. The intensity of color, i.e., chroma of the samples, for the RWO treatments and control was not significantly different. The chroma of the RWO baked potato strips was measured in the range of 36.06 – 38.67, whereas, chroma of the control samples was 36.70 ± 0.54.

Correlation

Pearson correlation coefficients between heat transfer and quality parameters are given in Table 3.5. Both overall and radiant heat transfer coefficients in RWO were inversely correlated with required cutting force and corresponding linear distance. This implies that the increase in overall or radiant heat transfer coefficients resulted in moderate decline in required cutting force of the RWO baked potato strips. There was no correlation found between the heat transfer coefficients and color of the RWO baked potato strips. However, inverse and strong correlation was found between average surface temperature of potato strips, and the lightness and hue of the potato strips. Moreover, required cutting force of the potato strips and corresponding linear distance moderately correlated with the average surface temperature of the potato strips. For instance, an increase in the average surface temperature of potato strips during RWO processing caused increase in cutting force of the baked potato strips. Puncture force of the RWO baked potato strips was also moderately correlated with the average surface temperature of the potato strips. There was no significant correlation found between moisture content and heat transfer coefficients or average surface temperature of the potatoes.

Among twelve treatments in RWO, none of the treatment met the entire quality characteristics of the deep-fat fried potato strips. Treatment #7 and #10 had the closest quality to the deep-fat fried samples in terms of texture. Since processing time of the treatment #10 was also the shortest among RWO treatments, it was chosen for further analysis. However, treatments #2, #3, #6 and #9 had the similar quality with the control in terms of color and moisture content. Treatment #6 was chosen for further analysis because of being the second shortest treatment among those four treatments and the best treatment of the pilot study.

Sensory Analysis

Trained panel was used to validate the instrumental analysis result, similar to that described by Chan and others (2013). Color of the potato strips from treatment #6, #10 and control was determined as 100.0 ± 0.4, 59.5 ± 2.0 and 77.1 ± 0.9, respectively. The trained panel also verified the significant difference between the color of RWO baked potato strips at 365°C for 6.5 min and deep-fat fried samples. However, similarity between the color of the RWO processed potato strips at 315°C for 12 min and that of deep-fat fried samples was rejected by the panel. Belt marks and dark spots on the edges of the potato strips affected visual perception of the panelists. Even though colorimeter had large aperture size, 5 cm in diameter, it did not detect the color difference between RWO baked potato strips at 315 °C for 12 min and deep-fat fried potato strips.

Texture scores of the potato strips from treatments #6, #10 and control were 54.2 ± 5.1, 68.1 ± 6.1, 74.0 ± 1.3, respectively. Trained panel determined that the difference between texture of the RWO baked potato strips from treatment #10 and control samples was insignificant. However, the trained panel indicated that there was a significant difference in texture of the RWO baked potato strips at treatment #6 and the deep-fat fried samples. Therefore, trained panel stated that RWO processing at 365 °C for 6.5 min produced potato strips the most similar to the deep-fat fried counterparts.

It is important to note that, modified JAR scale was used for trained panel, even though that scale is generally used for consumer sensory evaluations. However, the validity of the 150 mm unstructured modified JAR scale was confirmed by the results of control samples. Both color and texture evaluations of control samples were close to 75 mm, labeled as typical French fry color/texture score.

Severity

Mean surface temperature of all RWO treatments, denominator of the exponent part of the severity formula (Equation 4), was calculated as 124.3 °C. Cutting force, puncture force, lightness, hue and moisture content of the RWO baked potato strips as functions of severity are given in Figure 3.4. Corresponding R^2 values were in the range of 0.68 – 0.91, which indicates that the experimental data can be estimated by the regression equations 5-9.

$$Cutting\ force\ (N) = 163.1\ x \log(Severity) - 242.4 \quad (R^2=0.75) \quad (5)$$

$$Puncture\ force\ (N) = 5.3\ x \log(Severity) - 7.3 \quad (R^2=0.68) \quad (6)$$

$$Lightness = -76.12\ x \log(Severity) + 199.09 \quad (R^2=0.86) \quad (7)$$

$$Hue° = -64.1\ x \log(Severity) + 194.2 \quad (R^2=0.91) \quad (8)$$

$$Moisture\ content\ (\%) = -108.85\ x \log(Severity) + 244.02 \quad (R^2=0.88) \quad (9)$$

Cutting force of the control treatment was close to severity of 1.67, and lightness, hue and moisture content of the control treatment was at severity of 1.75 – 1.77. Increase in the severity of the RWO processing resulted in potato strips with higher cutting/puncture force, darker and more brown color and lower moisture content.

Conclusions

RWO processed par-fried potato strips dramatically reduced the fat content. Instrumental analysis indicated that some of the RWO processed potato strips were similar to the deep-fat fried potato strips in texture but different in color and moisture content. However, some of the RWO processed potato strips were similar to the fried samples in color and moisture content, but different in texture. Texture of the RWO baked potato strips was negatively correlated with overall and radiant heat transfer coefficient. However, surface temperature of the potato strips were positively and negatively correlated with texture and color of the RWO baked potato strips, respectively. Trained panel confirmed the similarity of the texture of the deep-fat fried potato strips and RWO baked potato strips at 365 °C for 6.5 min, however, did not confirm the similarity of the color. Consumer acceptability of the RWO processed potato strips at 365°C for

6.5 min should be investigated to check whether suggested treatment meets consumer's demands as well. Another suggestion to improve the product is to use a combination of two methods: an alternative heating method to increase temperature at the center of the potato strips followed by a surface heat treatment by RWO to improve color and texture of the potato strips.

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Table 3.1: Experimental Design of RWO processing[1]

Treatment #	Set Point Temperature[2] (°C)	Total Processing Time[3] (min)
1	290	13
2	290	14.5
3	290	16
4	315	9
5	315	10.5
6	315	12
7	340	7.5
8	340	9
9	340	10.5
10	365	6.5
11	365	8
12	365	9.5

[1]: Potato strips were fried in a deep-fat fryer at 177.5 ± 1.3 °C for 3 min as a control treatment.

[2]: Mean wall temperatures were 293.7 ± 3.5, 318.4 ± 2.6, 344.0 ± 3.4 and 368.6 ± 4.3 °C for the set point temperatures of 290, 315, 340 and 365 °C, respectively.

[3]: The deviation in processing times was 0.1 – 0.5 min.

Table 3.2: Heating times, and, mean surface temperature, heat flux, overall (U) and radiant (h_R) heat transfer coefficients of RWO treatments during baking potato strips (n=3)

Treatments #	Heating time[1] (min)	Surface temperature (°C)	Heat flux (W/m^2)	U (W/m^{2}K)	h_R (W/m^{2}K)
1	9.1	119.4[cde]	11957[ef]	69.1[bcd]	64.4[bc]
2	10.2	122.5[bcde]	11220[ef]	65.8[bcd]	62.1[bc]
3	10.8	127.2[abc]	10245[f]	61.1[d]	57.2[c]
4	6.8	115.7[de]	12771[de]	63.2[cd]	57.1[c]
5	7.8	128.7[abc]	13362[de]	70.7[abcd]	66.1[abc]
6	8.9	128.7[abc]	13269[de]	70.4[bcd]	66.0[abc]
7	5.4	113.9[e]	17369[b]	75.8[ab]	70.3[ab]
8	6.1	126.6[abc]	16157[bc]	74.1[abc]	69.2[ab]
9	7.5	124.5[abcd]	14541[cd]	66.7[bcd]	61.2[bc]
10	4.6	120.6[bcde]	19957[a]	81.7[a]	75.7[a]
11	5.8	130.1[ab]	16626[bc]	70.7[abcd]	65.0[abc]
12	6.8	133.2[a]	17031[b]	72.3[abc]	67.9[abc]
Standard error		3.4	835	3.8	3.8

[1]: Heating time was the time from entrance of samples to RWO till air temperature and surface temperature were equal (Figure 3.2, Zone 2).

[abcdef]: Least square mean followed by same letter within the same column show not significant difference with treatment ($p>0.05$).

Table 3.3: Moisture and fat content of the frozen, RWO baked and deep-fat fried potato strips (n=6)

Treatments #	Moisture Content (%) wet basis	Fat Content (%) dry basis
1	57.50^{bB}	9.79^{bB}
2	55.23^{cB}	9.83^{bB}
3	49.92^{cB}	10.30^{bB}
4	61.35^{bB}	9.62^{bB}
5	61.48^{bB}	9.34^{bB}
6	50.98^{cB}	10.90^{bB}
7	62.46^{bB}	9.38^{bB}
8	58.49^{bB}	10.45^{bB}
9	49.34^{cB}	10.90^{bB}
10	61.21^{bB}	9.55^{bB}
11	60.25^{bB}	10.30^{bB}
12	50.80^{cB}	10.06^{bB}
Control[1]	51.73^{cB}	50.69^{aA}
Raw Material[2]	72.58^{aA}	9.72^{bB}
Standard error	1.23	0.65

[1]: Deep-fat frying of potato strips at 177 °C for 3 min

[2]: Frozen par-fried potato strips

[abc]: Least square means followed by same letters within same column show not significant difference with control treatment (p>0.05).

[ABC]: Least square means followed by same letters within same column show not significant difference with raw material (p>0.05).

Table 3.4: Texture and color of the RWO baked and deep-fat fried potato strips (n=9, unless otherwise stated)

Treatments #	Texture – Cutting test[1]		Texture – Puncture force[2]		Color		
	Force (N)	Linear distance	Force (N)	Linear distance	Lightness	Chroma	Hue (°)
1	35.11[a]	41.21[a]	1.74[a]	4.62[b]	70.34[a]	37.70[a]	85.60[a]
2	45.45[a]	50.02[a]	2.01[a]	5.03[a]	68.45[b]	38.16[a]	83.68[b]
3	52.57[a]	58.83[a]	2.34[a]	5.29[a]	64.95[b]	38.09[a]	80.41[b]
4	30.22[a]	35.80[a]	1.42[b]	4.34[b]	71.76[a]	37.54[a]	86.91[a]
5	37.26[a]	41.90[a]	1.89[a]	5.14[a]	70.35[a]	38.50[a]	85.18[b]
6	46.80[a]	57.98[a]	1.74[a]	4.91[a]	65.97[b]	38.67[a]	81.10[b]
7	25.94[b]	31.77[b]	1.50[b]	4.78[a]	72.60[a]	37.08[a]	88.05[a]
8	40.11[a]	46.26[a]	1.68[a]	5.31[a]	67.55[b]	37.45[a]	83.27[b]
9	41.18[a]	48.90[a]	1.84[a]	5.09[a]	64.77[b]	38.22[a]	80.50[b]
10	27.26[b]	32.55[b]	1.40[b]	4.69[b]	72.06[a]	37.77[a]	87.24[a]
11	34.90[a]	39.59[a]	1.91[a]	5.20[a]	66.57[b]	36.43[a]	83.71[b]
12	44.83[a]	53.91[a]	2.10[a]	4.74[b]	60.75[c]	36.06[a]	79.28[c]
Control[3]	22.00[b]	28.76[b]	1.17[b]	3.77[b]	65.93[b]	36.70[a]	82.77[b]
Standard error	1.60	1.95	0.13	0.33	0.71	0.54	0.61

[1]: Required maximum cutting force, to halve the five baked/fried potato strips, and linear distance of the jagged force response.

[2]: Required maximum force to penetrate 3 mm diameter puncture probe into the baked/fried potato strips for 6 mm, and the linear distance of corresponding force response; n=3.

[3]: Deep-fat frying of potato strips at 177 °C for 3 min

[abc]: Least square means followed by same letters within same column show not significant difference with control treatment ($p>0.05$).

Table 3.5: Correlation[1] between heat transfer parameters and quality characteristics of the RWO baked potato strips

Parameters[2]	Cutting force	Cutting test - Linear distance	Puncture force	Puncture test - Linear distance	Lightness	Chroma	Hue	Moisture content
U	-0.43	-0.38	-0.27	-0.15	0.12	-0.12	0.19	0.13
	(0.011)	(0.025)	(0.12)	(0.39)	(0.51)	(0.48)	(0.27)	(0.46)
h_R	-0.39	-0.34	-0.2	-0.14	0.08	-0.13	0.16	0.087
	(0.024)	(0.046)	(0.25)	(0.44)	(0.65)	(0.46)	(0.38)	(0.62)
Surface	0.40	0.39	0.40	0.21	-0.69	-0.24	-0.61	-0.32
	(0.016)	(0.019)	(0.016)	(0.22)	(<.0001)	(0.16)	(<.0001)	(0.058)

[1]: Pearson correlation coefficients between two parameters are significant when p-value < 0.05. P-values are given in parenthesis.

[2]: U: Overall heat transfer coefficient; h_R: Radiant heat transfer coefficient; Surface: Surface temperature of potato strips

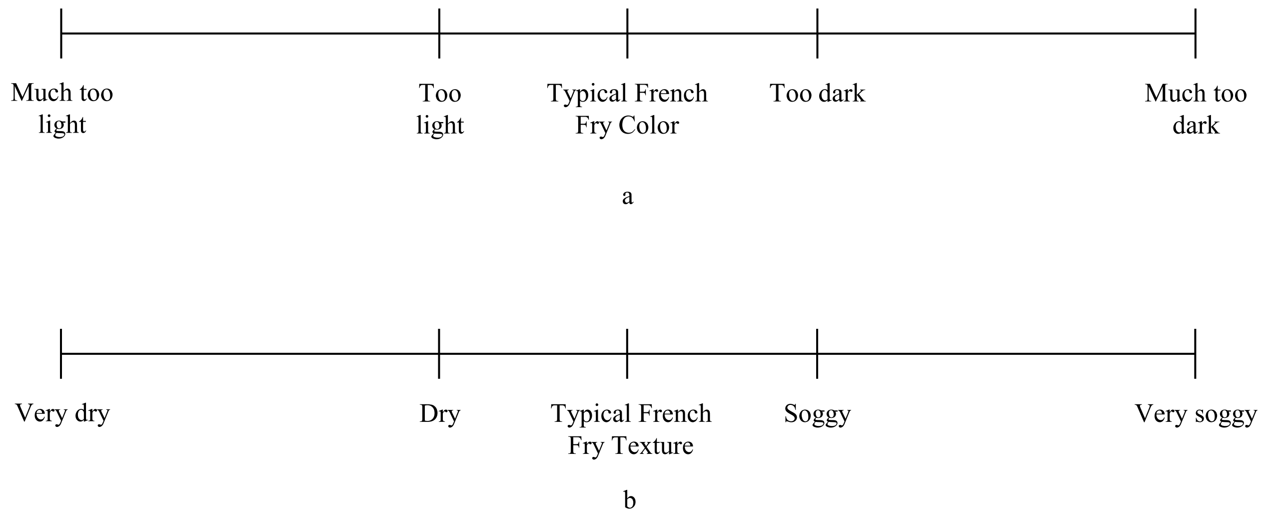

Figure 3.1-Unstructured 150 mm modified just-about-right scale used for the sensory evaluation of color (a) and texture (b) of the baked/fried potato strips.

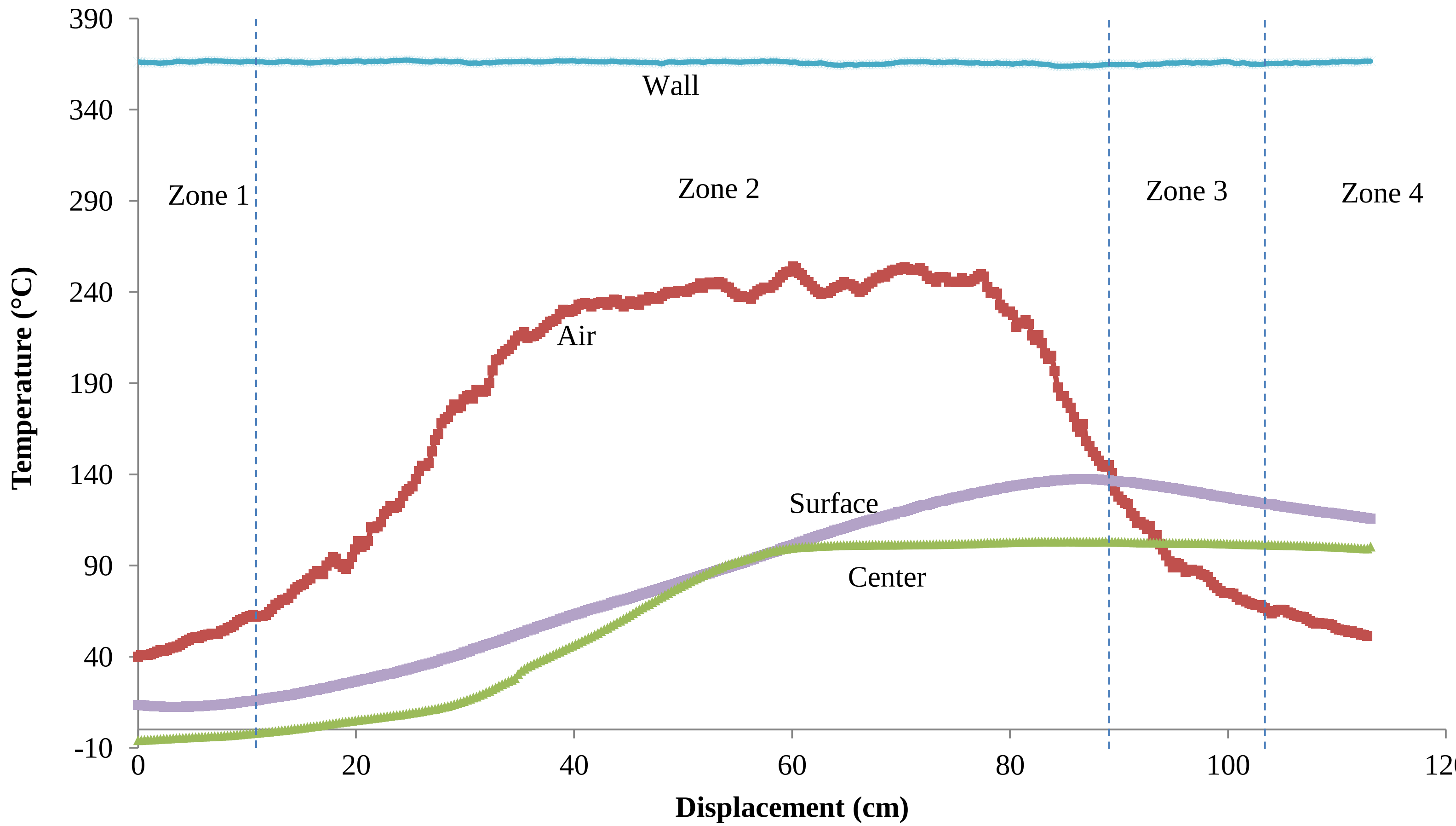

Figure 3.2: Typical temperature vs. displacement graph for the potato strips processed at 365 °C for 6.5 min in RWO. Wall: Wall temperature of RWO; Air: Air temperature surrounding the potato strip; Surface: Surface temperature of the potato strip; Center: Center temperature of the potato strip; Zone 1: Entrance zone of RWO; Zone 2: Heating zone of RWO; Zone 3: Cooling zone of RWO; Zone 4: Exit zone of RWO. Total length of RWO is 113 cm.

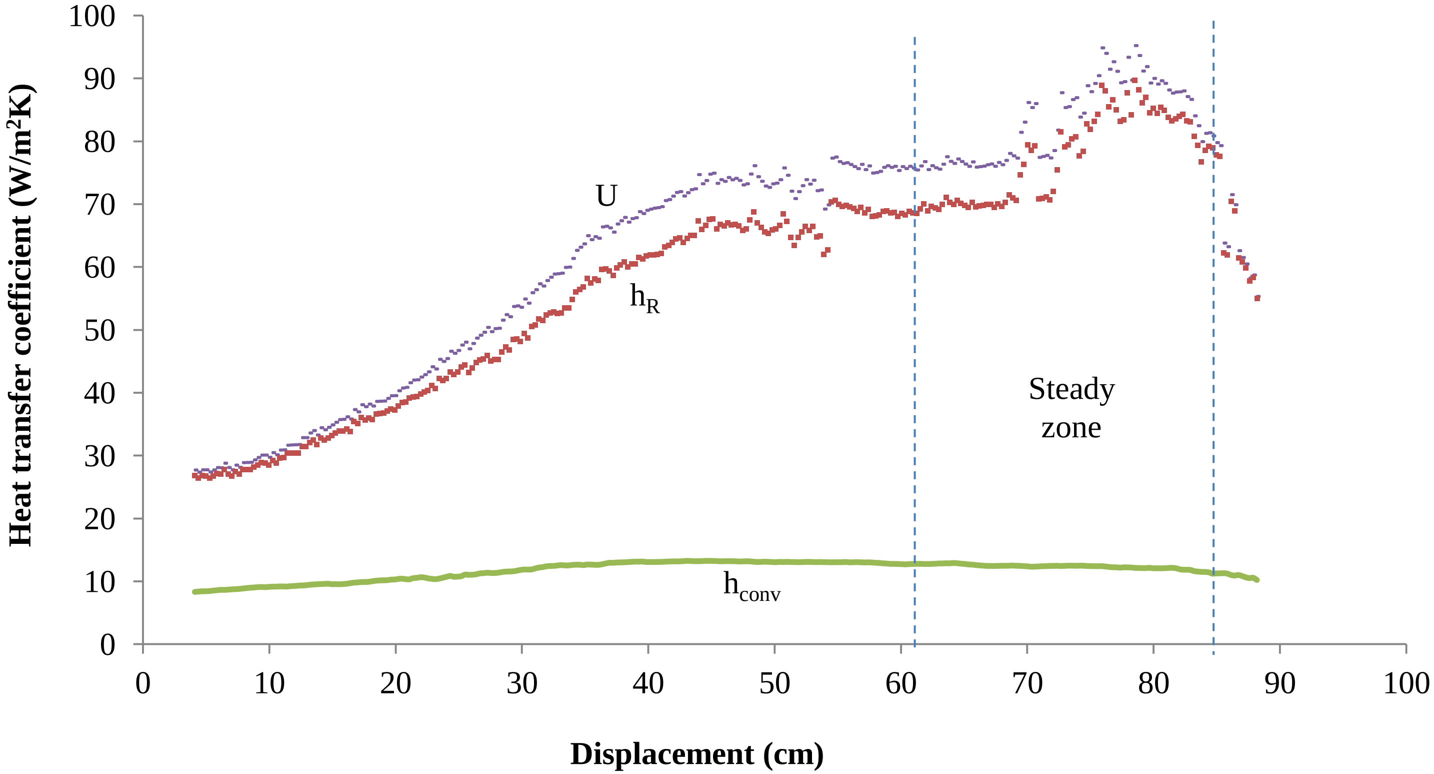

Figure 3.3: Heat transfer coefficients during RWO processing of potato strips at 365 °C for 6.5 min. U: Overall heat transfer coefficients; h_R: Radiant heat transfer coefficient; h_{conv}: Natural convective heat transfer coefficient; Steady zone: The zone where the center temperature of the potato strip and air temperature surrounding the product remains constant. Total length of RWO is 113 cm.

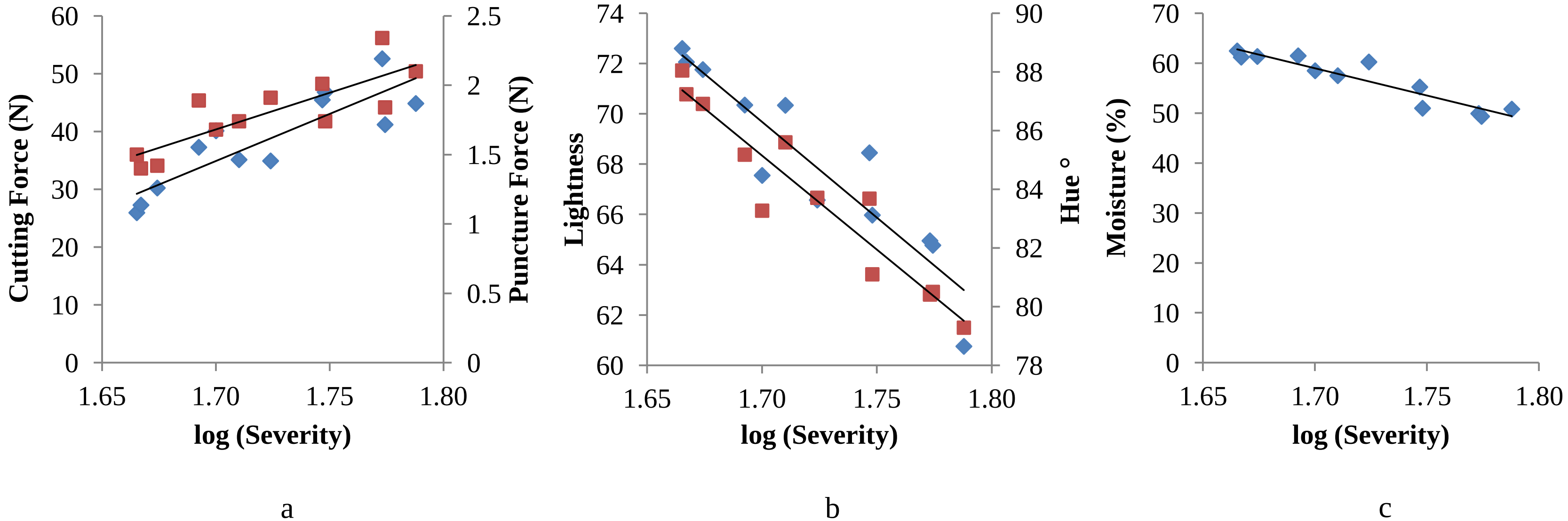

Figure 3.4: Cutting force (◆, a), puncture force (■ , a), lightness (◆ , b), hue angle (■ , b) and moisture content (c) of the RWO baked potato strips with respect to severity index.

CHAPTER 4

CONSUMER ACCEPTABILITY AND QUALITY EVALUATION OF POTATO STRIPS BAKED IN A RADIANT WALL OVEN[1]

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[1]Kirmaci, B., R.K. Singh and R.L. Shewfelt. Accepted by *International Journal of Food Properties.*

Abstract

Instrumental and sensory quality characteristics of potato strips baked in a Radiant Wall Oven (RWO) was evaluated and compared to deep-fat fried and conventional oven (CO) baked samples. Even though RWO baked potato strips had one-fourth the fat content of the deep-fat fried samples, there was no significant difference in chroma, cutting and puncture force of RWO baked and deep-fat fried samples. Consumer acceptability of RWO baked potato strips was 65.7% and 85.7% before and after revealing the nutrition facts, respectively. Both were lower than acceptability of deep-fat fried samples. However, 36.5% of consumers were willing to purchase RWO baked samples.

Keywords: Color, infrared heating, sensory, texture.

Introduction

French fries are very popular food, and served at any fast food restaurant. Quality of the potato strips includes golden yellow color, crispy crust, mealy core and oil content. Color of the potato strips is enhanced due to Maillard reaction between reducing sugar and amino acid of the product during heating. Reducing sugars are seen as the most contributors to the color enhancement of the fried potato strips (Sahin 2000).

The other quality characteristic of a potato strip is its texture. Crispiness is a texture attribute that is related to the total number of fractures occurring during deformation of the food when bitten with the incisors (Tunick and others 2013). Crispiness of a food product can be evaluated by instrumental analysis, as well as sensory analysis. Different kinds of instrumental methods used to evaluate the crispiness have been reviewed by Miranda and Aguilera (2006). Puncture test with a probe (1 – 3 mm) assesses surface of the fried products. This test can give information about springiness of the product, toughness of the crust and softness of the core (Pedreschi and others 2001). Kramer shear or knife blade shear tests are used to determine the hardness, i.e. peak force before fracture, of the potato strips.

Commercially available French fries have 12.5 – 15.5 % oil content on wet basis (USDA ARS 2013). As amount of fat in the diet has become a concern, efforts to reduce the oil content of fried products were started (Gamble and Rice 1988). Infrared (IR) heating was studied to reduce the fat content of the potato strips. Weaver and Huxsoll (1970) suggested improving crispiness and lowering oil content by pre-drying potato strips prior to blanching. Furthermore, Lloyd and others (2004) proposed an IR processing as an alternative to deep-fat frying by quartz halogen radiant emitters. Recently, Bingol and others (2012) used IR heating to reduce fat uptake of French fries during blanching.

Kirmaci and Singh (2013) also suggested baking potato strips in an IR based Radiant Wall Oven (RWO) at 365 °C for 6.5 min, as shown in Chapter 3. They reported that RWO baked potato strips had comparable quality to the deep-fat fried samples. They stated that trained panel also verified the similar texture in both RWO baked and deep-fat fried potato strips. Trained panel, however, cannot be correlated to consumer acceptability. Therefore, they suggested investigating consumer acceptability of the RWO baked potato strips at 365 °C for 6.5 min. Objectives of this study were *(i)* to instrumentally measure and compare color and texture of RWO baked, conventional oven (CO) baked and deep-fat fried potato strips, and *(ii)* to evaluate and compare consumer acceptability and willingness to purchase of RWO baked potato strips to deep-fat fried and conventional oven baked samples.

Materials and Methods

Sample Preparation

Forty five boxes (0.9 kg) of par-fried frozen potato strips (Great Value - Regular Cut French Fries, Walmart Inc., Bentonville, AR) were purchased from a national supermarket and stored in walk-in freezer at -40 °C. Par-fried frozen potato strips were sorted to have approximately 1cm in width and 1cm thickness. The sorted potato strips were cut to have 5 cm length, and then, stored in a freezer at -20 °C prior to further processing. Frozen par-fried potato strips had 75 ± 1 % moisture, and 8 ± 1 g fat per 100 g dry solids, respectively. Three different processes, described below, were conducted in triplicate. Baked/fried potato strips were placed on a food warmer (Model No. GRFFB, Hatco Corp., Milwaukee, WI) having 500 W infrared heat lamp and 250 W base heating element. Samples stayed for 2 min on the food warmer to control the temperature of the samples before color and texture analysis. Samples that stayed for more than 5 min on the food warmer were discarded due to absorption of moisture by the crust of the potato strip that caused loss of crispiness (Onwulata and others 2012).

RWO Processing

Potato strips were baked in a radiant wall oven (Pyramid Food Processing Equipment Manufacturing Inc., RWO-12-36, Tewksbury, MA) at 365 °C for 6.5 min, as described by Kirmaci and Singh (2013). RWO was heated by combustion of natural gas. Heated stainless alloy elliptical tube wall emitted infrared radiation to potato strips that were placed on the perforated conveyor belt (0.3 x 1.2 m). In addition to radiation and natural convection, conduction also contributed to the heating mechanism, since belt was also heated by the oven. Baked potato strips were placed in a warm stainless steel pan, and then, transferred immediately to the food warmer.

Deep-fat Frying

Potato strips were fried at 177 °C for 3 min with 5 L peanut oil in a deep-fat fryer. Oil was discarded after 10 h of usage. Excessive oil on the fried potato strips was drained on a piece of paper towel placed on a ceramic plate, and then, strips were immediately placed in a stainless steel pan on the food warmer.

CO Baking

Potato strips were baked on an aluminum baking sheet (Naturals Baker's Half Sheet, Nordic Ware, Minneapolis, MN) in a conventional oven (GE Profile, General Electric Company, Fairfield, CT) at 204 °C for 20 min, as suggested by the manufacturer. Baked strips were placed on a warm stainless steel pan, and then, immediately transferred to the food warmer.

Temperature Monitoring

Temperatures of center and underneath the surface of the potato strips were monitored by Teflon (Polytetrafluoroethylene - PTFE) coated type T thermocouples (Omega Engineering Inc., Stamford, CT) with a portable data logger (RDXL121-D, Omega Engineering Inc., Stamford, CT). Temperature of the wall in RWO was measured by type K thermocouple (Omega Engineering Inc., Stamford, CT). Furthermore, temperatures of the oil in the deep-fat fryer, temperature of the air in the RWO and conventional oven were measured by the same type of thermocouple. A thermocouple was inserted to the product after piercing the potato strips by a hypodermic needle.

Shrinkage

Width and thickness of the middle of the potato strips before and after each processing were measured by a caliper. Percent difference in area, calculated by multiplying width with thickness, of each potato strip before and after processing was reported as deformation in shape.

Moisture and Fat Content

Moisture content of the baked potato strips was determined by vacuum oven method of the Association of Official Analytical Chemists (AOAC 1995). About 2-3 g samples placed in pre-dried thimbles made from No.1 Whatman Paper, and then, dried in a vacuum oven (Cole-Parmer Instrument Co., Vernon Hills, IL) at below 61 kPa at 70 °C for 24 h. The fat content of the baked potato strips was measured by the Soxhlet method (AOAC 1995). Samples that were dried for moisture content analysis were placed in Soxhlet to extract oil with petroleum ether for 8 h in a Pyrex Distillation Unit. Fat content was gravimetrically calculated after removal of solvent from samples, and it was reported as percentage of oil per total solids of potato strips.

Instrumental Texture – Cutting Force

Cutting force of the potato strip samples was determined by the Texture Analyzer (TA.XT2i, Stable Micro Systems Ltd., Hamilton, MA) with chisel knife blade attachment. For each treatment, 5 baked potato strips, adjacent to each other, were placed on the slotted base to cover the area. Width and thickness of the potato strips were also measured by a caliper. A 5-kg load cell was used to detect maximum necessary amount of force exerted on the sample to divide the samples into halves. Pre-test cross arm speed was 1.5 mm/s and test speed was 2 mm/s. Texture Analyzer was calibrated prior to the test. Three measurements were taken for each replication.

Instrumental Texture – Puncture Force

Surface of the potato strip was evaluated by the Texture Analyzer (TA.XT2i, Stable Micro Systems Ltd., Hamilton, MA) with 3 mm puncture probe for each nine strips. Thickness of the potato strips was measured by a caliber. Pre-test cross arm speed was 1.5 mm/s and test speed was 2 mm/s. Probe was allowed to travel 6 mm after touching the sample, and, peak force was reported as puncture force.

Color

Color of the potato strips samples was measured by a colorimeter (model CR-410, Konica Minolta Sensing Inc., Ramsey, NJ). Color measurements were taken, after calibration with a white standard calibration cap. CIE color space was used to quantify the color of the samples in which lightness (L), chroma (saturation or brightness) and hue angle were determined. Nine potato strips were placed adjacent to each other, and, color was measured, as colorimeter averaged three readings for a single measurement. As baking altered the color of the bottom surface of the potato strip, both top and bottom surface of the strips were measured. In the case of deep-fat frying, color of the two opposite surfaces was measured. A total of six measurements were taken for each replication.

Consumer Acceptability

Consumer acceptability test and willingness to purchase of potato strip samples were evaluated by sensory analysis. Over one hundred individuals at the University of Georgia served as sensory panelists. All panels were conducted at the sensory laboratory in the Department of Food Science and Technology over a three-day period. White fluorescent lighting was used throughout the evaluation sessions and sensory booths had positive air flow to prevent any aroma circulation from the sample preparation area. Three pieces of processed potato strip samples were placed in a 3-digit coded paper sample cup for each treatment, and then were served to the panelists immediately. Water at room temperature and unsalted top saltine crackers were used as palate cleansers between samples.

First, panelists read and signed the consent form stating that voluntarily participating in the sensory test. Then, panelists were asked to evaluate the samples in terms of overall acceptability in pre-determined order. The order of sample evaluation was designed according to randomized. Panelists recorded their evaluation on a 3 point structured hedonic scale labeled as “superior”, “acceptable” and “unacceptable” for each samples. Panelists marked their willingness to purchase on the 5-point scale, labeled as “definitely would buy”, “probably would buy”, “might or might not buy”, “probably would not buy”, and “definitely would not buy”. At the end of the analysis, nutrition fact and total calorie of the RWO baked and deep-fat fried samples were revealed to each panelist. Then, each panelist was again asked about the acceptability of the RWO baked samples. Total frequency of “superior” and “acceptable” was reported as acceptability of the samples. Total frequency of “definitely would buy” and “probably would buy" choices were reported as willingness to purchase. Total percentage of acceptability was also reported after revealing the nutrition facts.

Statistical Analysis

Each treatment was replicated three times, and the order of treatments was randomized. One-way analysis of variance (ANOVA) was used to analyze the data using SAS (9.3, SAS Institute Inc., Cary, NC). Means were separated by Tukey's test at 95% confidence level. Frequency of the consumer acceptability and willingness to purchase data was determined using Microsoft Office Excel 2007 (Microsoft Corp., Redmond, WA).

Results and Discussion

Processing Conditions

Heating rates of the deep-fat fryer, RWO and CO for underneath the surface of the potato strip were 89.6 ± 3, 33.5 ± 0.4, and, 11.6 ± 2 °C/min, respectively. Heating rates of center of the potato strip in the deep-fat fryer, RWO and CO were 79.1 ± 5, 33.0 ± 2, and, 9.7 ± 0.6 °C/min, respectively. The highest heating rate was observed in deep-fat fryer and the lowest was occurred in CO. Potato strips were baked at 369.8 ± 5 °C for 6.6 ± 0.2 min in RWO. The variation in the processing time in RWO was due to variation in the belt speed. In deep-fat fryer, potato strips were fried at 177.8 ± 2 °C for 3 min. Potato strips were baked at 206.1 ± 16 °C in the CO for 20 min.

Shrinkage

All of three treatments caused shrinkage. Deep-fat fried potato strips retained their original size the most among other treatments, by losing 14 ± 5% of their dimensions. The highest deformation occurred in CO baking. It caused potato strips to lose 29 ± 7% of their original dimensions. Whereas, shrinkage in RWO baked potato strips was 20 ± 5% of their original dimensions. The results are in agreement with those of Andrés and others (2013) that they reported almost 40% and 10% volume loss in frozen par-fried potatoes after air-frying (convective heating in hot air) at 180 °C for 30 min and deep-fat frying at 180 °C for 4 min, respectively.

Moisture and Fat Content

Moisture content of the RWO baked, CO baked and deep-fat fried potato strips were 69 ± 1 %, 62 ± 2 % and 59 ± 2 % on wet basis, respectively. Moisture content of the RWO baked potato strips was significantly ($p<0.0001$) higher than that of deep-fat fried and CO baked samples. Whereas, moisture content of the CO baked potato strips was not significantly different than that of deep-fat fried samples. The fat content of the RWO baked, CO baked and deep-fat fried potato strips were 7.56 ± 0.6, 7.42 ± 1.03, and 42.15 ± 2 g fat per 100 g dry solids, respectively. Deep-fat fried potato strips had the highest fat content ($p<0.0001$). It was more than five times of the fat content of RWO and CO baked samples. There was no significant difference between fat content of the RWO and CO baked potato strips.

Texture

Maximum peak force of all three treatments for cutting and puncture tests are given in Table 4.1. CO baked potato strips had the hardest ($p<0.01$) texture among three treatments. Whereas, cutting force of the potato strips baked in RWO was not significantly different than that of deep-fat fried samples. However, Kramer shear test revealed that Controlled Dynamic Radiant (CDR) heated French fries had significantly higher maximum force than immersion fried and oven baked French fries (Lloyd and others 2004). When dimensions of the potato strips, used during texture analysis, were taken into account (Table 4.1), the interpretations of the cutting force results did not change. Rommens and others (2010) reported that outer potato strips, taken from outer part of the potato, had less moisture content than inner potato strips, taken from inner part of the potato. Effect of this variation was balanced by using five potato strips in each experiment. It has been reported that Kramer shear test of restructured sweet potato strips was more precise than three-point bending test and puncture test of the same samples (Walter Jr and others 2002). They used eight strips in Kramer shear test, whereas only one strip was used in the other two tests with higher number of replications.

Puncture test also showed similar results with cutting force test, except the force required to rupture CO baked potato strips. Even though CO baked samples had significantly ($p<0.05$) higher puncture force than that of RWO baked samples, there was no significant difference between puncture force of CO baked and deep-fat fried samples. When puncture force was divided by the thickness of the potato strips, used in puncture test, CO baked samples had significantly ($p<0.01$) higher puncture force than RWO baked and deep-fat fried samples. Lloyd and others (2004) reported no significant difference in maximum peak force of the CDR heated, immersion fried and oven baked French fries, when these samples were punctured with 1mm probe.

Even though RWO baked potato strips had significantly ($p<0.0001$) higher moisture content than deep fat-fried samples, cutting and puncture force of the two samples were not significantly different. On the other hand, CO baked and deep-fat fried potato strips had similar moisture content, the former samples had significantly ($p<0.01$) higher cutting force than the latter. These results are in agreement with those of van Loon and others (2007) and Sanz and others (2007). It has been reported that different pre-drying and par-frying conditions alter the crispiness of the French fries, despite the fact that the final moisture content of the samples were not significantly different between samples (van Loon and others 2007). Sanz and others (2007) also concluded that crispiness cannot be assessed by solely considering moisture content of the samples.

Color

Consumer acceptance is affected by color of a product. Color is quantified in CIE Lab color space. Conversion of ‘a’ (redness/greenness) and ‘b’ (yellowness/blueness) readings to chroma and hue angle was accomplished, as human perception of color is more related to chroma and hue angles (Shewfelt 1993). Lightness, chroma and hue angle of the deep-fat fried, RWO, and CO baked potato strips are given in Table 4.1. RWO baked potato strips had significantly ($p<0.001$) higher lightness and hue angle than deep-fat fried and CO baked potato strips. Whereas, CO baked potato strips had significantly ($p<0.0001$) higher chroma than deep-fat fried and RWO baked samples. These results are in agreement with those of Lloyd and others (2004) for French fries heated in CDR heater. They reported that lightness of the IR heated French fries was significantly higher than immersion fried and oven baked samples. However, they indicated no significant difference between IR heated and immersion fried French fries in terms of ‘b’. They also reported ‘b’ of the oven baked French fries was significantly higher than that of IR heated and immersion fried samples. Lightness and hue angle of the RWO baked potato strips was 67 ± 3 and 84 ± 3 °, respectively. Romani and others (2009) reported 67.46 and 95.80° as lightness and hue angle of the French fries that were deep-fat fried at 180 °C for 3 min.

Consumer Acceptability

In 105-member consumer panel, RWO processed potato strips at 365 °C for 6.5 min had 65.7% acceptability. On the other hand, deep fat fried and oven baked French fries had 97.1% and 84.8% acceptability, respectively. RWO baked potato strips had lower acceptability than deep-fat fried and CO baked samples. Lloyd and others (2004) conducted consumer acceptability test on

CDR heated, oven baked and immersion fried French fries with 9-point hedonic scale. They indicated no significant difference in overall acceptability of CDR heated and immersion fried French fries. However, they stated that oven baked French fries had significantly lower overall acceptance than CDR heated and immersion fried samples.

When panelists were asked the follow-up question after nutrition facts were given, more than half (58.3%) of the panelists changed their opinion about RWO baked potato strips from unacceptable to acceptable. After follow-up question, acceptability of the specially treated French Fries was 85.7%. This showed that consumers were likely to trade off their quality standards while having reduced-fat potato strips. It is important to note that nutrition fact of CO baked samples were not revealed and not re-tested. Therefore, one should not compare the acceptability of RWO baked potato strips after revealing nutrition facts to the acceptability of CO baked samples.

RWO baked potato strips had the lowest willingness to purchase value (36.5%) among three treatments. Whereas, 83.8% and 50.5% of the panelists were willing to purchase the deep-fat fried and oven baked samples, respectively. Sensory analysis indicated that RWO baked potato strips have commercial potential, but further product development is needed to increase willingness to purchase by potential consumers.

Conclusion

Texture and chroma of the RWO baked potato strips were not significantly different than that of deep-fat fried samples. However, there were significant differences in moisture content, lightness, hue angle values between RWO baked and deep-fat fried samples. Although the differences, RWO baked potato strips were accepted by the consumer panel. Moreover, revealing the reduced-fat content of the RWO baked samples increased the acceptability. However, acceptability of the deep-fat fried was the highest. On the other hand, only one-third of the consumer panelists were willing to purchase the RWO baked potato strips. This result indicates that some improvement in the final product by either modifying the raw material or additional processing such as pre-cooking is needed.

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Table 4.1: Texture and color of the RWO[1] and CO[2] baked, and, deep-fat fried potato strips

Treatment	Cutting[3]		Puncture[4]		Color[5]		
	Force (N)	Force/area (N/cm^2)	Force (N)	Force/thickness (N/cm)	Lightness	Chroma	Hue (°)
RWO[1]	19 ± 3[b]	4.2 ± 0.6[b]	1.3 ± 0.3[b]	1.3 ± 0.3[b]	67 ± 3[a]	36 ± 2[b]	84 ± 3[a]
CO[2]	37 ± 6[a]	9.1 ± 2[a]	2.3 ± 3[a]	2.8 ± 3[a]	65 ± 4[b]	39 ± 3[a]	79 ± 6[b]
Fryer	22 ± 3[b]	4.6 ± 0.5[b]	1.3 ± 0.6[ab]	1.3 ± 0.6[b]	62 ± 2[b]	35 ± 1[b]	79 ± 2[b]

[1]RWO = Radiant wall oven
[2]CO = Conventional oven
[3] n=9
[4] n=3
[5] n=18
[abc]Mean and standard deviation followed by same letters within same column show not significant difference ($p>0.05$).

CHAPTER 5

QUALITY OF THE PRE-COOKED POTATO STRIPS PROCESSED BY RADIANT WALL OVEN[1]

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[1]Kirmaci, B. and R.K. Singh. To be submitted to *LWT- Food Science and Technology*.

Abstract:

Steam processing was paired with the Radiant Wall Oven (RWO) to bake reduced-fat potato strips. Quality characteristics of RWO processed pre-cooked potato strips was investigated by both instrumental and sensory analysis. Par-fried frozen potato strips, purchased from supermarket, were sorted and cut to have 5 x 1 x 1 cm^3 dimensions. Potato strips were pre-cooked in steam chamber for 75 or 90 s. Then, steam-processed potato strips were heated in RWO at different temperatures: 450 °C for 3 or 3.5 min, at 500 °C for 2 or 2.5 min, at 550 °C for 1.5 or 2 min. Frozen samples were fried in deep-fat fryer at 177 °C for 3 min as a control. Yield, shrinkage, moisture, fat, color, and texture of the baked/fried potato strips were evaluated instrumentally. Based on the instrumental analysis, RWO processing at 500 °C for 3 min, regardless of steam processing time, resulted in the baked potato strips the most similar to the control samples. A trained panel indicated that texture of the potato strips, baked in RWO at 500 °C for 3 min after steam processing for 90 s, was not significantly different than that of the control samples. Finally, a 41-member consumer panel indicated 51.2% acceptability and 35% willingness to purchase for the RWO-baked pre-cooked potato strips when compared with control samples of 100% acceptability and 82.5% willingness to purchase. However, acceptability rose to more than 75% by the consumer panel for the RWO-baked pre-cooked potato strips when fat content and corresponding calories were revealed.

Keywords: color, infrared heating, potato strips, sensory, texture.

Practical Application:

Potato strips were baked in a Radiant Wall Oven (RWO) at 500 °C for 3 min after steam processing for 90 s. The baked potato strips had 87.5% less fat than deep-fat fried potato strips.

Moreover, quality characteristics of RWO baked potato strips were similar to the fried samples in terms of texture, chroma, shrinkage and yield. When consumers were told about fat content and corresponding calories, acceptability of the product was over 75%. Consumers are willing to compromise sensory quality for calorie reduction in potato strips.

Introduction

Potato is considered a staple food around the world. Raw Russet Burbank potatoes consist of 78.6% water, 18.1% carbohydrate, 2.1% protein and 0.1% fat (USDA ARS 2014a). More than half of the processed potato crop has been utilized as frozen French fries for the last six years (USDA ERS 2014). French fries are very popular and can be found at any quick serve restaurant. Fat content of French fries available at quick service restaurants is in the range of 12.5 – 15.5% wet basis (USDA ARS 2014b). Because of health issues, consumers are becoming more interested in the nutrition value of the fast food products within the past two years, according to 87% of fast food operators (NRA 2014). Lowering fat intake has been advised as it decreases cardiovascular risk on short-term, although long term effects were not known (Rees and others 2013). Furthermore, lowering energy intake by fat reduction was found to be associated with lower body weight (Hooper and others 2012).

In recent years, reduction of fat content of the French fries has attracted interest from consumer and food industry. French fries are produced by deep-fat frying in which potatoes gain all of the oil except the structural fat that found in potato. Efforts to reduce fat content of the French fries have been redirected at modifying raw material or the cooking process. Modification of the raw material for production of reduced-fat French fries has been accomplished using enzymes or outer parts of potatoes (Lisińska and others 2007; Rommens and others 2010). Unit operations in French fry production has also been modified to reduce fat absorption by improving blanching, pre-drying, or par-frying (Aguilar and others 1997; van Loon and others 2007; Agnieszka and others 2008; Ahmad Tarmizi and Niranjan 2013).

Infrared (IR) heating has also been used to reduce the fat content. IR heating was utilized as a dry blanching treatment of potatoes to reduce fat absorption during frying (Bingol and others

2012). Lloyd and others (2004), and, Kirmaci and others (2015) investigated to replace final frying with infrared heating. While the former used quartz halogen radiant emitters, the latter used a Radiant Wall Oven (RWO). Infrared radiant heating involves transfer of electromagnetic waves from emitted surface by radiation. When IR electromagnetic waves hit the surface of the product, the incident radiation is absorbed, reflected and transmitted. Absorbed electromagnetic waves causes change in molecular vibrational state leading to radiative heating (Decareau 1985). Heat transfer occurs mainly through radiation in RWO. A RWO contains a perforated conveyor belt surrounded by stainless alloy elliptical tube which is heated by natural gas combustion. The heated tube emits IR through the product. As IR heating replaces frying in RWO processing, reduced-fat products can be manufactured.

Quality of a product, especially when new techniques were used to make specific improvements on the original one, is important and should be determined. Color, texture, oily mouth feel were the most important quality attributes of French fries, besides the oil content (Weaver and others 1975). The light golden-brown color of French fries is a result of the reaction between reducing sugars and free amino acids during frying, known as Maillard reaction (Márquez and Añón 1986). When not limited by lowering reducing sugar content of the raw potato, this reaction will cause excessive darkening, off-flavor and acrylamide formation (Sahin 2000; Rommens and others 2010; Lisiñska 1989). Texture of the French fries can be described as a mealy-like baked potato core wrapped with a porous, crisp and oily crust (Weaver and others 1975; Miranda and Aguilera 2006; Pedreschi 2009).

Consumer acceptability/preference, or any affective analysis, cannot be inferred from either descriptive sensory analysis or instrumental analysis. Thus, a thorough quality analysis of a specific product requires affective consumer evaluation, in addition to the instrumental analysis.

A nine-point hedonic scale has been widely used to determine the consumer acceptability (Barrett and others 2010). Using a three-point acceptability scale was also suggested determining the consumer acceptability by reporting the frequency of the each response (Shewfelt 1999).

In the previous study, RWO was used to bake potato strips at 365 °C for 6.5 min to have similar quality attributes with deep-fat fried ones (Kirmaci and others 2015). A doubling of preparation time for French fries when compared with deep-fat frying could reduce profitability for the restaurant and cause inconvenience to the consumer. To shorten the processing time, RWO can be operated at higher temperature using precooked potato strips rather than frozen ones. We envision that a combination of steam and RWO processing improves the previously suggested new technique to bake potato strips while reducing the total processing time.

The objectives of this study were *(i)* to investigate the quality characteristics of RWO processed pre-cooked potato strips by both instrumental and sensory analysis in comparison with deep-fat fried counterparts, and, *(ii)* to determine consumer acceptability of the selected RWO processed pre-cooked potato strips based on instrumental and sensory analysis.

Materials and Methods

Sample Preparation

A total number of 127 packages of 0.9 kg par-fried frozen potato strips (Great Value - Regular Cut French Fries, Walmart Inc., Bentonville, AR) were purchased from a local supermarket and stored in a walk-in freezer at -40 °C. For each treatment, 81 strips were sorted from the packages to have 1 cm x 1 cm cross-section, and cut to have 5 cm in length. Then, strips were placed in a zippered, plastic bag and stored overnight in a freezer at -20 °C in order to be processed. Moisture and fat content of the frozen par-fried potato strips was 73.56 ± 0.32% and 11.47 ±

0.28 g fat/100 g dry solid, respectively. Nine strips (46.6 ± 1.4 g) were processed for each instrumental analysis per treatment. A food warmer (Model No. GRFFB, Hatco Corp., Milwaukee, WI), having 500W infrared heat lamp and 250W base heating element, was used to control the temperature of the samples before color and texture analysis. Samples were placed on the food warmer for 2 min for instrumental analysis. Any samples that stayed for more than 5 min on the warmer were discarded during sensory analysis.

Experimental Design

Frozen potato strips were partially cooked in a steam chamber (Pyramid Food Processing Equipment Manufacturing Inc., Tewksbury, MA) for 75 s or 90 s. The steam chamber was pre-heated from 56.7 ± 1.3 °C to 92.8 ± 0.3 °C, before heating the potato strips. During steam processing of potato strips, the steam chamber temperature rose above 99.0 ± 0.3 °C in 23 s, and kept at 99.4 ± 0.3 °C. After steaming, pre-cooked potato strips were transferred immediately to the radiant wall oven (Pyramid Food Processing Equipment Manufacturing Inc., RWO-12-36, Tewksbury, MA) and placed on a disposable aluminum foil sheet that had 6.35 cm width and 30.48 cm length. Steam processed potato strips were heated in RWO at six different time – temperature combinations (Table 5.1). To keep the processing times close to that used in deep-fat frying, the pre-cooked potato strips were processed in the RWO processing at high temperatures. As a control treatment, par-fried frozen potato strips were fried in 5 L peanut oil at 177 °C for 3 min using a deep-fat fryer (GE Model 168997, General Electric Company, Fairfield, CT). Fried potato strips were drained on a paper towel. Oil of the fryer was replaced after each 10 h of usage. Each treatment was conducted in triplicate.

Wall temperature of the RWO and oil temperature of the deep-fat fryer were monitored by Type K (XCIB-K-4-6, Omega Engineering Inc., Stamford, CT). Heating in steam chamber was also monitored by Type T thermocouples.

Yield

The moisture gain or loss during steam cooking and RWO processing was determined gravimetrically. Weight of the 9 frozen par-fried potato strips, steam cooked potato strips and RWO processed and deep-fat fried potato strips measured by analytical balance in triplicate. Then, percentage of yield after steam processing and RWO baking was calculated by Equation 1 & 2, respectively:

$$\% \, Yield_{steam} = 100 - \frac{Weight\ of\ frozen\ samples - Weight\ of\ steamed\ samples}{Weight\ of\ frozen\ samples} \times 100 \quad (1)$$

$$\% \, Yield_{RWO} = 100 - \frac{Weight\ of\ frozen\ samples - Weight\ of\ RWO\ baked\ samples}{Weight\ of\ frozen\ samples} \times 100 \quad (2)$$

for steam cooking and RWO baked / deep-fat fried samples, respectively.

Shrinkage

Width and thickness of the middle of the potato strips before and after RWO processing or deep-fat frying were measured by a caliper. Shrinkage was then calculated by percent change in total area of nine strips before and after processing, as shown in Equation 3:

$$\% \, Shrinkage = \frac{Total\ Area\ of\ frozen\ samples - Total\ Area\ of\ RWO\ baked\ samples}{Total\ Area\ of\ frozen\ samples} \times 100 \quad (3)$$

Moisture and Fat Content

Moisture content of the frozen, RWO baked and deep-fat fried potato strips was determined gravimetrically by vacuum oven method (AOAC 1995). Baked/fried potato strips were submerged into liquid nitrogen for 20 s and stored at -20 °C in a freezer until analysis. After homogenization under liquid nitrogen, 2 – 3 g samples were placed into pre-dried thimbles.

Vacuum oven (Cole-Parmer Instrument Co., Vernon Hills, IL) at below 61 kPa at 70 °C for 24 h was used to dry the samples. Oil in the dried samples was extracted in Soxhlet by petroleum ether in 8 h. Excess petroleum ether in the samples were then removed in vacuum oven, and fat content of the samples was calculated as oil weight per 100 g total solids of potato strips.

Instrumental Texture – Cutting Test

Cutting force of the RWO baked and deep-fat fried potato strips were determined using Texture Analyzer (TA.XT2i, Stable Micro Systems Ltd., Hamilton, MA) with a 5 kg load cell. Cross arm with chisel knife blade (45°) attachment halved the five potato strips that were placed adjacent to each other. Thickness and width of the potato samples were determined by a caliper. The peak force normalized by the cross sectional area of the potato strips was reported as the cutting force of the samples. The equipment was calibrated prior to the analysis. Pre-test and test speed were set at 1.5 mm/s and 2mm/s, respectively. The experiment was repeated nine times for each treatment.

Instrumental Texture – Puncture Force

Texture Analyzer (TA.XT2i, Stable Micro Systems Ltd., Hamilton, MA) was used to evaluate surface of the middle part of the potato strip by inserting 3 mm puncture probe. A 5 kg load cell used to detect puncture force, the required maximum force to penetrate the probe into the samples for 6 mm. Pre-test and test speed was same as cutting test, and Texture Analyzer was calibrated before conducting the test. Nine potato strips were tested for each treatment and analysis was replicated three times.

Color

Color of the RWO baked and deep-fat fried potato strips were quantified by CIE color space using a colorimeter (Model# CR-410, Konica Minolta Sensing Inc., Ramsey, NJ). Lightness (L), chroma (saturation or brightness), and, hue angle were determined. Colorimeter was calibrated with a white standard prior to the analysis. Surface color in contact with the belt, and the opposing surface of the baked samples was measured. Color of the two opposing surfaces was measured for the deep-fat fried samples. The experiment was repeated nine times for each treatment.

Sensory Analysis

All sensory experiments were done at the sensory laboratory of the Department of Food Science and Technology at University of Georgia. White fluorescent lighting was used throughout the evaluation sessions and positive air flow at the sensory booths prevented any aroma circulation from the sample preparation area. Three potato strips from each treatment were placed into a 3-random digit coded paperboard food tray (#25 Southland, The Southern Champion Tray, Chattanooga, TN), and then served to the panelists immediately. Panelists were given water at room temperature and unsalted top saltine crackers and asked to cleanse their palate between samples. At the end of evaluations, panelists were given a bite-size food reward.

<u>Trained Panel.</u> After statistically analyzing the instrumental analysis data, two RWO treatments that produced the most similar product with deep-fat fried potato strips were selected. A trained panel was conducted to determine the better treatment among those two treatments. The panel, consisting of 11 members, recruited from the individuals who like to eat French fries. The panelists were familiarized with the typical color and texture of the French fries at one of the quick serve restaurant in Athens, GA before the evaluations. The panelists evaluated one RWO processed pre-cooked potato strip and control samples in pre-determined randomized order in each evaluation session. Each RWO treatment was evaluated in duplicate; therefore, trained-panel testing was completed in four sessions.

Panelists used the unstructured 150 mm modified just about right (JAR) scale to evaluate the color and texture of the samples. The line was labeled "Much too dark" at 150 mm, "Too dark" at 100 mm, "Typical French fry color" at 75 mm, "Too light" at 50 mm, and "Much too light" at 0 mm for color evaluation. The scale for texture evaluation was labeled similar to the color evaluation scale (Figure 5.1). After evaluation, a ruler was used to convert responses to the numbers, and least square mean scores were reported with standard error.

Consumer Acceptability. Consumer acceptability and willingness to purchase of the best RWO treatment, determined by trained panel, and control treatment were evaluated by 41-member consumer panel over a two-day period, as described by Kirmaci and others (2015). Panelist were given three point acceptability scale, labeled as "superior", "acceptable" and "unacceptable" for each samples, to evaluate the acceptability of the samples. For willingness to purchase, panelists were given the 5-point scale, labeled as "definitely would buy", "probably would buy", "might or might not buy", "probably would not buy", and "definitely would not buy".

Upon completion of evaluation, fat content and corresponding calorie of the samples were revealed to the panelist. Then, each panelist was asked about the acceptability of the RWO baked samples again. Consumer acceptability of samples was calculated, before and after nutritional information was revealed, as the total frequency of "superior" and "acceptable". Willingness to purchase of samples was reported as the total frequency of "definitely would buy" and "probably would buy".

Statistical Analysis

Experiments were conducted in a randomized order. Time-temperature combinations were randomized, and then steam processing condition (75 s or 90 s) was randomized within each combination. Data was analyzed by One-way analysis of variance (ANOVA) using SAS (9.3, SAS Institute Inc., Cary, NC). Least square means (LS-means) of the RWO baked samples were compared to that of control sample by Dunnett's test at 95% confidence level. Sensory analysis data from trained panel was analyzed using PROC MIXED procedure, since each treatment had its own variation. Sensory analysis data from consumer panel was analyzed using Microsoft Office Excel 2007 (Microsoft Corp., Redmond, WA).

Results and Discussion

Steam and RWO Processing

Temperature at the center of the potato strips after steam processing for 75 s and 90 s was significantly different, and the center temperatures were 66.8 ± 2.7 °C and 77.2 ± 1.9 °C, respectively ($p<0.05$). Gelatinization of potato starch started at 61.1 – 61.6 °C and peaked at 65.9 °C (Shiotsubo 1984; Ratnayake and Jackson 2008). End gelatinization temperature of potato starch was reported as 79 – 79.4 °C (Ratnayake and Jackson 2008; Belitz and others 2009). Ratnayake and Jackson (2008) stated that degree of gelatinization was 36% and 55% at 65 °C and 75 °C, respectively. When the effect of two steam processing treatments was analyzed by comparing the quality characteristics of the final products, the only significant difference between two treatments was the moisture content ($p<0.05$). Baked potato strips that were steamed for 90 s had higher moisture content than baked potato strips that were steamed for 75 s (data not shown). However, there were no significant difference between two treatments in terms of cutting force, puncture force, lightness, chroma, hue angle, shrinkage, yield and fat content.

Proposed total processing times (2.75 – 5 min) were shorter than suggested 6.5 min processing time by Kirmaci and others (2015). Integration of steam processing to RWO processing reduced the processing times by 22 – 57%. Since, potato strips were already pre-cooked, RWO was operated at higher temperatures than 365 °C, used in the previous study (Kirmaci and others 2015). As temperature increased in RWO, wavelength of the infrared electromagnetic waves decreased according to Wien's displacement law. Therefore, RWO processing improved the color and texture of the potato strips by removal of the moisture around the surface due to low penetration. The corresponding wavelengths of IR energy were 4, 3.74 and 3.52 µm for the operating temperatures of 450, 500 and 550 °C, respectively. Thus, IR heating occurred at far-infrared region (FIR).

Mean wall temperatures were measured as 452 ± 3, 501 ± 3 and 550 ± 2 °C for the set point temperatures of 450, 500 and 550 °C, respectively. On the other hand, variation at the belt speed caused deviation at the RWO processing time in the range of 0.01 – 0.05 min (Table 5.1). Potato strip surface in contacting with the belt had marks in the preliminary experiments. Hence, aluminum foil sheet was used to prevent marks on the potato surface. At the end of baking, potato strips were transferred to the food warmer by holding in aluminum foil.

Yield

Steam processing increased the yield, as steam condensed on the potato strips during the process. However, there was not any significant difference in the yield of steam processed potato strips for 75 s and 90 s. The yield of the steamed potato strips was 119.2 ± 1.48% and 118.1 ± 1.1% for 75 s and 90 s steam processing, respectively.

Deep-fat frying, in which moisture is lost by evaporation and fat is absorbed, resulted in 74.21 ± 1.21% yield. Only yield of treatment #7 and #8 was not significantly different from that of control treatment (Table 5.2). All the other treatments had significantly higher yield than control treatment ($p<0.01$). Even though samples gained weight during steam processing, RWO processing caused baked samples to have less weight than their original weight.

Shrinkage

Shrinkage in deep fat fried and RWO processed pre-cooked potato strips was in the range of 12.6 – 16.3% (Table 5.2). However, the effect of both methods was not significantly different than each other. Kirmaci and others (2015) reported that when only RWO used to bake the potato strips at 365 °C for 6.5 min, it caused significantly more shrinkage than deep-fat frying. In the current study, yield showed that potato strips gained 18 – 19% weight during steam processing. That added moisture and the moisture found in the raw material was removed during RWO processing. That might be the reason for the difference between two studies in terms of shrinkage. Taiwo and Baik (2007) investigated the effect of frying on the shrinkage of sweet potato discs. They reported that shrinkage in diameter of the fried sweet potato discs was in the range of 6.7 – 10.2%. Furthermore, the thickness of the samples was lowered by 18.3% (Taiwo and Baik 2007).

Moisture and Fat Content

Moisture and fat content of the RWO baked pre-cooked potato strips are given in Table 5.2. The moisture content of the treatment #10 was significantly higher than that of frozen par-fried potato strips ($p<0.05$). There was not any significant difference in the moisture content of frozen par-fried potato strips and RWO baked potato strips according to treatments #1, #6, and #9. The rest of the treatments #2, #3, #4, #5, #7, #8, #11, #12, and control caused potato strips to have significantly lower moisture content than frozen par-fried potato strips ($p<0.05$). Moisture content of the all RWO processed pre-cooked potato strips was significantly higher than that of deep-fat fried samples ($p<0.0001$).

Deep-fat fried samples had the highest fat content among all treatments. All of the RWO baked pre-cooked potato strips were significantly in lower fat content than both deep-fat fried and frozen par-fried potato strips ($p<0.0001$). RWO processing of potato strips after steam processing resulted in 85.1 – 90% reduction of fat content with respect to deep-fat fried samples. Moreover, fat content of the RWO baked potato strips after steam processing was lower than the reported fat content of potato strips, 7.56 ± 0.6 g fat per 100 g dry solids, only RWO processed at 365 °C for 6.5 min (Kirmaci and others 2015). It was observed that some oil was released on the aluminum foil after potato strips were transferred to the RWO. Condensed moisture from steam processing was also removed during RWO processing in the current study, besides the original moisture in the raw material. Higher fat reduction might also be related to extra moisture removal from the product by carrying the fat, as steam distillation is one of the methods to extract oils (Charles and Simon 1990; Ahmad Tarmizi and Niranjan 2013).

Texture

Cutting and puncture force of the baked/fried potato strips are given in Table 5.3. Cutting force of the potato strips, that were RWO processed at 500 °C for 3 min (treatment #7 & #8), was not significantly different than that of control treatments. It is important to note that, besides cutting force, yield of these treatments was not significantly different than yield of deep-fat frying. Even though moisture content of the samples baked by RWO treatments #7 and #8 were significantly higher than control, cutting force of the potato strips was not significantly different. Treatments with a significantly higher yield than the control (treatments # 1 – 6 and # 9 – 12), had significantly less cutting force than that of control treatment ($p<0.01$).

When surface of the RWO baked or deep-fat fried potato strip samples were evaluated by 3-mm puncture probe, any significant difference was not observed between any RWO treatments and control. The variation in the texture data of potato chips or French fries was associated with the non-uniform distribution of starch and other compounds in the potato tuber (Miranda and

Aguilera 2006). Puncture and fracture/cutting tests are the most common means of evaluating texture of French fries (Walter Jr and others 2002; Lloyd and others 2004; Miranda and Aguilera 2006; van Loon and others 2007; Bingol and others 2012). Walter Jr and others (2002) stated that Kramer Shear test of restructured sweet potato French fries had the lowest coefficient of variation when compared to puncture and three-point bending test. Kirmaci and others (2015) used the 3 mm puncture probe with Texture Analyzer to evaluate the surface of the RWO baked potato strips, and were able to distinguish the treatments statistically. However, puncture force test with the same equipment and the same settings did not detect any textural difference between samples.

Color

Lightness, chroma and hue angle of RWO processed pre-cooked potato strips are given in Table 5.3. Lightness and hue angle of the all RWO processed pre-cooked potato strips were significantly higher than that of deep-fat fried counterparts ($p<0.001$). Whereas, chroma of the baked/fried potato strips was in the range of 35.3 – 37.64, and there is not any significant difference in the chroma of the all RWO processed pre-cooked and deep-fat fried samples. These results are in agreement with those of Kirmaci and others (2015) for RWO baked potato strips at 365 °C for 6.5 min. The data suggest that modification of RWO processing by addition of steam processing did not improve the product in terms of color. It should be noted that some parts of the RWO baked potato strips were darker.

Results of instrumental analysis revealed that treatments #7 and #8 were most similar in quality attributes to deep-fat fried counterparts. Texture, chroma, shrinkage and yield of these samples were not significantly different than those of fried samples. Therefore, potato strips, RWO processed at 500 °C for 3 min after steam processing for 75 s or 90 s, were chosen to be evaluated by trained panel. As only chroma of the all RWO processed pre-cooked potato strips were not significantly different than that of control samples, color was not taken into account when selecting the treatments leading to the most similar quality of fried French fries. It is important to note that treatments #7 and #8 resulted in 87% and 88% fat reduction with respect to deep-fat frying. Moreover, processing time of the treatments #7 and #8 was shorter by 34% and 30% than that of previous research in which potato strips were processed in RWO for 6.5 min, respectively (Kirmaci and others 2015).

Sensory Analysis

Control treatment, and treatments #7 and #8, were evaluated by trained panel to determine the treatment that resulted in the most similar product to deep-fat fried samples. Then, consumer acceptability and willingness to purchase of that treatment and control were determined by consumer panel.

Sensory Descriptive Analysis. Color of the potato strips from treatment #7, #8 and control was determined as 64.9 ± 3.0, 69.6 ± 3.0 and 77.7 ± 1.7, respectively. Results of trained panel data showed that color of the RWO processed pre-cooked potato strips from treatment #7 and #8 were significantly lighter than that of control treatment as seen in the instrumental color analysis ($p<0.05$).

Texture of the potato strips from treatment #7, #8 and control was determined as 88.6 ± 4.3, 86.8 ± 6.5, 76.2 ± 2.1, respectively. The panel determined that the RWO processed potato strips at 500 °C for 3 min after steam processing for 75 s were soggier than texture of control samples ($p<0.05$). However, it found no significant difference in between potato strips that were RWO processed after steam processing for 90 s (treatment #8) and deep-fat fried in terms of texture.

Therefore, potato strips that had 87.5% less fat than the control samples (treatment #8) were chosen to be evaluated by consumer panel.

Consumer Acceptability. The results indicated consumer acceptability of 51.2% for RWO baked potato strips at 500 °C for 3 min after steam processing for 90 s and 100% for the control samples. Results of consumer acceptability suggest that the modification of RWO processing by addition of steam processing did not improve the product. Furthermore, when only RWO was used to bake potato strips at 365 °C for 6.5 min, consumer acceptability of those samples was 65.7% (Kirmaci and others 2015). Panelists were also asked about acceptability of the RWO processed pre-cooked samples again after the nutritional information of the samples were shared with them. Half of the panelists, who rated the product as unacceptable, prioritized the reduced-fat content, acceptability of the RWO processed pre-cooked potato strips, thus, increased to 75.6%. A similar tendency of consumer panelists lowered their expectation from a product as a result of demand for the reduced-fat product was observed previously (Kirmaci and others 2015). Willingness to purchase of the RWO processed pre-cooked potato strips and control samples were 35% and 82.5%, respectively. Willingness to purchase of RWO processed pre-cooked potato strips was very close to the that of RWO baked potato strips at 365 °C for 6.5 min (Kirmaci and others 2015). Consumer panel showed that integration of steam processing to RWO processing for baking potato strips did not meet consumer's expectations.

Conclusions

RWO baking of steam processed potato strips resulted in fat reduction drastically when compared to deep-fat frying. However, total processing time was only decreased 30% with respect to previous research (Kirmaci and others 2015). RWO processing at 500 °C for 3 min after steam processing for 75/90 s produced the best quality potato strips in terms of texture, chroma, shrinkage and yield. However, trained panel perceived the texture of RWO baked potato strips at 500 °C for 3 min after steam processing for 75 s soggier than the control. Consumer panel of potato strips, that were RWO processed at 500 °C for 3 min after steam processing for 90 s, had 51.2% and 75.6% before and after revealing the nutritional information of the treatment and control samples, respectively. In contrast to rise in the consumer acceptability due to reduced-fat contents, low willingness to purchase showed that further research is needed to improve the quality of the RWO baked potato strips. The integration of steam and RWO processing to bake potato strips reduced cooking time but did not improve the product quality. Steam processing might be replaced by superheated steam processing, as the latter will not condense on the potato strips.

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Table 5.1: Experimental design of pre-cooking and RWO processing of potato strips[1]

Treatment #	Steam Processing[2]	RWO processing	
	Time (s)	Set point Temperature[3] (°C)	Time[4] (min)
1	75	450	3
2	90	450	3
3	75	450	3.5
4	90	450	3.5
5	75	500	2.5
6	90	500	2.5
7	75	500	3
8	90	500	3
9	75	550	1.5
10	90	550	1.5
11	75	550	2
12	90	550	2

[1]: Potato strips were fried in a deep-fat fryer at 177.6 ± 1.7 °C for 3 min as a control treatment.

[2]: Steam chamber temperature increased above 99.0 ± 0.3 °C in 23 s, and stayed at 99.4 ± 0.3 °C.

[3]: Mean wall temperature was 452 ± 3, 501 ± 3 and 550 ± 2 °C for the set point temperatures of 450, 500 and 550 °C, respectively.

[4]: Mean processing time was 1.54 ± 0.02, 2.07 ± 0.01, 2.55 ± 0.02, 3.05 ± 0.02 and 3.59 ± 0.05 min when the belt speed was set for the processing time of 1.5, 2, 2.5, 3 and 3.5 min, respectively.

Table 5.2: Yield, shrinkage, moisture and fat content of the RWO baked and deep-fat fried potato strips

Treatment #	Yield[1] (%)	Shrinkage[1] (%)	Moisture content[2] (% wet basis)	Fat content[2] (% dry basis)
1	87.66^{a}	15.1^{a}	72.41^{aB}	3.97^{bC}
2	84.81^{a}	16.3^{a}	72.01^{aC}	4.81^{bC}
3	80.59^{a}	13.7^{a}	68.46^{aC}	5.45^{bC}
4	81.6^{a}	13.9^{a}	70.83^{aC}	5.89^{bC}
5	85.07^{a}	15.6^{a}	70.99^{aC}	5.88^{bC}
6	85.1^{a}	16.2^{a}	72.62^{aB}	4.83^{bC}
7	78.17^{b}	12.6^{a}	68.5^{aC}	5.22^{bC}
8	79.26^{b}	13.8^{a}	69.43^{aC}	4.93^{bC}
9	92.78^{a}	13.6^{a}	74.53^{aB}	5.15^{bC}
10	93.8^{a}	12.8^{a}	75.07^{aA}	4.66^{bC}
11	84.61^{a}	15.0^{a}	70.17^{aC}	4.88^{bC}
12	84.57^{a}	15.3^{a}	70.93^{aC}	4.05^{bC}
Control[3]	74.21^{b}	12.7^{a}	55.60^{bC}	39.53^{aA}
Raw material[4]	n/a[5]	n/a	73.56^{aB}	11.47^{bB}
Standard error	1.2	1.7	0.32	0.28

[1]: n=3

[2]: n=6

[3]: Deep-fat frying of potato strips at 177 °C for 3 min

[4]: Frozen par-fried potato strips

[5]: non applicable

[ab]: Least square means followed by same letters within same column show not significant difference with control treatment ($p>0.05$).

[ABC]: Least square means followed by same letters within same column show not significant difference with raw material ($p>0.05$).

Table 5.3: Texture and color of the RWO baked and deep-fat fried potato strips

Treatment	Texture		Color[3]		
	Cutting force[1] (N/cm^2)	Puncture force[2] (N)	Lightness	Chroma	Hue (°)
1	3.37[b]	1.33	73.14[a]	36.23[a]	89.49[a]
2	3.78[b]	1.32	74.0[a]	37.31[a]	89.42[a]
3	4.47[b]	1.66	73.98[a]	37.01[a]	88.42[a]
4	4.36[b]	1.44	73.49[a]	37.64[a]	88.26[a]
5	3.56[b]	1.29	72.2[a]	37.42[a]	88.1[a]
6	3.82[b]	1.44	72.23[a]	35.91[a]	88.37[a]
7	5.35[a]	1.61	71.89[a]	37.0[a]	86.75[a]
8	5.34[a]	1.88	72.34[a]	37.05[a]	87.15[a]
9	2.90[b]	1.29	72.22[a]	35.58[a]	89.84[a]
10	2.93[b]	1.45	73.23[a]	35.3[a]	90.33[a]
11	4.25[b]	1.70	71.94[a]	36.87[a]	88.03[a]
12	4.31[b]	1.50	71.36[a]	36.15[a]	87.93[a]
Control[4]	5.8[a]	1.38	69.17[b]	36.6[a]	84.53[b]
Standard error	0.24	0.15	0.35	0.35	0.24

[1]: Required cutting force normalized by the cross-sectional area to cut the five baked/fried potato strips (n=9).

[2]: Required peak force to penetrate 3 mm diameter puncture probe into the baked/fried potato strips for 6 mm (n=3).

[3]: n=18

[4]: Deep-fat frying of potato strips at 177 °C for 3 min

[ab]: Least square means followed by same letters within same column show not significant difference with control treatment ($p>0.05$).

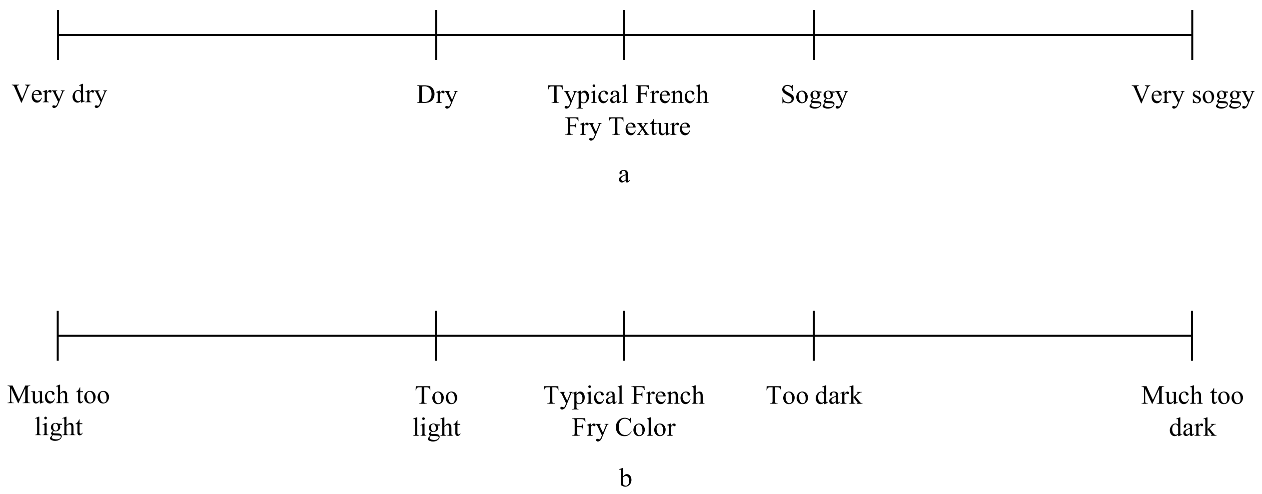

Figure 5.1-Unstructured 150 mm modified just-about-right scale for the evaluation of texture (a) and color (b) of baked/fried potato strips.

CHAPTER 6

CONCLUSIONS

RWO processed par-fried potato strips dramatically reduced the fat content. Instrumental analysis indicated that some of the RWO processed potato strips were similar to the deep-fat fried potato strips in texture but different in color and moisture content. However, some of the RWO processed potato strips were similar to the fried samples in color and moisture content, but different in texture. Texture of the RWO baked potato strips was negatively correlated with overall and radiant heat transfer coefficient. However, surface temperature of the potato strips were positively and negatively correlated with texture and color of the RWO baked potato strips, respectively. Trained panel confirmed the similarity of the texture of the deep-fat fried potato strips and RWO baked potato strips at 365 °C for 6.5 min, however, did not confirm the similarity of the color.

Texture and chroma of the RWO baked potato strips were not significantly different than that of deep-fat fried samples. However, there were significant differences in moisture content, lightness, hue angle values between RWO baked and deep-fat fried samples. Although the differences, RWO baked potato strips were accepted by the consumer panel. Moreover, revealing the reduced-fat content of the RWO baked samples increased the acceptability. However, acceptability of the deep-fat fried was the highest. On the other hand, only one-third of the consumer panelists were willing to purchase the RWO baked potato strips. Consumers were willing to compromise sensory quality for calorie reduction in potato strips.

RWO baking of steam processed potato strips resulted in fat reduction drastically when compared to deep-fat frying. However, total processing time was only decreased by 30% with respect to previous research. RWO processing at 500 °C for 3 min after steam processing for 75/90 s produced the best quality potato strips in terms of texture, chroma, shrinkage and yield. However, trained panel perceived the texture of RWO baked potato strips at 500 °C for 3 min after steam processing for 75 s soggier than the control. Consumer acceptability of potato strips, that were RWO processed at 500 °C for 3 min after steam processing for 90 s, was 51.2% and 75.6% before and after revealing the nutritional information of the treatment and control samples, respectively. In contrast to increase in the consumer acceptability due to reduced-fat contents, low willingness to purchase showed that further research is needed to improve the quality of the RWO baked potato strips. The integration of steam and RWO processing to bake potato strips reduced cooking time but did not improve the product quality.

Future studies should focus on an alternative heating method to increase temperature at the center of the potato strips followed by a surface heat treatment by RWO to improve color and texture of the potato strips. For instance, superheated steam processing might replace the steam processing, as the former will not condense on the potato strips. Another suggestion is to optimize the raw material that will be specifically baked in RWO, by investigating the conditions of pre-treatments such as blanching, pre-drying, and par-frying.