Heat transfer coefficients during baking of potato strips in a pilot scale radiant wall oven

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ABSTRACT

A pilot scale radiant wall oven (RWO) was used to bake potato strips at 12 different time-temperature combinations within 16 min at 290°C to 6.5 min at 365°C. Radiant and overall heat transfer coefficients were experimentally determined for each RWO treatment by monitoring temperature and heat flux. Correlation between heat transfer parameters and quality of the samples was also determined. It was determined that 92%–94% of the overall heat transfer coefficient was contributed by radiant heat transfer. While no correlation was found between color of the RWO baked potato strips and heat transfer coefficients, texture of the RWO baked potato strips was negatively correlated with overall and radiant heat transfer coefficients. Radiant heating could be used as a surface treatment to bake potato strips to mimic the surface of fried strips without increasing their fat content.

Introduction

French fries are a popular food made from potatoes. In 2016, 19.2 billion kg of potatoes were produced in the US, and 65% of which were utilized as French fries. Because of its availability in all fast food restaurants and high fat content (12.5–15.5% wet basis), French fries are considered as a contributor to increasing obesity rates. Thus, French fries production has been studied at different processing steps to lower its fat content. Some of the efforts involve radiative heating technology to bake the potato strips.

Radiation is one of the three different modes of heat transfer along with conduction and convection. In conduction, heat is transferred by lattice vibration and/or particle collision where physical contact is present. Heat transfer occurs by the natural or forced movement of the fluid (air, oil, etc.) around the product in convection mode. Whereas in radiative heating, heat is transferred by the electromagnetic waves. Wavelength or frequency of the electromagnetic waves determine the type 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. The shorter wavelength, the deeper the energy penetrates into the food in IR heating. This allows IR heating to be used as surface heat treatment.

Surfaces having higher temperature than 0 K emit IR energy according to Stefan-Boltzmann law. The total emissive power of an IR heating source is proportional to the fourth power of its absolute surface temperature. Electric and gas-fired heaters can be used as an IR heating source. Electric heaters convert electric energy into thermal energy that is transferred by electromagnetic waves, such as halogen heaters. In gas-fired heaters, IR heat is emitted by a surface that is heated by combustion of natural or combustible gas. Lloyd et al. (6) utilized halogen emitters to process potato strips. They have reported lighter and less uniform in color, harder in texture potato strips with lower moisture content.
than immersion fried potato strips. In another study, Nelson III et al. (7) applied this heating technology on chicken patties achieving 16% less oil and lighter color than oil immersion fried chicken patties. Radiant wall oven (RWO), a gas-fired IR heater, has been studied to bake potato strips.[5,8] In those studies, instrumental and sensory analysis showed that RWO baked potato strips had similar quality attributes as their immersion fried and conventional oven baked counterparts. In another study, texture and lightness of the RWO baked breaded chicken nuggets were not significantly different than those of immersion fried breaded chicken nuggets.[9] Since heat transfer coefficient is also surface phenomena in the case of radiation and convection, its relationship with the quality of the product was also investigated. The objectives of this research were two-fold: (i) to experimentally determine overall and radiative heat transfer coefficients during baking of potato strips and (ii) to evaluate the relationship between heat transfer coefficients and quality parameters of RWO baked potato strips.

**Materials and methods**

**Sample preparation and RWO processing**

Commerically available 69 packages of 0.9 kg each frozen par-fried regular cut French fries (Great Value – Regular Cut French Fries, Walmart Inc., Bentonville, USA) and 4 packages of 0.9 kg each frozen par-fried steak cut French fries (Great Value – Regular Cut French Fries, Walmart Inc., Bentonville, USA) were obtained from a national supermarket. French fries were sorted, cut to have 5 cm length and stored in a walk-in freezer at −40°C.

Nine potato strips (48 ± 1 g) were baked in an RWO (Figure 1, Pyramid Food Processing Equipment Manufacturing, Tewksbury, MA) at twelve different time–temperatures combinations (Table 1). The temperatures were selected based on the lowest RWO operation temperature and preliminary experiments. RWO has stainless alloy elliptical tube that emits IR radiation to the product moving on a continuous wire-mesh belt. The total length of the oven is 113 cm, including the entrance and exit zones. The entrance zone is called a heating zone, and the exit zone is a cooling zone. Each zone has 10 cm length, and airflow is prevented in these zones. The elliptical tube was heated by combustion of natural gas and the gas flow was automatically controlled to adjust the temperature. The wavelength range at which maximum emission occurs during RWO processing was 4.5–5.2 μm. At those wavelengths, penetration depth of IR radiation is lower causing to rapidly heat the surface of the product. Hence, the crust is developed at the surface and the color is formed due to non-enzymatic browning. Each treatment was replicated three times and the order of treatments was randomized.

**Temperature monitoring**

Radiant wall temperature and 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 for 2.5 cm 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 using an inconel overbraided Type K thermocouple (XCIB-K-4-6, Omega Engineering Inc., Stamford, CT) that was bolted against the wall.
Heat transfer

Radiant, natural convective and overall heat transfer coefficients were determined experimentally for each RWO treatments in triplicate based on heat flux to the potato strips, radiant wall temperature, surface temperature of the product and the temperature of the air surrounding the product that were all monitored during baking potato strips in RWO. Heat flux toward 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)\[10\]

$$U_{RWO} = \frac{q''}{(T_{wall} - T_{surface})}$$  \hspace{1cm} (1)

where $q''$, $T_{wall}$, and $T_{surface}$ are the heat flux through the product (W/m²), 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)\[11\]:

$$h_{conv} = 1.3196 \times \left\{ \frac{T_{air} - T_{surface}}{D_{eq}} \right\}^{0.25}$$  \hspace{1cm} (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)\[11,12\]:

$$h_{R} = U_{RWO} - h_{conv} \times \left( \frac{T_{air} - T_{surface}}{T_{wall} - T_{surface}} \right)$$  \hspace{1cm} (3)

**Quality parameters**

Moisture content, color (lightness, chroma and hue) and texture (cutting force, puncture force and their corresponding linear distances) of the RWO baked potato strips were reported by Kirmaci and Singh (5). In this paper, relationship between heat transfer coefficients and quality parameters were investigated.

**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 data were analyzed using PROC MIXED procedure, as each treatment had its own variation.

![Figure 2. Typical temperature vs. displacement graph for the potato strips baked at 365 °C for 6.5 min in Radiant Wall Oven (RWO).](image-url)
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).

Results and discussion

**RWO processing of potato strips**

RWO had 11.1 cm entrance and exit zone at both ends (Figure 2, zones 1 and 4). Temperature monitoring indicated that at 80.8 ± 2.1 cm, temperature of the air surrounding the product started to decrease. 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 2, zone 2), from product entrance to RWO till the point where temperature of air surrounding product equaled the surface temperature of the product, was 78.9 ± 1.6 cm in RWO. Corresponding heating times for each treatment are given Table 2.

Heat flux and overall and radiant heat transfer coefficients during RWO treatments are given in Table 1. All of these parameters were averaged from the corresponding values within the steady zone (Figure 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/m², 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/m².

The range of overall and radiant heat transfer coefficient was 61.1–81.7 W/m² K and 57.1–75.7 W/m² 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/m² K[13] and 151.1 W/m² K for non-breaded chicken nuggets.[14] 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,

Table 2. Correlation* between heat transfer coefficients and quality of the radiant wall oven baked potato strips.

| Parameters | 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)          |
| hR         | −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)          |

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

![Figure 3](image-url) *Figure 3. Heat transfer coefficients during Radiant Wall Oven (RWO) processing of potato strips at 365°C for 6.5 min. U: Overall heat transfer coefficients; hR: Radiant heat transfer coefficient; hconv: 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.*
respectively. Overall, radiant heat transfer coefficients of RWO treatments within the same temperature were not significantly different from each other. As seen from Figure 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/m² 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.

**Correlation**

Pearson correlation coefficients between heat transfer and quality parameters are given in Table 2. 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 moisture content or color of the RWO baked potato strips. Based on our previously published study, Kirmaci and Singh (5), 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.

**Conclusion**

Heating in RWO was primarily due to the radiant heating. Based on its lower penetration depth, RWO can be used to alter texture and color of the surface of the food products such as French fries without increasing the fat content. Heat transfer coefficient can give guidance to scale up or down the equipment and be used to compare similar equipment or processes. Texture of the RWO baked potato strips was negatively correlated with overall and radiant heat transfer coefficient. However, no significant correlation was found between color of the RWO based potato strips and heat transfer coefficients.

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**Disclosure statement**

No potential conflict of interest was reported by the author(s).
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