

## ABSTRACT

MELITO, HELEN SHIRLEY. An Alternative Frying Process for Wheat and Gluten-Free Donuts. (Under the direction of Dr. Brian E. Farkas).

Fried foods are enjoyed worldwide as snacks or part of a meal. However, because these foods are deep-fried in oil, they tend to have a high fat content. Previous study on a partial- (par-) frying, infrared- (IR-) finishing process showed that French fries cooked by this process had significantly lower fat content than fully-fried French fries (13% vs. 19%, respectively,  $\alpha=0.05$ ). It was hypothesized that this par-frying, IR-finishing process would be able to produce both wheat and gluten-free (GF) donuts with a lower fat content but still instrumentally and sensorially comparable to fully-fried wheat donuts, the control.

Experiments were separated into three groups: wheat par-fried, IR-finished donuts, GF fully-fried donuts, and GF par-fried, IR-finished donuts. Four different formulations of GF donuts were tested, each formulation using a different combination of GF flours (commercial GF flour and rice flour) and hydrocolloids (pregelatinized rice flour and xanthan gum). Donuts were fried with and without a methylcellulose coating (0.5 g methylcellulose in 50 g water), which was brushed on before proofing. All of the par-fried, IR-finished donuts were par-fried for 64 s and finished in an IR oven. Two different IR cooking times (45 s or 53 s for wheat donuts, 39 s or 45 s for GF donuts) and four different distance combinations from the IR emitters to the food were tested. Mass, volume, and density changes, percent moisture and fat, crust color, and crust and crumb rheological properties of all donuts were compared to those of the control. Sensory testing was also performed on selected donuts using a 9-point hedonic scale (1: dislike extremely, 9: like extremely) to measure overall acceptance, aroma, taste, and texture/mouthfeel.

Statistical analysis ( $\alpha=0.05$ ) showed that all wheat par-fried, IR-finished donuts (25.6%-30.6%), most of the GF fully-fried donuts (26.3%-32.2%), and all GF par-fried, IR-finished donuts (23.7%-28.2%) had a significantly lower fat content than the wheat control (33.7%). Setting the emitters in either a height gradient from 45 mm to 25 mm or at a height of 35 mm above the top of the donut and using either IR time produced wheat par-fried, IR-finished donuts that were most instrumentally similar to the control, while using the same emitter settings and an IR-finishing time of 39 s produced GF par-fried, IR-finished donuts that were the most instrumentally similar to the control. Gluten-free fully-fried donuts made with a higher ratio of commercial GF flour to rice flour were more instrumentally similar to the control than donuts made with an equal ratio of commercial GF flour to rice flour, regardless of hydrocolloid used.

Sensory scores of the wheat par-fried, IR-finished donuts (overall acceptance of 5.28-5.85) showed no significant differences from the control (5.83) with the exception of one lower appearance score (5.69 for the par-fried, IR-finished donut versus 6.57 for the control). All GF fully-fried donuts (overall acceptance of 4.33-4.68) and all GF par-fried, IR-finished donuts (overall acceptance of 3.81-4.44) received significantly lower sensory scores than the control (overall acceptance of 6.37 and 6.94, respectively). These results indicated that the GF donuts were not as well liked as the control.

Overall, the par-frying, IR-finishing process was shown to significantly lower the fat content of both wheat and GF donuts while producing donuts instrumentally and sensorially comparable to fully-fried donuts made with the same formulation. This process may be used instead of a full-frying process to produce donuts instrumentally and sensorially similar to fully-fried donuts, but with a significantly lower fat content.

An Alternative Frying Process for Wheat and Gluten-Free Donuts

by  
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## **Dedication**

To my family, for their constant love and support.

And to Dr. Calhoon, for figuring out why I was so sick and starting my interest in food science.

## **Biography**

Helen Shirley Melito, the eldest child of Joel and Shirley Melito, was born September 11, 1984 and grew up in southeastern Michigan. She moved to Wilmington, NC just before she entered eighth grade and lived there until she finished high school. After graduating high school, she attended Drexel University in Philadelphia to pursue a degree in chemical engineering. During the first of three six-month co-ops, Helen was diagnosed with multiple food allergies and gluten intolerance. The necessary diet changes and food substitutions for foods she had been used to eating her entire life sparked an interest in food science. She began taking food science classes as electives and became very interested in food science. Rather than change her degree program, Helen decided to complete her chemical engineering degree, with a minor in food science, and attend graduate school to continue her food science education. She was accepted as a graduate student at NC State in 2007 and began her Master's work in food science that fall. Her thesis work has focused on using infrared to finish partially-fried donuts to reduce the fat content of the donuts while keeping the instrumental and sensorial properties of the donut comparable to fully-fried donuts. Helen will graduate with an M. S. in food science in the spring of 2009. Over the summer she plans to complete a three-month internship at General Mills to gain experience in the food industry and will continue on to a Ph. D. at NC State in the fall.

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## List of Symbols

### Roman Letters:

A	area of the emitting blackbody ( $m^2$ )
$A_e$	emitter surface area ( $m^2$ )
$A_g$	surface area of the grain ( $m^2$ )
B	constant derived from steam table data
C	dry basis moisture content (kg liquid/kg solid)
$C_{eq}$	concentration of moisture at equilibrium (% moisture, dry basis)
$C_g$	moisture concentration in the grain (% , dry basis)
$C_i$	initial moisture concentration (% moisture, dry basis)
$c_p$	specific heat of the food (kJ/kg K)
$c_{pi}$	specific heat of species i (J/kg $^{\circ}$ C)
$C_s$	concentration of moisture at the surface (% moisture, dry basis)
$C_{\infty}$	moisture content of the air (kg moisture/kg air).
$C_{\beta}$	concentration of liquid water (kg/ $m^3$ )
D	mass diffusivity ( $m^2/s$ )
D	particle diameter (m)
$D_{\beta\sigma}$	diffusivity of liquid water in the solid ( $m^2/s$ )
$D_m$	moisture diffusivity ( $m^2/s$ )
$E_g$	total emission of radiation per unit surface area per unit time ( $W/m^2$ )
$E_{\lambda}$	emitter emissive power ( $W/m^2$ )
$F_{ge}$	view factors between the grain and emitter
$F_{gp}$	view factors between the grain and plate
h	heat transfer coefficient ( $W/m^2^{\circ}$ C)
$h_c$	convective heat transfer coefficient ( $W/m^2$ K)
$h_{eff1}$	empirical constant
$h_{eff2}$	empirical constant
$h_{fg}$	latent heat of vaporization (J/kg)
$h_m$	convective mass transfer coefficient (m/s)
$h_{\sigma}^I$	enthalpy of the solid phase in the crust (J/kg)
$h_{\sigma}^{II}$	enthalpy of the solid phase in the core (J/kg)
$h_{\beta}$	enthalpy of liquid (J/kg)
$H_{\gamma}$	enthalpy of vapor (J/kg)
$\Delta H_{\gamma}$	latent heat of vaporization (J/mol)
k	thermal conductivity ( $W/m^{\circ}$ C)
$k_1$	empirical constant
$k_2$	empirical constant
$k_3$	empirical constant
$k_{eff}^I$	effective thermal conductivity of the region I ( $W/m^{\circ}$ C)
$K_m$	convective mass transfer coefficient (m/s)
n	space increment subscript

$N_{ix}$	flux of species $i$ in the $x$ -direction ( $\text{kg/m}^2 \text{ s}$ )
$P$	distribution of radiation due to internal adsorption
$P_i$	pressure of species $i$ ( $\text{N/m}^2$ )
$PT$	total density of radiation at the product surface ( $\text{W/m}^2$ )
$q_r$	radiant heat flow rate ( $\text{W}$ )
$q_r$	radiative heat component ( $\text{W}$ )
$r$	radial distance from the surface of the kernel ( $\text{m}$ )
$R$	distribution of radiation due to internal adsorption
$R$	kernel radius ( $\text{m}$ )
$RT$	total density of radiation at the product surface ( $\text{W/m}^2$ )
$t$	time increment subscript
$T$	temperature ( $\text{K}$ )
$T$	emitter temperature ( $\text{K}$ )
$T$	temperature ( $^{\circ}\text{C}$ )
$T_{\text{air}}$	air temperature ( $^{\circ}\text{C}$ )
$T_e$	emitter temperature ( $\text{K}$ )
$t_f$	final time
$T_i$	initial temperature ( $\text{K}$ )
$T_p$	plate temperature ( $\text{K}$ )
$T_s$	temperature at the surface of the kernel ( $\text{K}$ )
$T_s$	temperature of the food at the surface ( $\text{K}$ )
$T_x$	% transmission
$T_0$	% transmission at the surface of the food
$T_{\infty}$	temperature of the air ( $\text{K}$ )
$\Delta t$	time increment ( $\text{s}$ )
$U$	velocity at which the interface moves ( $\text{m/s}$ )
$V$	volume of the kernel ( $\text{m}^3$ )
$x$	distance from the surface of the food ( $\text{cm}$ )
$\Delta x$	distance increment ( $\text{m}$ )

### Greek Letters:

$\alpha$	absorptivity
$\alpha$	thermal diffusivity ( $\text{m}^2/\text{s}$ )
$\beta$	liquid water
$\epsilon_e$	emissivities of the emitter
$\epsilon_g$	emissivities of the grain
$\epsilon$	emissivity of the surface
$\epsilon_i$	volume fraction of species $i$
$\epsilon_p$	emissivities of the plate
$\phi$	oil phase
$\gamma$	water vapor
$\lambda$	latent heat of vaporization ( $\text{kJ/kg}$ )

$\lambda$	wavelength in vacuum (m)
$\lambda_{\max}$	peak wavelength ( $\mu\text{m}$ )
$\rho$	reflectivity
$\rho_d$	density of the dry product ( $\text{kg}/\text{m}^3$ )
$\rho_i$	density of species $i$ ( $\text{kg}/\text{m}^3$ )
$\rho_s$	density at the surface of the food ( $\text{kg}/\text{m}^3$ )
$\sigma$	solid
$\sigma$	Stefan-Boltzmann constant ( $5.670 \times 10^{-8} \text{ W}/\text{m}^2 \text{ K}$ )
$\tau$	transmissivity
$\tau$	spectral extinction coefficient ( $\text{cm}^{-1}$ )

# **Chapter 1: Introduction**

Fried foods are enjoyed worldwide due to their palatable texture and taste (Guallar-Castillón et al., 2007). Americans in particular consume large amounts of fried food (Nawar, 1998), whether it with a meal, such as chicken nuggets, French fries, and other fast-food products, or for a snack, such as potato chips. However, fried foods tend to have a high fat and saturated fat content and are energy dense rather than nutrient dense. The rising overweight and obesity trends in America are often attributed to the increased consumption of fast foods and fried foods (Nawar, 1998). With 66% of the American population considered overweight and 50% of those who are overweight considered obese, obesity-related diseases such as cardiovascular disease, hypertension, and Type II diabetes, have become a major health concern (National Center for Health Statistics, 2006). This has caused many consumers to become more health conscious, resulting in an increased demand for foods with the same texture and taste of fried foods but with a lower calorie and fat content.

Food allergies and intolerances are an additional health concern both in America and worldwide. Gluten intolerance, or celiac disease, affects about 1% of the American population. People with gluten intolerance are sensitive to the gluten proteins found in wheat, as well as similar proteins found in rye, barley and possibly oats. Consuming these proteins causes an immunological response in the small intestine, resulting in inflammation of the intestinal lining. Over time, the inflammation leads to deterioration of the intestinal villi, causing malabsorption of nutrients (Schober et al., 2003; Presutti, 2007). This can result in many health problems, including gastrointestinal problems, weight loss, nutrient deficiencies, osteopenia, and epilepsy. It is also associated with other autoimmune diseases,

such as Type I diabetes (Hischenhuber et al., 2006; Presutti et al., 2007). Wheat allergy also indicates sensitivity to wheat proteins, although the proteins in wheat causing the allergy may not be gluten. Wheat allergy differs from gluten intolerance in the reaction mechanism, although the symptoms may be the same. When a person with wheat allergy consumes wheat, an IgE-mediated response stimulates a histamine release that causes a variety of symptoms such as nausea, GI distress, hives, and anaphylaxis (Hischenhuber et al., 2006).

The only treatment currently available for both gluten intolerance and wheat allergy is a lifelong avoidance of wheat and wheat-containing products such as commercial soups and sauces. Individuals who are gluten intolerant must also avoid products containing gluten (Hischenhuber et al., 2006). Currently, there are some gluten-free analogs to commonly consumed products, such as bread, cereals, and cookies. However, the texture and taste of these products differs from wheat products and product acceptability varies widely.

There has been considerable research done on formulating and improving gluten-free breads, but few studies have been performed on other gluten-free products, particularly fried products such as breaded foods or deep-fried doughs. The studies that are available on fried gluten-free foods have noted that gluten-free flours have significantly lower oil uptake than wheat flour due to the differences in flour proteins (Shih et al., 2001; Shih and Daigle, 2002; Shih et al., 2005; Jackson et al., 2006). It was suggested that gluten-free flours be used in battered, fried products or in fried doughs to lower fat content (Shih and Daigle, 1999; Shih et al., 2001).

There are several ways to lower fat content in deep-fried foods. One method, mentioned above, is to change or add ingredients of the food to reduce oil uptake while

frying. Ingredients that have decreased hydrophobicity, such as rice flour, have been used to produce deep-fried foods with significantly lower oil content, as have ingredients that form barriers to physically block oil from entering food during cooking, such as methylcellulose (Annapure et al., 1999; García et al., 2004). Another method to reduce fat content is to partially fry the food and finish cooking using another method, such as convective or infrared heating. Provided that the correct processing parameters are used, this method can yield products with the crisp, crunchy crust and soft interior of a fully-fried product, but with a significantly lower fat content than the fully-fried product.

To develop a method that lowers fat content in fried foods, it is important to understand how heat and mass are transferred during frying, particularly if frying is partially or completely replaced with another heating method. Frying is a common process that produces foods with a crisp, crunchy crust and a soft interior. This is largely due to the heating profile of foods during frying. After a food is placed in a deep fryer, the heat flux provided to the food rapidly increases to a peak of about  $30,000 \text{ W/m}^2$ , then decreases as cooking progresses (Farkas and Hubbard, 2000). Moisture present on the surface of the food vaporizes and evaporates, drying the surface and causing crust formation. As cooking progresses, the crust continues to dry and increase in thickness (Farkas and Hubbard, 2000). The drying creates a porous structure, allowing oil to enter the food and ultimately increasing fat content (Mellema, 2003).

Infrared heating as a replacement for deep-frying has not been extensively studied; it has mainly been used for drying or baking (Krishnamurthy, 2008). Infrared heating of particular interest because of its ability to provide a high heat flux that can easily be

controlled. This allows the heat flux profile found in frying to be duplicated. Lloyd (2003) developed a process that used infrared heating to reproduce the heat flux of frying. The process was able to produce French fries that were instrumentally and sensorially comparable to fully-fried French fries. The process consisted of five pairs of emitters placed above and below a conveyor belt. The emitters were positioned such that as the food traveled along the belt, the heat flux incident on it was comparable to the heat flux during frying. Placing the emitters on both sides of the belt allowed symmetrical heating of the food. Modeling by Yaniv (2006) showed the effects of radiant flux intensity, air temperature, spectral properties, and the convective heat transfer coefficient on the food temperature and crust thickness during infrared heating. The model showed good agreement to the experimental temperature data for the first 150 seconds of heating (Yaniv, 2006).

Because infrared heating has been successfully used to create a fried-like texture and taste in potatoes, it was desirable to investigate the use of infrared heating to cook other fried products, such as donuts. Donuts, which are traditionally deep-fried, are a popular breakfast and snack item. However, donuts are high in fat and, being made from dough containing wheat flour, contain both wheat and gluten. In addition, donuts significantly increase in volume during frying, unlike French fries. This increase in volume during heating may pose a processing challenge for a system using infrared heating, as heat flux greatly depends on the distance of the food from the emitter (Yaniv, 2006). Developing infrared processing parameters for both wheat and gluten-free donuts allows for the production of a healthier food item, the production of a gluten-free analog to a popular food item, and an increased understanding of infrared heating as a frying replacement.

The overall goal of this study was to create wheat and gluten-free donuts finish-fried by infrared radiation with a lower oil content and comparable sensory characteristics and acceptability to traditional deep-fried wheat donuts. This goal was broken down into three main objectives:

1. To determine the combination of par-frying and infrared parameters that produce the highest quality wheat donut as compared to a traditionally fried wheat donut by instrumentation and sensory analysis.
2. To quantify the effects of different hydrocolloids mixed with different gluten-free flours on the physical properties and sensory aspects of traditionally fried gluten-free donuts, as measured by instrumentation and sensory analysis, and to determine which formulation most comparable to traditionally fried wheat donuts.
3. To determine the combination of partial-frying and infrared parameters that produce the highest quality gluten-free donut when compared to both a fully-fried gluten-free donut and a traditionally fried wheat donut by instrumentation and sensory analysis.

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## **Chapter 2: Literature Review**

## **2.1. Frying**

### *2.1.1. Overview of immersion frying*

Immersion frying, or deep frying, involves immersing a food in oil that is heated to above the boiling point of water. The food is allowed to remain in the oil until a desired internal temperature is achieved (Farkas and Hubbard, 2000). Immersion frying is a very common method of food preparation and is typically used in snack food and fast-food preparation (Farkas et al., 1996). It is a process that rapidly dries foods (Silva et al., 2005), has a high throughput, and produces food with taste and textural properties that are desirable by consumers (Farkas and Hubbard, 2000). Immersion frying has also been used experimentally to dry nonfood substances, such as compressed sewage (Silva et al., 2005) and beech wood (Gernier et al., 2007). In these cases, frying was used for drying because of the high rates of heat and mass transfer. High heat and mass transfer rates during frying allow rapid drying with a relatively low energy expenditure in comparison to other drying methods. In addition, the uptake of frying oil into the sewage sludge resulted in a fuel source with a high heating value, over 20 MJ/kg (Silva et al., 2005)

Immersion frying is a complex process involving physical changes in the food, chemical reactions, and heat and mass transfer between two distinct regions separated by a moving boundary. Physical changes include increased oil content and temperature, decreased moisture content, shrinkage or swelling of the food, and crust development and growth. Chemical reactions include protein denaturation, starch gelatinization, surface pyrolyzation, and flavor development. The two regions, the crust and the core, are defined by their proximity to the surrounding oil and by their physical properties. Almost all of the oil

absorbed is in the crust, while the core provides most of the moisture, mass and nutritional content. The texture of both the crust and the crumb is important during consumption: fried products generally have a soft, moist crumb and a crisp, crunchy crust. Crust thickness increases during frying and can be considered a moving boundary with simultaneous heat and mass transfer occurring in each region (Farkas et al., 1996).

There are four stages of frying. In the first stage, initial heating, the product is immersed into oil and the surface heats to the boiling temperature of the surface water. Initial heating is a short stage, on the order of 10 seconds. Heat transfer occurs mainly at the surface as free convection with no boiling. Because there is no boiling, little water is lost from the food. The onset of boiling indicates the second stage, surface boiling. During surface boiling, there is a sudden loss of free moisture at the surface due to evaporation of vapor, causing the onset of crust formation. Surface boiling also results in an increase in the surface heat transfer coefficient. The third stage, or the falling rate stage, is the longest stage. Most of the moisture loss in the food occurs during this stage, as moisture vaporizes and travels from the core to the crust. In addition, the crust thickens, causing a decreased heat transfer due to increasing crust thickness and low thermal conductivity, and the core temperature approaches the boiling point. There is also a steady decrease in the rate of vapor mass transfer. The fourth stage, or the bubble end point, occurs when moisture loss from the food becomes negligible. This may be caused by removal of all liquid water from the sample or a reduction of heat transfer to the core (Farkas et al., 1996).

### *2.1.2. Mathematical modeling of immersion frying*

Mathematical models of cooking processes are useful tools for determining how heat and moisture are transferred through the food during cooking. They can also provide an estimation of processing parameters needed to produce a quality food product. There have been several attempts to model the frying process. Dagerskog (1979b) developed an early one-dimensional model for pan frying. Beef patties, which consisted of six thin (3.5 mm) slices of meat stacked on top of each other, were fried in a double-sided pan fryer, and a model was developed to simulate the heat and mass transfer occurring during frying. The model used finite differences to determine the temperature at various depths in the meat patty. Heat transfer in the meat patty was modeled in two separate regions: the evaporation zone (crust) and the center (core). The thicknesses of each zone were held constant. Internal mass transfer was calculated by determining the relationship between temperature and water holding capacity at each time step. The effect of mass transfer on heat transfer was also taken into account. The model was assumed to be symmetrical around the center of the patty. Volume change of the patty was ignored, material properties were held constant, material properties of the crust were based on those of the core, and only the transfer of water from the core into the crust was taken into account. However, the model showed good agreement with experimental results. Mass transfer during frying was correlated to heat penetration into the patty in both the experimental and predicted results. Frying temperatures between 140°C and 180°C had very little effect on core temperature. This was due to the increased thermal conductivity of the crust at lower frying temperatures, increasing heat transfer to the core (Dagerskog, 1979b).

Farkas et al. (1996) modeled heat and mass transfer during immersion frying as a Stefan type problem, used previously for freezing and freeze-drying. Heat and mass transfer in the crust and core were modeled as one-dimensional in an infinite slab with the crust as a moving layer. The crust and the core were considered the two main regions of the slab. The crust was assumed to consist of only solid and vapor and to have physical and thermal properties similar to that of an insulating material. Mass transfer of oil into the crust was considered to have a negligible effect on heat transfer; only the transfer of water and vapor from the core were considered. The core was assumed to consist of only solid and liquid water. Convective and advective heat transfer in the crust and core were considered, as was mass transfer of liquid water. Mass transfer of oil or other substances in the core was considered negligible. The heat and mass transfer equations follow:

$$\text{Heat transfer (crust)} \quad k_{eff}^I \frac{\partial^2 T}{\partial x^2} + N_{ix} c_{pi} \frac{\partial T}{\partial x} = \left( \epsilon_\gamma \rho_\gamma c_{p\gamma} + \epsilon_\sigma \rho_\sigma c_{p\sigma} \right) \frac{\partial T}{\partial t} \quad (2.1)$$

$$\text{Heat transfer (core)} \quad k_{eff}^{II} \frac{\partial^2 T}{\partial x^2} + N_{ix} c_{pi} \frac{\partial T}{\partial x} = \left( \epsilon_\beta \rho_\beta c_{p\beta} + \epsilon_\sigma \rho_\sigma c_{p\sigma} \right) \frac{\partial T}{\partial t} \quad (2.2)$$

$$\text{Mass transfer (crust)} \quad \frac{\partial}{\partial x} \left( \rho_\gamma \frac{\partial P_\gamma}{\partial x} \right) = 0 \quad (2.3)$$

$$\text{Mass transfer (core)} \quad D_{\beta\sigma} \frac{\partial^2 C_\beta}{\partial x^2} = \frac{\partial C_\beta}{\partial t} \quad (2.4)$$

where  $k_{eff}^I$  is the effective thermal conductivity of the region I (W/m °C),  $N_{ix}$  is the flux of species  $i$  in the  $x$ -direction (kg/m<sup>2</sup> s),  $c_{pi}$  is the specific heat of species  $i$  (J/kg °C),  $\epsilon_i$  is the volume fraction of species  $i$  (m<sub>i</sub><sup>3</sup>/m<sub>t</sub><sup>3</sup>),  $\rho_i$  is the density of species  $i$  (kg/m<sup>3</sup>),  $P_i$  is the pressure of species  $i$  (N/m<sup>2</sup>),  $\beta$  is liquid water,  $\gamma$  is water vapor,  $\sigma$  is solid,  $C_\beta$  is the concentration of

liquid water ( $\text{kg/m}^3$ ), and  $D_{\beta\sigma}$  is the diffusivity of liquid water in the solid ( $\text{m}^2/\text{s}$ ). Initial and boundary conditions were given as:

$$T = T_0 \quad \text{at } t = 0 \text{ for all } x \quad (2.5)$$

$$c = c_0 \quad \text{at } t = 0 \text{ for all } x \quad (2.6)$$

$$X(t) = 0 \quad \text{at } t = 0 \quad (2.7)$$

Core region:

$$\frac{\partial T}{\partial x} = 0 \quad \text{at } x = 0 \text{ for } t > 0 \quad (2.8)$$

$$T = T_{bp} \quad \text{at } x = X(t) \text{ for } t > 0 \quad (2.9)$$

$$\frac{\partial c_\beta}{\partial x} = 0 \quad \text{at } x = 0 \text{ for } t > 0 \quad (2.10)$$

$$c_\beta = 0 \quad \text{at } x = X(t) \text{ for } t > 0 \quad (2.11)$$

Crust region:

$$k_{eff}^I \frac{\partial T}{\partial x} = h_\phi (T_\phi - T|_{x=L}) \quad \text{at } x = L \text{ for } t > 0 \quad (2.12)$$

$$k_{eff}^I \frac{\partial T}{\partial x} + k_{eff}^{II} \frac{\partial T}{\partial x} + N_{\gamma\alpha} (h_\beta - H_\gamma) = U (\varepsilon_\gamma \rho_\gamma (H_\gamma - h_\beta) + \varepsilon_\sigma \rho_\sigma (h_\sigma^I - h_\sigma^{II})) \quad \text{at } x = X(t) \text{ for } t > 0 \quad (2.13)$$

$$P_\gamma = P_{\gamma 0} \quad \text{at } x = L \text{ for } t > 0 \quad (2.14)$$

$$P = \exp\left(\frac{-\Delta\hat{H}_\gamma}{RT} + B\right) \quad \text{at } x = X(t) \text{ for } t > 0 \quad (2.15)$$

where  $H_\gamma$  and  $h_\beta$  are the enthalpy of the vapor and liquid, respectively (J/kg),  $\phi$  is oil,  $U$  is the velocity at which the interface moves (m/s),  $h_\sigma^I$  and  $h_\sigma^{II}$  are the enthalpies of the solid phase in the crust and core, respectively (J/kg),  $\Delta H_\gamma$  is the latent heat of vaporization (J/mol), and  $B$  is a constant derived from steam table data. The food was assumed to initially consist of only the core, with the crust developing in the second stage of frying. The model showed good agreement with experimental data and was found to accurately predict moisture profiles, temperature profiles, and crust thickness (Farkas et al., 1996). The model also revealed valuable information about heat and mass transfer during the frying process. The heat and mass transfer in the immersion frying process were similar to freeze-drying and high temperature air-drying (Farkas et al., 1995). Heat transfer in the core occurred mainly through conduction and mass transfer. Mass transfer of water to the crust/core interface was carried out by two different modes. The first mode was the movement of the interface into the core region. When heat transfer increased, movement of the crust into the core region also increased, causing increased water vapor production at the interface. The second mode was the movement of water from the core to the interface via diffusion. Each mode dominated during different phases of frying (Farkas et al., 1996).

The model used by Farkas et al. (1996) had many assumptions, some of which were addressed by other researchers. The model was specific to only a slab and was not valid for composite foods such as chicken nuggets. In addition, it did not take into account gases, such as water vapor or air, present in the core of the food and did not account for shrinkage or other physical changes of the food. Baik and Mittal (2005) developed a heat and mass transfer model for deep-fried tofu that took shrinkage into account. The model had good

agreement with the experimental temperature, thickness, and moisture content. Shrinkage was found to be dependent on moisture content but not temperature. Kassama and Ngadi (2005) studied moisture transfer and pore development in deep-fried chicken meat at several oil temperatures. Models were developed for both porosity and oil uptake. Porosity was found to increase with increasing oil temperature and frying time and had a linear relationship with moisture loss. Oil content was hypothesized to have an exponential relationship with moisture loss. Tangduangdee et al. (2003) developed a model to predict heat and mass transfer during frying in frozen composite foods. Chicken breast meat coated with batter was used both as a model composite food and for validation of predicted center temperature. The model showed good agreement with experimental results when a 0.3 mm vapor space was added between different material layers. Center temperature depended on the batter thickness and vapor layer thickness and did not significantly depend on oil temperature. Farid (2001) developed a quasi-steady-state model for heat and mass transfer in frying and drying processes. The model had reasonable agreement with many foods, such as freeze-dried meat, thin and thick fried potato chips, and air-dried potato chips. The model was also reported to predict the rate and extent of frying and drying in foods.

### *2.1.3. Fried foods and obesity*

Fried foods are a part of the typical diet for all ages, cultures, and societies. In American, fried food is a multibillion dollar industry and continues to grow (Innawong et al., 2006; MacMillian et al., 2008). Typical fried foods include items such as chicken nuggets, French fries, and other fast-food products, snack products such as potato and tortilla chips,

and fried pastries such as donuts. Fried foods are widely accepted and enjoyed due to their relatively low cost (Nawar, 1998) and enjoyable texture and taste (Guallar-Castillón et al., 2007).

Americans consume more fried food per person compared to people from other countries (Nawar, 1998). They also tend to dine out more often, especially at fast-food restaurants (Nawar, 1998; Taveras et al., 2005), and with increasing frequency (Nicklas et al., 2001; Taveras et al., 2005). Unfortunately, the typical American diet, which is high in fat and saturated fat, has been linked to problems such as heart disease, obesity, and certain types of cancer (Kennedy et al., 1999). The consumption of high-fat foods, especially fried foods, has been directly correlated to overweight and obesity in both children (Taveras et al., 2005) and adults (Guallar-Castillón et al., 2007). Fats have a higher energy density than other macronutrients; a diet including a large amount of high-fat foods generally leads to a higher overall energy consumption than a diet lower in high-fat foods (Kennedy et al., 1999).

The World Health Organization (WHO) has defined overweight as a body mass index (BMI) of  $\geq 25$  and obese as a BMI of  $\geq 30$  (World Health Organization, 1995). Based on these definitions, 67% of Americans are overweight and 50% of those who are overweight are obese (National Center for Health Statistics, 2006). Obesity-related diseases are a major cause of death in the US and obesity significantly increases the risk of Type II diabetes, hypertension, cardiovascular disease, dyslipidemia, and other chronic diseases (Nicklas et al., 2001). In addition, the prevalence of obesity also causes major economic impact. The total cost of health care and lost productivity due to overweight and obesity in the US was estimated to be \$117 billion in 1995 (Wolf and Colditz, 1998). The cost from health care

alone was estimated at \$61 billion in 1995 and almost \$93 billion in 2002 (Finklestein et al., 2003). However, despite the cost and prevalence of obesity, Americans are reluctant to give up fried and other high-fat foods, most likely due to the highly acceptable taste and texture provided by the fat and frying process.

#### *2.1.4. Donut immersion frying and fat reduction*

Donuts are a very popular fried food. In 2007, sales of all types of donuts in the US were about \$659 million. Krispy Kreme<sup>®</sup> and Entenmann's<sup>®</sup> were the most popular brands, earning \$140 million and \$91 million in sales, respectively (Top 5 Brands of Donuts, 2007). Donuts are typically eaten with breakfast or as a snack. Though there are a wide variety of donut shapes, icings, fillings, and flavors available, there are two main types of donuts: cake donuts and yeast donuts. Yeast donuts are made from a sweet yeast dough and are leavened only by yeast. After mixing, the dough is rolled out and allowed to rise to 3/4 proof before frying. Jelly donuts and other filled donuts are typically made from yeast dough, as the finished donuts have a firm yet elastic, bread-like structure and can be filled without crumbling (Sultan, 1969). Cake donuts are prepared from a soft, batter-like mixture that is dropped by a machine directly into hot oil or fat. They are usually leavened only by baking powder. However, baking soda is sometimes added to cake donuts made with whole-wheat flour in addition to baking powder to improve the finished volume, as whole wheat flour tends to yield baked products a lower finished volume. Because more sugar is added to the cake donut batter, cake donuts are generally sweeter than yeast donuts and, as their name implies, have a soft, cake-like crumb. Crullers are typically made from a more viscous cake

dough (Sultan, 1969). A combination donut leavened by both yeast and baking powder can also be made; these donuts are called World's Fair donuts. The dough is half-proofed before being fried and produces a finer structure than yeast donuts. This type of dough is usually used in variety donuts (Sultan, 1969).

Because they are immersion fried, donuts tend to be high in fat. Krispy Kreme<sup>®</sup> glazed donuts have about 12 g of fat per serving (52 g) (Krispy Kreme, 2007) and Entenmann's<sup>®</sup> glazed donuts have about 15 g of fat per serving (64 g) (Calorie-count, 2007). Fifty percent of the total calories per serving in either brand of donut come from fat (Krispy Kreme, 2007; Calorie-count, 2007). Most of the fat content in donuts is from oil absorbed during frying. Due to the rising number of people considered overweight or obese, a significant amount of research has been done on ways to reduce fat content of and fat absorption in fried foods, including donuts. Research on fat reduction in donuts has generally focused on donut composition, although some work has been done on external factors such as oil temperature, atmospheric pressure, and batter temperature. It is important to note that changing any of these factors affects more than the oil content, so the effects on all donut properties affected by the modification of donut composition or cooking parameters will be discussed.

To be able to reduce the amount of oil uptake in fried foods, it is necessary to understand the mechanism for oil uptake during immersion frying. As a food is fried, the surface begins to dry due to evaporation of moisture. This surface drying causes a porous crust to form (Farkas et al., 1996; Mellema, 2003). As the drying continues during the frying process, the crust thickens (Farkas et al., 1996; Mellema, 2003) and the pores in the crust

become larger, especially at high rates of drying (Mellema, 2003). Oil migration into the food occurs when the pressure from water vapor migrating from the core to the crust is not sufficient to prevent oil from entering, either due to low moisture content in the core or an inability of moisture to migrate from the core to the crust (Mellema, 2003). It has been found that most of the oil uptake occurs after frying. As the food cools, evaporation of vapor from the food ceases, the pressure in the pores in the crust decreases, and oil on the surface of the food moves into the pores via suction (Moriera et al., 1997; Vitrac et al., 2002; Baik and Mittal, 2005; van Vliet et al., 2007). Interestingly, the majority of oil absorbed during and after frying is located in the crust of the food (Farkas et al., 1996; Normén et al., 1998; Mellema, 2003).

The type of oil used in frying (Wheeler and Stingley, 1963; Rimac-Brcic et al., 2004) and the batter temperature do not appear to affect oil absorption (Wheeler and Stingley, 1963). In yeast donuts, oil absorption tends to decrease with increasing oil temperature but increases with increasing cook time (Vélez-Ruiz and Sosa-Morales, 2003). However, the oil content of the donuts was shown to decrease after a certain frying time. The frying time at which the oil content began to decrease was temperature dependent and the decrease in oil content was lower with increased oil temperature. Vélez-Ruiz and Sosa-Morales (2003) attributed these effects to a desorption phenomenon, hypothesizing that the oil desorption was due to structural changes in the donuts. Yeast donut crumb was found to become more compact after prolonged cooking; the denser crumb could have prevented absorption of more oil (Vélez-Ruiz and Sosa-Morales, 2003).

Both frying time (Pinthus et al., 1992; Khalil, 1999; Krokida et al., 2000; Garica et al., 2002) and oil temperature (Pinthus et al., 1992; Khalil, 1999; García et al., 2002) have been found to affect oil content. Increased frying time generally increases the oil content of fried foods (Moreira et al., 1995; Vélez-Ruiz and Sosa-Morales, 2003; Kassama and Ngadi, 2005; Tan and Mittal, 2006) due to the formation and increase in size of pores in the crust, which allows increased oil uptake (Kassama and Ngadi, 2005). Oil content has been found to decrease with increasing oil temperature in many fried foods, including rusk rolls (van Vliet et al., 2007), yeast donuts (Vélez-Ruiz and Sosa-Morales, 2003), and cake donuts (Tan and Mittal, 2006). Vélez-Ruiz and Sosa-Morales (2003) hypothesized that at a certain, temperature-dependent, time in the frying process, the structure of the food changed and did not allow additional oil absorption. This time was shorter for higher frying temperatures; the less time a food has to absorb oil, the lower the final fat content.

Oil temperature, cooking time, and atmospheric pressure have been found to affect more than oil content. Vélez-Ruiz and Sosa-Morales (2003), and Tan and Mittal (2006), using oil temperature ranges of 180°C to 200°C and 165°C to 180°C, respectively, found that increased oil temperature resulted in decreased volume, increased density, increased firmness, increased crust darkening, and increased thermal diffusivity in both cake and yeast donuts. Tan and Mittal (2006) also studied the effects of vacuum frying (up to 9 kPa of vacuum) on cake donut properties and found that volume increased, firmness decreased, and density decreased with increasing vacuum. Fat content was found to be significantly affected by both frying temperature and amount of vacuum. Lower frying temperatures and higher vacuum levels resulted in an increased fat content. Some properties of finished donuts have

been shown to be a function of cooking time. Volume, chewiness, cohesiveness, gumminess, springiness, force to break crust, and force to compress crumb increase, and density were shown to decrease as frying time increased (Tan and Mittal, 2006). However, Vélez-Ruiz and Sosa-Morales (2003) found that yeast donut volume reached a maximum, then decreased after a certain cooking time. The frying time at which the maximum volume was reached was temperature dependent and decreased with increased temperature. Vélez-Ruiz and Sosa-Morales (2003) also found the heat capacity and thermal conductivity of donuts to be independent of oil temperature over the range studied. The necessary frying time, or the time needed for the donut center to reach 99°C, and donut crust color change appeared to be independent of level of vacuum; moisture content appeared to be independent of both level of vacuum and frying temperature (Tan and Mittal, 2006).

The effect of moisture content on oil absorption has been studied by several researchers. Initial moisture content has been shown to significantly affect the final fat content. Cake donuts with high initial moisture content were shown to have lower oil uptake, lower crust and crumb hardness, higher final moisture content, lower final fat content, and a smaller volume increase than cake donuts with low initial moisture content. Donuts with low initial moisture content tended to have cracks in the surface of the dough, enabling oil to flow easily into the donut while frying and increasing oil uptake (Tan and Mittal, 2006). Dough consistency, which largely depends on moisture content, is closely related to oil uptake. Too soft a dough results in high oil uptake; a firmer dough results in lower oil uptake (Shih et al., 2001). Moisture content also affects crust darkening: donuts with higher moisture content have less crust darkening. Crust darkening is a result of temperature rise and water loss in

the crust. The majority of crust darkening is from Maillard browning reactions, which start when the surface of the donut reaches approximately 140°C. High initial moisture content has been shown to reduce the extent of the Maillard reaction, resulting in a lighter crust (Olsson et al., 2005). Initial moisture content affects many aspects of the finished donut, so it is necessary to find a balance between producing a very low-oil donut and producing a donut with acceptable texture and appearance.

The amount of leavening agent and lecithin has been shown to affect oil absorption in donuts. Donuts made with tartrate baking powder absorbed more oil than those made with sulfate-phosphate baking powder: 17-23% versus 14-19%, respectively (McComber and Miller, 1976). Adding lecithin to the donut formulation also resulted in increased oil uptake. Donuts with added lecithin had a fat content of 19-23%; donuts without added lecithin had a fat content of 14-17%. Lecithin lowers surface tension, allowing a relatively stable fat foam layer to form on the surface of the donuts and resulting in increased oil uptake (McComber and Miller, 1976).

Different proteins can affect donut properties in many ways. Egg white, soy protein isolate, skim milk powder, and whey powder decreased oil absorption from 15% to 11-12% in cake donuts when used in place of whole egg. It was hypothesized that the denaturation of these proteins caused the reduction in oil uptake (Mohamed et al., 1995). Replacing whole egg partially or completely with other proteins resulted in an average 65% decrease in final volume and a 50-300% increase in firmness. Moisture content and crust color were also affected by the protein used; the effects depended on the water-binding ability and amount of Maillard reactants present, respectively. Mohamed et al. (1995) concluded that the proteins

that gave the best overall sensorial and instrumental properties were skim milk powder, egg white, and egg yolk.

The effects of different flours on cake donut properties have also been studied. Replacing a small fraction (3%) of the wheat flour used in donuts with different varieties of soy flour resulted in a 22-52% decrease in oil uptake (Martin and Davis, 1986). Shih et al. (2001) studied the effects of modified and unmodified rice flours mixed with wheat flour on various donut properties and compared the results to those of donuts made with only wheat flour. Oil uptake decreased by up to 64%, depending on the rice flour type used and the level of wheat flour replacement. Final moisture content also depended on flour type, although all donuts had a final moisture content of 18-21%. Replacing wheat flour with unmodified rice flour reduced the dough viscosity; replacing wheat flour with modified rice flour increased dough viscosity. This was attributed to the fact that unmodified rice flours generally have a lower water-holding capacity than wheat flour, while modified rice flours have a higher water holding capacity. Up to 50% replacement of wheat flour with unmodified rice flour or 25% replacement of wheat flour with modified rice flour did not significantly affect donut firmness, although 50% replacement with modified rice flour significantly increased hardness. Sensory results showed that texture and taste at up to 20% replacement with modified flour were comparable to wheat donuts, but taste and texture were negatively affected at  $\geq 40\%$  replacement because of the extreme softness of the donuts (Shih et al., 2001).

Many studies have examined the effects of different hydrocolloid coatings on oil absorption in various fried foods, mainly fried potatoes. Hydrocolloids possess film-forming,

thermal gelling, and hydrophilic properties. Coatings containing hydrocolloids can reduce oil absorption during deep-frying by creating a physical barrier between the oil and the food, preventing moisture from escaping and oil from entering the food (Annapure et al., 1999). Pinthus et al. (1992) reported that an alginate coating on deep-fried restructured potato products reduced oil uptake by over 15%. Gum tragacanth, gum arabic, and xanthan gum coatings have been shown to reduce oil uptake in deep-fried potatoes by 6%, 19%, and 8%, respectively (Annapure et al., 1999). Cellulose derivatives have also been shown to lower oil content of deep-fried foods. A carboxymethylcellulose (CMC) coating was used to reduce the oil uptake of deep-fried potato strips and chickpea dough by 36-54% (Rumac-Brncic et al., 2004) and 13% (Annapure et al., 1999), respectively. Khalil (1999) combined CMC with pectin and calcium chloride to make a coating for deep-fried potato strips that reduced oil uptake by 54%, although a coating of only pectin and calcium chloride lowered the oil uptake by 40%. Annapure et al. (1999) used a hydroxypropylmethylcellulose (HPMC) coating to reduce the oil uptake in deep-fried chickpea dough by 13%. Methylcellulose (MC) coatings have also been successful in reducing oil uptake 35-40% for fried potato strips (García et al., 2004). Although most studies have been performed on potato products, it is hypothesized that similar coatings would be effective in lowering the oil uptake in deep-fried donuts.

## **2.2. Gluten-free foods and gluten sensitivity**

### *2.2.1. Gluten sensitivity*

Celiac disease, or sensitivity to wheat and other cereals containing gluten, affects as many as 1 in 100 people worldwide (Ciacci et al., 2007). Gluten is the protein component of

wheat flour and has two main fractions, gliadin and glutenin (Hayta and Schofield, 2005). Individuals with celiac disease are sensitive to the gliadin fraction, as well as secalins, hordeins, and possibly avidins. Secalins, hordeins, and avidins are proteins that are part of gluten-like compounds found in rye, barley, and oats, respectively (Schober et al., 2003). This sensitivity is due to incomplete digestion of gluten in the intestinal tract, which produces peptides that cause an immunogenic response from CD4+ T lymphocytes (T-cells) in the small intestine (Hischenhuber et al., 2006). When the peptides are attacked by the antigen-presenting cells, the result is inflammation of the mucosa in the small intestine (Presutti et al., 2007). If the immune reaction is ongoing, the villi lining the intestinal tract deteriorate, causing the intestinal lining to become smooth (Ciacci et al., 2007). Degradation of the intestinal tract can cause symptoms such as weight loss, nausea, diarrhea, vomiting, headaches, and nutritional deficiencies due to malabsorption of nutrients. If the disease is not treated, other organ systems, such as the liver, skin, nervous system, bones, and endocrine system can also become affected. However, because the intestinal tract can compensate for the damage if it is relatively limited, most cases of celiac disease are either silent (no overt symptoms) or latent (potential to develop disease) (Presutti et al., 2007).

Wheat allergy is another form of sensitivity to gluten. It is an IgE-mediated reaction to the ingestion of wheat proteins, specifically the gluten and gliadin fractions (Hischenhuber et al., 2006; Kozai et al., 2006). Wheat allergy has similar symptoms to celiac disease, such as gastrointestinal distress, headaches, urticaria, and dermatitis, but can also cause symptoms that can be immediately life-threatening depending on their severity, such as anaphylaxis and asthma. These symptoms can be either immediate or delayed, occurring any time between

directly after ingestion to 1-2 days after ingestion. Immediate responses tend to be more severe than delayed responses, as bronchial obstruction and anaphylaxis is much more likely to occur. Responses that are delayed for 1-2 days are thought to be T-cell mediated, rather than IgE mediated (Hischenhuber et al., 2006). Because of the possible severity of some symptoms, manufacturers in the US are required to label foods containing wheat (Food and Drug Administration, 2004). Wheat allergy is common in infants and children, but is less so in adults (Scibilia et al., 2006).

Celiac disease and wheat allergy can only be treated by adherence to a gluten-free (GF) diet, which allows the intestinal tract to repair itself while preventing further damage to the villi (Hischenhuber et al., 2006). The amount of gluten needed for patients to relapse has been reported to be as low as 0.1 g/ kg body weight per day (Laurin et al., 2002), so strict adherence to the diet is extremely important. GF foods are defined as having a gluten content not exceeding 200 ppm (Shih et al., 2006). Adapting and adhering to a GF diet is often challenging for celiac patients, as many foods either have gluten-containing cereals as a primary ingredient (baked goods, pastas, breakfast cereals, and snack foods) or include gluten-containing cereals as a thickener or filler (soups, many canned foods, gravies, and puddings). Finding foods that are gluten-free can be challenging and requires careful reading of ingredient labels (Presutti et al., 2007).

Over the past decade, manufacturers have become aware of the demand for GF products and have developed GF breads, baked goods, baking mixes, and pastas, among other GF products. Unfortunately, these products tend to be much more expensive than their gluten-containing counterparts, do not have the same texture, taste, shelf life, or overall

quality that their gluten-containing counterparts do, and can be extremely hard to find. For example, a loaf of wheat bread usually costs between \$0.99 and \$2.99, while a loaf of GF bread, such as rice bread, costs as much as \$6 to \$7 (Carrie, 2008). GF bread is typically much more compact and dense than the wheat bread, does not fold or bend well, and stales and molds very rapidly. The lack of gluten in GF bread is responsible for most of these problems. Storing the rice bread, as well as other GF products, in the freezer can prolong shelf life and quality (Cauvain and Young, 2007); many GF products are sold frozen for this reason. However, quality degrades even in the freezer.

The quality and variety of GF foods has noticeably improved over the past decade. Many GF foods now have textures and tastes that are very similar to their gluten-containing counterparts. This is probably due to a better understanding of both the functions of gluten in foods and how to replace gluten-containing ingredients with alternative ingredients without changing texture or taste.

### *2.2.2. Gluten and structure*

After the water-soluble material is removed from wheat flour, the resulting mass is about 75-85% protein, 5-10% lipids, and the remainder insoluble starch and carbohydrates (Wieser, 2006). As previously mentioned, gluten is the main protein component of wheat flour (Hayta and Schofield, 2005). With a molecular weight that varies from 30,000 to over 10 million daltons, gluten is one of the largest proteins in nature. Gluten contains many different amino acid mono-, oligo-, and polymers, but the two main fractions of gluten are gliadin and glutenin (Wieser, 2006). When flour is mixed with water, these two fractions

combine to create gluten (Bennion and Scheule, 2004). This process will be discussed in more detail later.

Gliadins increase dough viscosity and extensibility (Chiang et al., 2006). They are mostly present in wheat flour as monomers. There are four main types of gliadins:  $\alpha/\beta$ ;  $\gamma$ ;  $\omega 1,2$ ; and  $\omega 5$ .  $\alpha/\beta$ - and  $\gamma$ -gliadins are present in much larger proportions than  $\omega$ -gliadins. Structural differences among these four types of gliadins are small. However,  $\omega 1,2$ - and  $\omega 5$ -gliadins have more glutamine, proline, and phenylalanine and very little cysteine compared to  $\alpha/\beta$  and  $\gamma$  gliadins.  $\omega 5$ -gliadins also have a higher molecular weight.  $\alpha/\beta$ - and  $\gamma$ -gliadins have similar molecular weights and significantly less glutamine and proline than  $\omega$ -gliadins.  $\alpha/\beta$ -gliadins have longer repeating units on the carbon-terminal domain than  $\gamma$ -gliadins.  $\gamma$ -gliadins have more spaces for cross-linking, which is important for gluten formation and strength. Most gliadins have even numbers of cysteines. Gliadins with an odd number of cysteines act as terminators during glutenin polymerization in the formation of gluten. Because they are very elastic proteins, adding gliadins can improve dough extensibility.

Glutenins are elastic and cohesive, and contribute to dough strength and elasticity (Chiang et al., 2006). They are divided into three types: long high molecular weight ( $x$ -HMW), shorter high molecular weight ( $y$ -HMW), and low molecular weight (LMW). The exact molecular weight of glutenins generally depends on their disulfide structure. LMW glutenin subunits are similar to  $\alpha/\beta$ - and  $\gamma$ -gliadins in amino acid composition and molecular weight. Each wheat variety has about three to five types of HMW glutenin subunits, which

can be grouped into x or y. x- and y-HMW glutenin subunits differ in the nitrogen- and carbon-terminal domain, mainly in the number of cysteines and cross-links (Wieser, 2006).

When wheat flour is mixed with water, glutenins and gliadins begin to polymerize by connecting two cysteines with an interchain disulfide bond to form gluten (Wieser, 2006). Glutenins polymerize end-to-end, most likely head-to-tail, (Wieser, 2006), to form sheets of gluten as the dough is developed (Bache and Donald, 1998). The interchain disulfide bonds form cross-links between gluten strands, forming a gluten network that extends throughout the dough (Tilley et al., 2001). The strength of this network depends on the number of disulfide cross-links present. Increased cross-linking increases dough strength (Hayta and Schofield, 2005).

Several other factors are also important for the formation of gluten and gluten structure. The presence of oxygen or oxidizing agents is necessary for the formation of large gluten polymers (Wieser, 2006). Oxygen is generally present in the dough due to the mixing process; however, oxidizing agents, such as ascorbic acid and potassium bromate, can also be added to improve dough quality (Hayta and Schofield, 2005). Tyrosine is also important to gluten formation, as it forms interchain cross-links between gluten strands by covalent intermolecular bonding (Tilley et al., 2001). The amount of cysteine present can affect gluten structure as well: too much free cysteine can cleave disulfide bonds and inhibit tyrosine bond formation (Wieser, 2006). Non-covalent bonds, such as hydrogen, hydrophobic, and ionic bonds, are important to gluten structure during baking or other heating processes. Because the bond energies increase with temperature, these bonds help stabilize the gluten network during heating (Hayta and Schofield, 2005; Wieser, 2006).

### 2.2.3. *The role of gluten in frying*

Gluten has been shown to be an important contributor to the viscoelastic characteristics and volume of baked goods made from wheat dough (Bennion and Scheule, 2004). It also plays a significant role in bread crust formation. While bread crumb is a matrix made of a continuous phase of gelatinized starch and a continuous gluten network, bread crust is a continuous gluten network enclosing ungelatinized starch granules of varying sizes (Primo-Martín et al., 2006). The gluten network formed in the crust holds water, which softens the crust. Primo-Martín et al. (2006) found that crusts on breads made without gluten or with a protease that breaks down gluten were significantly harder than crusts on breads made with gluten intact. This difference in crust hardness was apparent as soon as two hours after baking (Primo-Martín et al., 2006).

Gluten is also important during the frying process. Chen et al. (1998) and Chiang et al. (2006) have studied several properties of gluten during frying using gluten balls. The gluten balls were prepared by mixing wheat flour and water to form a dough, then washing the dough under running water to remove the starch and other soluble components. Chen et al. (1998) fried the gluten balls in three stages using three fryers at different temperatures. The gluten balls underwent a significant volume increase in the first fryer as the water in the ball vaporized and moved to the surface. The second and third fryers fixed the color and rheological properties of the gluten balls (hardness, brittleness, etc.). There was little volume change in the second or third fryer. Chen et al. (1998) hypothesized that this was due to most of the moisture, which causes the gluten ball to expand as it vaporizes and travels to the surface of the ball, evaporating off in the first fryer. However, the moisture content of the

gluten balls was not measured so this hypothesis is unsupported. The lack of volume change in the second or third fryer may be due to crust formation preventing further expansion rather than a lack of moisture to evaporate and increase volume. Still, this study indicated that gluten plays a role in the volume increase, color, and rheological properties in fried doughs and batters.

Chiang et al. (2006) also examined the color and rheological properties of gluten balls. Gluten balls were made from flours with protein content between 7-14% and fried in the same manner as Chen et al. (1998). Increased gluten content improved the strength, elasticity, and water-holding ability of the dough: gluten balls made from wheat with a high protein content tended to absorb more water, expanded more when fried, and were not very brittle after frying. Gluten balls made with flours containing large amounts of HMW-glutenins,  $\omega$ -gliadins, and albumins/globulins had higher sensory scores. They were also a brighter yellow (resulting in higher consumer acceptance) than gluten balls made from other types of flour, indicating that gluten plays a role in color development during frying.

The effects of gluten on the properties of fried patties made from potato starch and wheat gluten under storage conditions (up to 4.5 hours at 4°C) were studied by Normén et al. (1998). No correlation was found between gluten and moisture migration from the core into the crust during storage but oil uptake and volume of the samples increased significantly with added gluten. The increased oil uptake in the patties made with gluten added was attributed to the higher amount of dry matter compared to the patties made without gluten (Normén et al., 1998). The network in the gluten-containing patties was softer and more heterogeneous, allowing moisture to escape during frying. Escaping moisture caused a porous structure; oil

could enter more easily through the pores (Normén et al., 1998). During storage, the force to puncture the crust decreased in all patties, although the gluten-containing patties were crisper than the pure potato starch patties. Gluten reduced moisture migration from the crumb to the crust, which kept the crust crisp, although it did not completely stop the crust from softening (Normén et al., 1998). Elasticity of all samples with added gluten increased with storage time. Increase in hardness over storage time was reduced with the addition of gluten. Normén et al. (1998) hypothesized that added gluten reduced the amount of starch gelatinization in the patties by increasing the dry mass content. When starch gelatinization occurs, amylose is leached from starch granules. The amylose associates and forms a network upon cooling, stiffening the gluten network. Less available water causes less starch gelatinization and a smaller amount of amylose released, resulting in a weaker network and decreased stiffening upon cooling (Normén et al., 1998).

#### *2.2.4. Gluten replacement*

The presence of gluten in foods has a large impact on the rheological, sensorial, and functional properties of the food. There is no one substance that can replace gluten entirely, although many studies have shown that a combination of several ingredients can replicate some of the effects of gluten on foods. Various GF flours, also called hypoallergenic flours, have been combined with hydrocolloids to produce a variety of baked goods and fried foods, some with rheological and sensorial properties similar to their gluten-containing counterparts.

Rice is a common flour used in GF products because it is hypoallergenic (Shih and Daigle, 2002). Knowing the protein and starch composition of rice flour is important in understanding how it behaves when cooked or fried. Rice flour has very low amount of protein compared to wheat flour. Most of the proteins in rice are hydrophobic and do not have the plastic and elastic properties of the hydrophilic gluten proteins in wheat; hydrophobic proteins do not swell in water at neutral pH (Kadan et al., 2001). Rice flours with low amylose content have been shown to give better crumb properties than rice flours with a higher amylose content (Kadan et al., 2001; Nishita et al., 1976). Because rice flour does not have gluten, products made with rice flour have very different textural and sensorial properties than similar products made with wheat flour. However, rice flour has been successfully used to make baked goods (Gallagher et al., 2003; Shih and Daigle, 2002; Kadan et al., 2001) and fried products (Shih et al., 2005; Shih and Daigle, 1999; Jackson et al., 2006). Rice fries (rice batter extruded in a French-fry shape) and rice batters have been developed in attempt to replace wheat products and reduce fat in fried products (Shih and Daigle, 2002).

Flours made from starchy tubers or GF grains are also used in GF baking (Cato et al., 2004). Such flours include soy (Moore et al., 2006), sorghum (Kulamarva et al., 2004), potato, corn, millet (Schober et al., 2003), and sweet potato (Shih et al., 2006). All of these flours have different baking properties and are usually blended to improve sensorial, nutritional, and rheological properties of GF baked goods (Schober et al., 2003; Sciarini, 2008). Nutritional content in particular is a concern, as GF products tend to be significantly lower in B vitamins, iron, protein and fiber than their wheat counterparts. (Gallagher et al.,

2004; Thompson, 2000; Marco and Rosell, 2008a). The difference is partly due to the difference in composition of wheat and GF flours and the fact that many products made with wheat flour are enriched or fortified. Because cereal products compose a large part of the general population's diet, there is a concern that people who consume primarily GF cereal grains are vulnerable to nutritional deficiencies (Gallagher et al., 2004; Thompson, 2000). To correct this problem, GF flours with different nutritional properties may be blended to approximate the nutritional properties of wheat (Pruska-Kedzior et al., 2008).

Polymeric substances, such as hydrocolloids, are needed to make GF bread (Moore et al., 2006). Hydrocolloids can be derived from fruits, seeds, seaweeds, plants, and microorganisms (Gallagher et al., 2004). They affect the rheological properties of the bread by mimicking the viscoelastic properties of gluten and affecting the pasting, swelling, gelatinization, and staling of starch. The hydrophilic groups in the hydrocolloids control swelling and gelatinization of starch granules, resulting in reduced hydration of the amorphous regions. This limits plasticization and restricts water, resulting in higher pasting and gelatinization temperatures. Hydrocolloids also affect the viscosity of the hot starch paste (Kobyłański et al., 2004) and can improve the shelf life of GF products, especially when combined with emulsifiers and added proteins (Pruska-Kedzior et al., 2008).

Several different hydrocolloids have been used in GF products. Cellulose derivatives, especially hydroxypropylmethylcellulose (HPMC), can increase water absorption, improve sensory characteristics, and soften doughs (Kobyłański et al., 2004). HPMC also increases viscosity without interacting with food components (Kadan et al., 2001). Xanthan gum, guar gum, locust bean gum (LBG), gelatin, pectin, HPMC, carboxymethylcellulose (CMC),

carrageenan, and agar have been used to increase the volume and improve the texture of GF bread (Gallagher, 2004; Pruska-Kedzior et al., 2008). Out of these hydrocolloids, xanthan gum and HPMC have been shown to give the largest volume increase in rice bread. LBG and guar gum have been shown to improve crumb structure, increase volume and retard staling in GF bread (Gallagher, 2004). Modified rice starches have also been successfully used to make GF products such as frying batters (Mohamed et al., 1998; Shih and Daigle, 1999). Pregelatinized rice flours have been found to increase dough viscosity, adhesiveness, and moisture content, and decrease oil absorption during frying (Shih and Daigle, 2002). Pruska-Kedzior et al. (2008) used highly methylated apple pectin as a structuring agent in GF bread. All of these experiments used different formulations for making GF products. It appears that the recipe used to make the GF product as well as the hydrocolloid(s) used impacts the rheological and sensorial properties of the product.

#### *2.2.5. Gluten-free baking*

Current GF products attempt to mimic their gluten-containing counterparts in appearance, texture, and taste. GF bread in particular has been studied, as bread is a major part of the diet in many countries (Kadan et al., 2001; Moore et al., 2006; Cato et al., 2004). A few of the major challenges in creating a formula for acceptable gluten free bread are taste, texture, and appearance. GF breads often have a low volume, dry and crumbly texture, and poor taste (Gallagher et al., 2003). A considerable amount of effort has been put into developing formulas and methods of making acceptable GF bread, as well as understanding how dough rheology changes through the addition of heat and various ingredients.

Many different GF flours and combinations GF flours have been studied to determine which flour(s) yield a product that is closest in taste and texture to its gluten-containing analog. Most studies have found that products made with several GF flours have better taste and texture properties than products made using only one GF flour. Kulamarva et al. (2004) studied rheological properties of sorghum flour blended with either 25% (flour weight) wheat flour or 25% soy flour. Doughs made with blended flours had better viscoelastic properties than pure sorghum flour doughs, with the sorghum/wheat blend having properties closer to that of pure wheat dough than the sorghum/soy blend. Another flour combination used in the preparation of GF pancakes is a combination of rice flour and sweet potato flour. Increasing the ratio of sweet potato flour to rice flour increased batter viscosity and pancake cohesiveness, and decreased pancake hardness. The sweet potato/rice batter and pancake properties were most similar to wheat batter and pancakes when the ratio of sweet potato flour to rice flour was 20:80% to 40:60% (Shih et al., 2006). Schober et al. (2003) examined cookies made from four different GF flour mixes: a commercial GF flour and three different GF flour combinations made from different amounts of rice flour, soy flour, buckwheat flour, corn starch, potato starch, and millet flakes. Textural properties of the doughs and cookies were found to be dependent on the water-holding properties and the starch and protein content of the flours. In general, firm, nonsticky doughs, such as those produced using rice flour, corn starch, potato starch, and soy flour, resulted in firm, thin, round cookies. Soft, sticky doughs, such as those produced using commercial GF flour, resulted in soft thick, oval cookies. Schober et al. (2003) hypothesized that flours with high starch and low protein contents produced doughs with increased stickiness and weaker structural stability. Because

the amount of leavening agent in the formulations was kept constant, the final volume of the cookies was attributed to dough strength: cookies made with softer doughs were observed to have greater final volume than cookies made with firmer doughs as long as there was no structural collapse in the cookies made with softer doughs (Schober et al., 2003). It is possible that the softer doughs allowed gas to move more easily through the dough than the firmer doughs, resulting in greater expansion during baking.

GF breads in particular have improved textural properties when they are made with more than one GF flour. In fact, most formulations for GF breads available in the literature use more than one flour, presumably for this purpose. Rice flour is commonly used in GF bread formulations, as it is hypoallergenic and does not have a strong flavor (Kadan et al., 2001; Cato et al., 2004; Sciarini et al., 2008). However, bread made with only rice flour is dry, crumbly, grainy, and stales rapidly (Kadan et al., 2001), so other flours are blended with rice flour to improve texture. Bread made with a blend of 10% rice bran and 90% rice flour was found to have significantly improved flavor and appearance as compared to bread made with 100% rice flour. The 10% rice bran bread was thought to be comparable to whole-wheat bread in terms of texture and taste. However, both rice flour breads had lower volume than a control bread made with wheat flour. The lower volume was attributed to the rice bran fiber and proteins interfering with gas retention (Kadan et al., 2001). A combination of short grain and long grain rice flours (10% and 90% of flour weight, respectively) produced breads with softer texture than bread made of 100% rice flour, although both rice flour breads were harder and more crumbly than the wheat control bread (Kadan et al., 2001).

Pruska-Kedzior et al. (2008) studied properties of GF doughs and breads made with several combinations of maize flour, maize starch, potato starch, rice flour, and buckwheat flour. Doughs made with maize flour or starch and potato flour were more networked and elastic than breads made with rice or buckwheat flour, which were less networked and viscous. Bread made with maize flour and potato starch had the largest final volume; bread made with maize starch or rice flour had a finer crumb than bread made with maize flour or buckwheat flour. With the exception of the bread made from maize flour and potato starch, all of the breads made received very high (4-5 on a scale of 1 to 5, 5 being “very acceptable”) sensory scores from a trained sensory panel. Sciarini et al. (2008) studied breads made with varying levels of rice, corn, and soy flours. Soy flour was found to have the greatest effect on both dough and bread characteristics; it increased batter consistency, softened bread crumb, improved bread volume, and retarded staling. Breads made with rice, corn, and soy flour had the softest texture, the highest volume, and the lowest staling rates, and were considered to have the best quality of all the breads made.

The amount of water and the temperature of the water added to GF baked goods affects both the dough produced and the final product. Kulamarva et al. (2004) studied the rheological properties of sorghum doughs mixed with varying amounts of water at either 22°C or 100°C. Higher water additions produced dough that was softer, gummier, and more cohesive. Pure sorghum doughs made with 100°C water were softer, more cohesive, gummier, and more adhesive due to starch gelatinization. In addition, using a 1:1 ratio of water and sorghum flour gave a better extensibility than a lower ratio of water to flour. However, composite flour doughs were less extensible, less cohesive, and had a higher

storage modulus when made with 100°C water. Kobylański et al. (2004) studied the effects of water on the onset of gelatinization, peak, and conclusion temperature of GF dough made with corn and cassava flours. Adding larger amounts of water decreased onset, peak, and conclusion temperatures due to increased plasticization of the starch with increased amount of water (Kobylański et al., 2004). Several studies have examined the effects of water on GF breads. Increasing the water added to the doughs increased specific volume and loaf height, and decreased crust and crumb firmness (Gallagher et al., 2003; McCarthy et al., 2005; Schober et al., 2005).

A considerable amount of research has been done on the effects of different proteins on GF products, especially breads. Soy and egg proteins have been shown to improve GF volume (Gallagher et al., 2003; Kobylański et al., 2004; Ribotta et al., 2004). Egg white proteins have been shown to increase peak and conclusion temperatures in dough made with corn and cassava flours. This effect was attributed to the denaturation and gelation of egg white that competes with gelatinization of starch by reducing the amount of water available. (Kobylański et al., 2004). Dairy powders can improve the handling properties of batter by increasing water-holding ability (Gallagher et al., 2003). However, adding milk powders to GF bread has a tendency to decrease loaf volume (Gallagher et al., 2003; Schober et al., 2005). Dairy powders have also been shown to increase crust browning and crumb hardness, as well as improve sensory acceptability. The amount of protein in the powder is important, as powders with higher protein content yield loaves with harder crust, smaller gas cells, and finer, denser crumb than powders with low protein content (Gallagher et al., 2003). Marco and Rosell (2008b) found that whey proteins decrease GF dough peak viscosity. Whey

proteins also decrease the elastic and viscous moduli of GF dough made with rice flour and potato starch, as does egg albumin; this indicates a weak dough. Soybean and pea proteins, on the other hand, increase the elastic and viscous moduli (Marco and Rosell, 2008b).

Adding transglutaminase (TGase) to GF breads, especially when other proteins are added, has a significant impact on the finished product (Marco and Rosell, 2008b). TGase is an enzyme that causes certain proteins to crosslink, which can produce a protein network in GF products that is similar to the gluten network found in wheat products (Moore et al., 2006). TGase has been shown to improve loaf volume and soften crumb of GF breads made with rice flour (Gujral and Rosell, 2004), as well as significantly increase the elastic modulus of GF dough (Marco and Rosell, 2008b). However, high levels of TGase can cause crumb hardness to increase because of the lower bake loss, higher crumb moisture, and higher water-holding ability from network formation (Moore et al., 2006). Marco and Rosell (2008a) found that GF breads made with TGase and soy flour had a more continuous crumb structure and increased crumb hardness due to protein crosslinking. Moore et al. (2006) found that TGase formed crosslinks in GF breads containing egg powder and skim milk powder; the bread containing egg powder and TGase formed a network similar to a gluten network. Both egg white and egg yolk were found to promote network formation. The amount of TGase needed for network formation depended on the protein; network formation was seen at 1  $\mu\text{g/g}$  and 10  $\mu\text{g/g}$  protein in breads made with egg powder and skim milk powder, respectively.

Little research has been done on the impact of lipid type on GF baked goods. Schober et al. (2003) studied biscuits (cookies) made from different combinations of fat

powders and GF flours. The rheological properties of the finished biscuits were found to depend on the stickiness and firmness of the dough. Firm, nonsticky doughs resulted in firm, thin, round biscuits; soft, sticky doughs resulted in soft thick, oval biscuits (Schober et al., 2003). Schober et al. (2003) hypothesized that increased dough firmness resulted in a lower rise during baking. It is possible that firmer doughs have slower movement of gas through the dough during baking compared to softer doughs, resulting in little dough expansion before the dough structure sets and prevents further expansion. Schober et al., (2003) also found that increased stickiness correlated with softer doughs. Fat powder addition (regardless of type) increased firmness, moisture content, and dough hardness, and decreased stickiness. The proteins and sugar in the fat powders were thought to contribute to dough hardness by providing structure and binding water, respectively (Schober et al., 2003).

It is interesting to note that in short doughs (cookies, etc.) with relatively high sugar content, sugar is responsible for the cohesiveness of the final product. According to Chevallier et al. (2000), crystalline sugar melts and reforms into an amorphous solid as the product is baked and cooled. The melting and solidifying of sugars traps proteins, starches, and lipids in a matrix. Lipids have also been shown to improve cohesiveness, although the mechanism for this behavior is currently unknown (Chevallier et al., 2000). Because sugar and not a protein matrix is responsible for the cohesiveness of higher-sugar dough, GF cookies, brownies, and other sweet baked goods with acceptable taste and texture should be easier to develop and manufacture.<sup>1</sup>

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<sup>1</sup> Based on personal experience, gluten-free cookies and brownies have a taste and texture much more like their gluten-containing counterparts than gluten-free bread does.

### 2.2.6. *Gluten-free-frying*

There is an increasing interest in frying using rice flour rather than wheat flour or corn starch to produce fried products that are lower in fat. Rice flour batters have been found to absorb less oil than wheat flour batters (Mohamed et al., 1998; Shih et al., 2004; Dogan et al., 2005; Shih et al., 2005; Xue and Ngadi, 2007) due to the nature of the starch and proteins in rice flour. Rice flours, usually made from long-grain white rice, have a high amylose content (Shih et al., 2004) that resists oil uptake (Mohamed et al., 1998; Altunakar et al., 2004; Shih et al., 2004). In addition, rice flours do not contain the lipophilic protein gluten, which increases oil uptake in wheat batters (Shih et al., 2004; Dogan et al., 2005). Using a rice flour-based batter also yields products that are less prone to lipid oxidation during freezing (Jackson et al., 2006). Several studies have found that fried, battered products made with a rice flour-based batter had acceptable sensory qualities. In addition, the oil content of those products was significantly lower than the oil content of the same type of products made with wheat flour (Shih et al., 2004; Shih et al., 2005; Jackson et al., 2006).

In addition to being used alone as a breading for various fried products, rice flour has been used in conjunction with gums, proteins, and modified starches (methylcellulose, etc.) to reduce the amount of oil absorbed by fried products. The hydrocolloids are either added to the product formula to increase moisture-holding capacity (Shih and Daigle, 2002; Shih et al., 2005) or added as a coating to form an oil-barrier film on the surface of the product (Shih and Daigle, 2002; García et al., 2004; Shih et al., 2005). This film physically prevents oil migration into the crust, decreasing the oil uptake of the food during frying (Annapure et al., 1999; García et al., 2002; Rimac-Brncic et al., 2004). Hydrocolloids shown to be effective in

reducing oil uptake through an oil-barrier mechanism include methylcellulose (Annapure et al., 1999; García et al., 2002; García et al., 2004), carboxymethylcellulose (Khalil, 1999; Rimac-Brncic et al., 2004), hydroxypropylmethylcellulose (Annapure et al., 1999), hydroxymethylcellulose (Annapure et al., 1999), pectin (Khalil, 1999), and gum arabic (Annapure et al., 1999). Rice based thickeners, such as pregelatinized rice flour, have also been shown to be effective for lowering oil content. Addition of pregelatinized rice flour to a batter increases its viscosity (Mohamed et al., 1998; Shih and Daigle, 1999; Shih et al., 2005). Adding small amounts of pregelatinized rice flour (less than 5% by weight of the total flour) (Shih et al., 2005) decreased the final oil content of the food (Shih and Daigle, 1999; Shih et al., 2005). Shih and Daigle, (1999) hypothesized that the lower oil content was due to increased batter pickup: more batter forms a harder crust, which acts as an oil barrier. Using pregelatinized rice flour over levels of 5% was shown to increase oil uptake (Mohamed et al., 1998; Shih et al., 2005). However, rice flour/pregelatinized rice flour batters generally had a lower fat content than wheat batters (Shih and Daigle, 1999; Shih et al., 2005). Pregelatinized rice flour also affected the texture and color of the fried batter, resulting in a harder, crisper, and darker product (Mohamed et al., 1998; Shih and Daigle, 1999; Shih et al., 2005).

Other GF flours, such as corn flour (Xue and Ngadi, 2007), tapioca flour, modified tapioca flour (Mohamed, et al., 1998), soy flour, amaranth flour, quinoa (Ahamed et al., 1997), and corn starch (Ahamed et al., 1997; Mohamed, et al., 1998), have also been used in fried foods. Because GF flours have different starch and protein compositions than wheat flour, they behave differently when fried. A fair number of studies have been conducted on

GF batters to determine their behavior during frying and if any general trends exist. Water loss and oil uptake decrease with increasing batter viscosity (Mohamed et al., 1998, Dogan et al., 2005, Shih et al., 2005). Batter viscosity has also been found to affect appearance, texture (Dogan et al., 2005; Shih et al., 2006), and sensory quality of finished products (Shih et al., 2006). Moisture, protein content, amylose, and amylopectin have been found to correlate with the linear expansion, elasticity, crunchiness, and oil absorption (Mohamed et al., 1998). An increased amylose content has been shown to decrease oil uptake (Mohamed et al., 1998; Altunakar et al., 2004; Shih et al., 2004). Increased amylose also increases the hardness and toughness of batter due to increased polysaccharide-polysaccharide interactions (Mohamed et al., 1998). It is important to note that these findings are based on the behavior of the GF flours as used in batters or breadings for products such as chicken nuggets and not in a dough-type product, such as hush puppies or donuts.

Very few studies have examined fried GF doughs, especially in terms of products designed to be GF analogues to wheat-containing foods. Most studies on fried doughs that have GF flours as part of the formula usually combine the GF flours with wheat flour, which generally improves the rheological properties of the dough (compared to dough made with only GF flour) and reduces the fat content of the fried product, but these products cannot be eaten by people with wheat or gluten sensitivities. Shih and Daigle (2002), however, examined cake donuts made from rice flour. Donuts were made with long-grain rice flour and waxy rice flour, with different amounts of pregelatinized rice flour added. All doughs were adjusted to similar viscosity by adjusting the amount of water added. Long grain rice flour doughs required less water and waxy rice flour dough required more water than wheat

dough to reach the same viscosity as the wheat dough. Adding pregelatinized rice flour increased dough viscosity. As several other studies found, moisture level increased as oil absorption decreased. Rice donuts were found to absorb less oil and have higher moisture content than wheat donuts. Pure long grain rice flour donuts absorbed slightly less oil than the wheat donuts, while waxy rice flour donuts absorbed significantly less oil. Waxy rice flour does not have much amylose, which tends to complex and is more lipophilic, therefore absorbing more oil. A pregelatinized rice flour content greater than 30% caused the dough to be too moist to fry properly. Donuts made with 10% PGRF had a favorable comparison to wheat donut in terms of firmness and texture. Donuts made with 20% PGRF were found to be “pleasantly soft and chewy”, although no formal sensory testing was done (Shih and Daigle, 2002).

## **2.3. Cooking of foods with infrared radiation**

### *2.3.1. Overview of infrared radiation*

Infrared (IR) radiation is a form of electromagnetic energy with a wavelength between 0.1 and 100  $\mu\text{m}$  that is transmitted in waves. Infrared radiation is included in thermal radiation, which encompasses infrared, visible, and ultraviolet wavelengths (Kreith and Bohn, 2001). Thermal radiation is one of the three main types of heating, the other two being conduction and convection (Welty et al., 2001). It is defined as the emission of heat from an object due to its temperature. This emission of heat is not dependent on any intervening medium; thermal radiation can occur through a vacuum (Kreith and Bohn, 2001).

When thermal radiation is incident on a surface it is either absorbed, transmitted, or reflected (Welty et al., 2001). Absorption is defined as the conversion of radiation to another form of energy, such as heat. Reflection is defined as the redirection of radiant energy away from the surface. Transmission is defined as radiation that passes through the material without being converted to another form of energy (Sandu, 1986). The sum of absorptivity, reflectivity and transmissivity is unity (Kreith and Bohn, 2001):

$$\alpha + \rho + \tau = 1 \quad (2.16)$$

where  $\alpha$  is absorptivity,  $\rho$  is reflectivity and  $\tau$  is transmissivity.

If a surface emits and absorbs the maximum possible amount of radiation at any wavelength and at any temperature, it is called a blackbody (Kreith and Bohn, 2001). An example of a near-perfect blackbody is a metal sheet coated with carbon black. Gray bodies are surfaces that have absorptivities independent of wavelength and monochromatic emissivities. Real surfaces may be approximated as gray bodies by taking an average emissivity and absorptivity over the desired temperature range (Kreith and Bohn, 2001).

From the Stefan-Boltzmann law, total radiation emission for any surface depends on temperature and emissivity (Kreith and Bohn, 2001):

$$E_g = \frac{q_r}{A} = \varepsilon \sigma T^4 \quad (2.17)$$

where  $E_g$  is the total emission of radiation per unit surface area per unit time ( $\text{W}/\text{m}^2$ ),  $q_r$  is the radiant heat flow rate (W),  $A$  is the area of the blackbody that is emitting ( $\text{m}^2$ ),  $\varepsilon$  is the emissivity of the surface,  $\sigma$  is the Stefan-Boltzmann constant ( $5.670 \times 10^{-8} \text{ W}/\text{m}^2 \text{ K}$ ), and  $T$  is

the temperature (K). For a blackbody,  $\epsilon_g$  is equal to one and the emissive power depends only on temperature (Kreith and Bohn, 2001).

As radiation is absorbed by a food, the amount transmitted decreases exponentially as the distance from the surface increases (Skjöldebrand et al., 1988):

$$T_x = T_0 e^{-\tau x} \quad (2.18)$$

where  $T_x$  is the percent transmission,  $T_0$  is the percent transmission at the surface of the food,  $\tau$  is the spectral extinction coefficient ( $\text{cm}^{-1}$ ), and  $x$  is the distance from the surface of the food (cm). Penetration depth in foods has been found to be dependent on both food composition and IR wavelength. For shorter IR wavelengths, the penetration depth ranges between 1 and 18 mm, for longer IR wavelengths, there is little surface penetration (Krishnamurthy et al., 2008). The penetration depth of IR waves is defined as the distance from the surface of the food to the depth that corresponds to 37% transmittance (Skjöldebrand et al., 1988). The spectral extinction coefficient, which is a physical property, plays a major role in determining the penetration depth. It is the sum of the absorption coefficient and the scattering coefficient (Siegel and Howell, 2002). Scattering is defined as a redistribution of energy in a material without any energy absorbed or lost (Birth, 1978). The spectral extinction coefficient is dependent on the food composition, temperature, and pressure, as well as the wavelength incident on the surface of the food (Siegel and Howell, 2002). Little information is available on the spectral extinction coefficients of foods, although there is some data available for bread (Skjöldebrand et al., 1988), biscuits (Wade, 1987), potato (Almeida et al., 2006), and pork (Dagerskog and Österström, 1979). In general, penetration of IR waves in foods is less than microwaves and high frequency waves,

but shorter IR wavelengths penetrate farther into foods than longer IR wavelengths (Olsson et al., 2005).

The amount of radiation absorbed by foods, which may be considered gray bodies, is dependent both on food properties and the wavelength of the IR radiation (Olsson et al., 2005). Absorption bands, or a range of wavelengths that are highly absorbed by the substance, have been found for water, carbohydrate (sugars), protein, and lipids (Sandu, 1986). Water absorbs a large amount of radiation, but the specific absorption bands depend on the phase of the water. Water vapor absorbs at 1.14, 1.38, 1.87, 2.7, and 6.3  $\mu\text{m}$ , with the 2.7 and 6.3  $\mu\text{m}$  bands having the strongest absorption. Liquid water absorbs at 1.19, 1.43, 1.94, 2.93, 4.72, 6.1, and 15.3  $\mu\text{m}$ , with the 2.93, 4.73, 6.1, and 15.3  $\mu\text{m}$  bands having the strongest absorption. Surprisingly, the temperature of the liquid water has no effect on these absorption bands (Sandu, 1986). Absorption bands do vary slightly with addition of hydrates and solutes, but not significantly. Ice absorbs at the same bands as liquid water. Proteins absorb strongly at 3.0-4.0  $\mu\text{m}$  and 6.0-9.0  $\mu\text{m}$ . Lipids absorb strongly over the entire IR spectrum but have the strongest absorption at 3.0-4.0  $\mu\text{m}$ , 6.0  $\mu\text{m}$ , and 9.0-10.0  $\mu\text{m}$ . Sugars absorb strongly at 3.0  $\mu\text{m}$  and 7.0-10.0  $\mu\text{m}$  (Sandu, 1986).

Mixing water, proteins, carbohydrates, and fats does not cause “spectral windows” (Sandu, 1986). That is, a food composed of carbohydrates, water, and lipids will not necessarily have the absorption bands of carbohydrate, water, and lipids. Though little is known about specific absorption bands for individual foods, it has been determined that the ability of a particular food to absorb IR radiation depends on the physiochemical nature of the food, optical thickness, and water content, as well as the wavelengths used (Sandu, 1986;

Sheridan and Shilton, 1999). Optical thickness is defined as the ability of a material to attenuate a given wavelength of radiation down its path length (Siegel and Howell, 2002). Increased optical thickness in a food results in decreased transmittance and increased reflection, although no theoretical explanation of this is available (Krishnamurthy et al., 2008). Water absorbs more of the longer IR wavelengths while shorter IR wavelengths are transmitted through water (Krishnamurthy et al., 2008). Therefore, foods with high water content will show absorption bands at different wavelengths than foods with lower water content.

### 2.3.2. *Infrared emitters*

Infrared radiation has been classified into three main types: near, middle, and far. The near infrared (NIR) range comprises wavelengths between 0.8 and 1.4  $\mu\text{m}$  (Olsson et al., 2005), mid infrared range comprises wavelengths between 1.4 and 3.0  $\mu\text{m}$ , and the far infrared (FIR) range comprises greater than 3.0  $\mu\text{m}$  (Sheridan and Shilton, 1999).

Sources that produce IR waves are called emitters. The design and materials used in the emitter depend on the desired emitted wavelengths. According to Lloyd (2003), short wavelength, or NIR, emitters are usually made of a quartz shell surrounding a tungsten filament. Medium wavelength, or MIR, emitters are generally one of three types. One type is a quartz envelope with a carbon filament or nickel chromium wire. A second type is a ceramic surface heated on one side by natural gas or other carbon-based fuels. MIR waves are emitted from the opposite side of the plate. The third type of MIR emitter is the heated metal sheath. The metal is a high-temperature alloy that encloses a nickel chromium wire

surrounded by packing composed of solid magnesium oxide. Long wavelength emitters, or FIR emitters, are usually made of woven quartz fabric coated in carbon black paint and heated by embedded resistance wires (Lloyd, 2003).

Wavelength is temperature dependent. The relationship between wavelength, emitter power, and temperature is described in Planck's Law (Siegel and Howell, 2002):

$$E_{\lambda}(\lambda, T) = \frac{3.742 \times 10^{-16}}{\lambda^5 \left( e^{\frac{0.01439}{\lambda T}} - 1 \right)} \quad (2.19)$$

where  $E_{\lambda}$  is the emissive power of the emitter ( $\text{W/m}^2$ ),  $\lambda$  is the wavelength in vacuum (m), and  $T$  is temperature (K). As the temperature of the IR source increases, the wavelengths emitted decrease (Siegel and Howell, 2002). Thus, NIR emitters operate at a higher temperature than MIR or FIR emitters; NIR, MIR, and FIR emitters typically operate at 1900-2200°C, 1500°C, and 600-700°C, respectively (Lloyd, 2003). However, all of these emitters operate at very high temperatures, which allows them to produce sufficient heat flux to cook foods. Heat flux from radiation is not significant at lower temperatures (27°C and lower); this is because the Stefan-Boltzmann constant is very small (Eqn. 2.17) (Kreith and Bohn, 2001). Because emissivity and therefore heat flux per unit area increases with the fourth power of temperature, high temperatures allow a significant heat flux to be emitted.

For any given IR emitter temperature, the radiation emitted is spread over a range of wavelengths. These wavelengths do not have an even distribution but are clustered around a peak wavelength (Wade, 1987; Skjöldebrand et al., 1988). Peak wavelength is defined as the

wavelength for a given temperature at which the emissive power is maximum. According to Wien's displacement law (Siegel and Howell, 2002):

$$\lambda_{\max} = \frac{2.898 \times 10^{-3}}{T} \quad (2.20)$$

where  $\lambda_{\max}$  is the peak wavelength (m) and T is the emitter temperature (K). As the emitter temperature increases, peak wavelength decreases (Sandu, 1986; Siegel and Howell, 2002).

The exact peak wavelength of an emitter depends on its operating temperature but the majority of emitters of a certain type have similar peak wavelengths. NIR emitters typically produce wavelengths between 0.2  $\mu\text{m}$  and 14  $\mu\text{m}$  with a peak wavelength of 1.4  $\mu\text{m}$  and MIR emitters typically produce wavelengths between 1  $\mu\text{m}$  and 14  $\mu\text{m}$  with a peak wavelength of 4.3  $\mu\text{m}$  (Lloyd, 2003). Little data is given on the wavelengths emitted by FIR emitters, but the peak wavelength is generally between 2.9  $\mu\text{m}$  and 3.6  $\mu\text{m}$  (Wisconsin Infrared Systems, 2005; American Health, 2009). This is lower than the peak wavelength for the MIR emitters, but the range of wavelengths generated, particularly the longer wavelengths, is greater in the FIR emitters than in the MIR emitters. In all type of emitters, 1/3 of wavelengths are shorter than peak wavelength and 2/3 of wavelengths are longer than peak wavelength. This distribution may be seen by plotting the emissive power calculated using Planck's Law over a range of wavelengths and temperatures (Sheridan and Shilton, 1999).

Although emitters produce a wide range of wavelengths, the range of wavelengths incident on a surface can be narrowed by filtering. Bandpass filters allow only certain ranges of wavelengths to pass through them. The range of transmitted wavelengths depends on the filter material (Lentz et al., 1995) and the geometry of the filter (Chase and Joseph, 1983).

Filter temperature and angle of incidence of radiation on the filter also affect the transmitted wavelengths, although these factors only change the transmitted wavelengths by a few micrometers (Baker and Yen, 1967). Bandpass filters have been used to narrow the range of wavelengths produced by an emitter to a region of interest (Krishnamurthy et al., 2008). Dagerskog and Österström (1979) used a bandpass filter to examine the effects of a specific IR region ( $\geq 1.5 \mu\text{m}$ ) on the frying of pork. Lentz et al. (1995) was able to filter the wavelengths produced by a quartz bulb with a tungsten filament by placing a thin water or dye-in-water filter between the emitter and the food to be heated, which filtered out wavelengths below  $0.8 \mu\text{m}$  and above  $1.3 \mu\text{m}$ . Lentz et al. (1995) also examined coated incandescent bulbs combined with a water jacket around the bulb to prevent the coating from flaking off during heating. This method also filtered out wavelengths below  $0.8 \mu\text{m}$  and above  $1.3 \mu\text{m}$ . Jun and Irudayaraj (2003) designed a FIR heating system that used several optical bandpass filters to examine the effects of different ranges of wavelengths ( $2.5\text{-}2.96 \mu\text{m}$ ,  $3.15\text{-}3.67 \mu\text{m}$ , and  $5.45\text{-}12.23 \mu\text{m}$ ) on the heating of soybean protein and starch powder.

### *2.3.3. Mathematical modeling of infrared heating*

The majority of research on IR heating of foods has been based on applications of IR heating rather than heat or mass transfer model development. Most foods studied have been in the shape of flat slabs. In order to model the heat and mass transfer that occurs during IR heating, it is important to understand how heat and mass are transferred during IR heating. In the case of food in the shape of a flat plate, as the infrared radiation is absorbed by the food, the food is heated nearly uniformly by radiation to the penetration depth, or depth of

attenuation (Sandu, 1986). At the boundary of radiation penetration, energy transfers deeper into the food via conduction (Sandu, 1986; Krishnamurthy, 2008). As the food heats, water near the surface vaporizes and evaporates off, causing moisture migration from the interior of the food through thermal diffusion. This is called the constant drying rate. The drying rate is constant and the temperature of the food is relatively low as long as evaporation is occurring only in the depth of attenuation. After the transfer of moisture becomes limiting, moisture vaporization and evaporation advances into the food and the food begins to dry. This is called the falling drying rate period (Sandu, 1986).

An early model of IR heating of hamburger patties was developed by Dagerskog (1979a). The model used finite difference methods to calculate the temperature distribution in the patty during heating:

For  $n=2$  to  $n=ns$ :

$$T_{n,t+1} = T_{n,t} + \alpha \left( \frac{\Delta t}{\Delta x^2} \right) (T_{n+1,t} - 2T_{n,t} + T_{n-1,t}) + \frac{\alpha}{k} \left( \frac{\Delta t}{\Delta x} \right) (PT(P_n - P_{n+1}) + RT(R_{n+1} - R_n)) \quad (2.21)$$

For  $n=1$  and  $n=ns+1$

$$T_{1,t+1} = T_{1,t} + 2\alpha \left( \frac{\Delta t}{\Delta x^2} \right) (T_{2,t} - T_{1,t}) + \frac{2\alpha h}{k} \left( \frac{\Delta t}{\Delta x} \right) (T_{air} - T_{1,k}) + \frac{2\alpha}{k} \left( \frac{\Delta t}{\Delta x} \right) (PT(1 - P_2) + RT(R_2 - R_1)) \quad (2.22)$$

where  $T$  is temperature ( $^{\circ}\text{C}$ ),  $n$  is a space increment subscript,  $t$  is a time increment subscript,  $PT$  and  $RT$  are the total density of radiation at the product surface ( $\text{W}/\text{m}^2$ ),  $P$  and  $R$  are the distribution of radiation due to internal adsorption,  $\Delta t$  is the time increment (s),  $\Delta x$  is the distance increment (m),  $\alpha$  is the thermal diffusivity ( $\text{m}^2/\text{s}$ ),  $k$  is the thermal conductivity

(W/m °C),  $h$  is the heat transfer coefficient (W/m<sup>2</sup> °C) and  $T_{\text{air}}$  is air temperature (°C). Mass transfer, volume change, and crust formation were ignored, and material and spectral properties were held constant. This model showed that the thickness of the food and IR flux had a strong influence on the rate of heating, while air temperature and peak wavelength of the IR emitter had a relatively weak influence (Dagerskog, 1979a). The lack of influence of the peak wavelength was probably due to the fact that the samples were only 14 mm thick. The thinness of the samples allows for rapid heating, so the change in IR penetration depth with peak wavelength was most likely masked. Therefore, this equation should only be used to predict the heating of relatively thin samples.

Later heat transfer models used unsteady-state one-dimensional heat transfer as a basis for modeling (Fasina et al., 1998; Shilton et al., 2002). The food to be heated was assumed to be an infinite slab and heat transfer was assumed to be one-dimensional from the surface of the food inward (Shilton et al., 2002):

$$\rho_s c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \rho_d \lambda \frac{\partial C}{\partial t} \quad (2.23)$$

In this equation,  $\rho_s$  is the density at the surface of the food (kg/m<sup>3</sup>),  $c_p$  is the specific heat of the food (kJ/kg K),  $\rho_d$  is the density of the dry product (kg/m<sup>3</sup>),  $\lambda$  is the latent heat of vaporization (kJ/kg), and  $C$  is the dry basis moisture content (kg liquid/kg solid). Initial conditions were considered to be  $T = T_i$  ( $T_i$  being initial temperature) at all locations in the food. Boundary conditions were:

$$k \frac{dT}{dx} = \sigma (T_{\infty}^4 - T_s^4) \quad \text{at } x = X \text{ for } 0 < t \leq t_f \quad (2.24)$$

$$\frac{\partial T}{\partial x} = 0 \quad \text{at } x = 0 \quad (2.25)$$

where  $\sigma$  is the Stefan-Boltzmann constant ( $5.670 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ ),  $T_\infty$  is the temperature of the air (K),  $T_s$  is the temperature of the food at the surface (K), and  $t_f$  is the final time. Physical properties of the food (thermal conductivity and density) were assumed to change with increasing temperature. Good agreement was found between the model and experimental results for nonfat beef patties (Shilton et al., 2002). However, the model did not take the volume change of the food into account. It also did not accurately predict the heat transfer of low- or full-fat beef patties, even if the amount of fat was as low as 10% of the total weight. Because the inaccuracy was thought to be due to internal convection that was not accounted for, a convection term was added to the thermal conductivity calculation to improve the agreement with the experimental results (Shilton et al., 2002):

$$k = \underbrace{(k_1 + k_2 T + k_3 T^2)}_{\text{(conduction term)}} + \underbrace{(h_{eff1} + h_{eff2} T)}_{\text{(convection term)}} \quad (2.26)$$

where  $k_1$ ,  $k_2$ ,  $k_3$ ,  $h_{eff1}$ , and  $h_{eff2}$  are all empirical constants. Adding the convection term to the heat transfer model enabled the calculation of a more accurate sample temperature profile, which improved heat transfer predictions (Shilton et al., 2002).

Lloyd (2003) developed a model to simulate the internal temperature profile in potato slices cooked by IR. This model was designed to predict the temperature in the crust and core regions separately by using a partial differential equation for each region. Heat transfer was assumed to be from both radiant and conductive mechanisms. The model showed good agreement with the experimental data, with the predicted temperature of the crust and core deviating less than  $3^\circ\text{C}$  from the experimental data.

A few studies have developed models for mass transfer during infrared heating. Fasina et al. (1998) developed a mass transfer model for the drying of barley kernels that was coupled with heat transfer. The kernels were assumed to be spherical, allowing the model to be expressed in spherical coordinates:

$$\text{For heat transfer: } \rho C_g \frac{\partial T}{\partial t} = \frac{k}{r} \left( \frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) \quad (2.27)$$

$$\text{For mass transfer: } \frac{\partial C}{\partial t} = \frac{D_m}{r} \left( \frac{\partial^2 C}{\partial r^2} + \frac{2}{r} \frac{\partial C}{\partial r} \right) + \left( \frac{\partial C}{\partial r} \right)^2 \frac{\partial D_m}{\partial C} \quad (2.28)$$

where  $C_g$  is the moisture concentration in the grain (% , dry basis),  $r$  is the radial distance from the surface of the kernel (m), and  $D_m$  is the moisture diffusivity ( $\text{m}^2/\text{s}$ ). Boundary conditions were given as:

$$T = T_i \quad \text{at } t = 0 \text{ for } 0 < r \leq R \quad (2.29)$$

$$C = C_i \quad \text{at } t = 0 \text{ for } 0 < r \leq R \quad (2.30)$$

$$-k A_g \left. \frac{\partial T}{\partial r} \right|_s = q_r + h_c A_g (T_e - T_s) + \rho V h_{fg} \frac{\partial C}{\partial t} \quad \text{at } t = 0 \text{ for } r = R \quad (2.31)$$

$$-D \left. \frac{dC}{dr} \right|_s = h_m (C_s - C_{eq}) \quad \text{at } t > 0 \text{ for } r = R \quad (2.32)$$

where  $T_i$  is the initial temperature (K),  $R$  is kernel radius (m),  $C_i$  is the initial moisture concentration (% moisture, dry basis),  $q_r$  is the radiative heat component (W),  $h_c$  is the convective heat transfer coefficient ( $\text{W}/\text{m}^2 \text{ K}$ ),  $A_g$  is the surface area of the grain ( $\text{m}^2$ ),  $T_e$  is the emitter temperature (K),  $T_s$  is the temperature at the surface of the kernel (K),  $V$  is the volume of the kernel ( $\text{m}^3$ ),  $h_{fg}$  is the latent heat of vaporization (J/kg),  $D$  is the particle diameter (m),  $h_m$  is the convective mass transfer coefficient (m/s),  $C_s$  is the concentration of

moisture at the surface (% moisture, dry basis), and  $C_{eq}$  is the concentration of moisture at equilibrium (% moisture, dry basis). The radiative heat was considered to be from both an IR heater and reflection from plates around the sample:

$$q_r = \frac{\sigma A_g (T_e^4 - T_s^4)}{\frac{1 - \varepsilon_g}{\varepsilon_g} + \frac{1}{F_{ge}} + \frac{1 - \varepsilon_e}{\varepsilon_e \left( \frac{A_e}{A_g} \right)}} + \frac{2\sigma A_g (T_p^4 - T_s^4)}{\frac{1 - \varepsilon_g}{\varepsilon_g} + \frac{1}{F_{gp}} + \frac{1 - \varepsilon_p}{\varepsilon_p \left( \frac{A_p}{A_g} \right)}} \quad (2.33)$$

where  $\sigma$  is the Stefan-Boltzmann constant ( $5.670 \times 10^{-8}$  W/m<sup>2</sup> K),  $A_e$  is the surface area of the emitter (m<sup>2</sup>),  $T_p$  is the plate temperature (K),  $\varepsilon_e$ ,  $\varepsilon_g$ , and  $\varepsilon_p$  are the emissivities of the emitter, grain, and plate, respectively, and  $F_{ge}$  and  $F_{gp}$  are the view factors between the grain and emitter and the grain and plate, respectively. The model showed fairly good fit with the experimental data: the average deviation in surface temperature and moisture content were 3.9°C and 0.6% (wet basis), respectively. However, the model did not take volume change, case hardening, or changing physical property data into account, which could account for the deviation of experimental data from predicted behavior.

Shilton et al. (2002) also developed a mass transfer model that was coupled with the heat transfer model mentioned above (Eqn. 2.23):

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad (2.34)$$

where  $D$  is the mass diffusivity (m<sup>2</sup>/s). Initial and boundary conditions were given as:

$$C = C_i \quad \text{at } t = 0 \text{ for all } x \quad (2.35)$$

$$\frac{dC}{dx} = 0 \quad \text{at } x = 0 \quad (2.36)$$

$$D \frac{dT}{dx} = K_m (C_\infty - C_s) \quad \text{at } x = X \text{ for } 0 < t \leq t_f \quad (2.37)$$

where  $K_m$  is the convective mass transfer coefficient (m/s) and  $C_\infty$  is the moisture content of the air (kg moisture/kg air). Temperature and moisture content were taken into account for mass diffusivity. Moisture loss during cooking was assumed to be similar to moisture loss during drying. Similar to the model developed for heat transfer (Eqn. 2.23), the mass transfer model showed good agreement with the experimental results of nonfat beef patties, but the accuracy of the predicted mass transfer decreased as the fat content of the patty increased. Again, adding a convection term (Eqn. 2.26) decreased the deviation between the predicted and experimental sample temperature and significantly improved the agreement of the mass transfer model. Sheridan et al. (2002) concluded that heat transfer in beef patties was highly dependent on the internal movement of melted fat by convection during heating, hence the improved agreement of both the heat and mass transfer models upon the addition of the convection term.

Yaniv (2006) expanded the model created by Lloyd (2003) to create a finite difference model that coupled heat and mass transfer to predict crust formation during IR heating. Model agreement in general was not very high, although the predicted trends in temperature and crust thickness agreed with the experimental data. Because the model did not account for mass diffusion or evaporation of moisture below 100°C, the model incorrectly predicted a lag phase for crust formation. In addition, a lack of optical property data was hypothesized to be the cause of the deviation of predicted temperature of the crust and core regions to the experimental data (Yaniv, 2006).

Models for IR heating that have been developed tend to focus on a particular food or type of food. They are most accurate with foods that can be modeled as flat slabs and do not work well for foods that have very rough surfaces or are irregular in shape. They also depend heavily on physical and spectral property data, most of which is unknown for foods. Much work remains to be completed before there is a functional universal model of heat and mass transfer for foods during IR heating.

#### *2.3.4. Use of infrared in food processing*

IR heating has been used to pasteurize, thaw, dry, and bake (roast) foods (Sakai and Hanzawa, 1994; Krishnamurthy et al., 2008). Each of these processes will be discussed in more detail in the sections below.

##### 2.3.4.1. Pasteurization

Little work has been done on using IR to pasteurize foods, although there has been an increasing interest in this pasteurization method over the past decade. In general, the number of microorganisms inactivated or destroyed by IR increase with increased power and temperature, and decreased wavelength (which increases total energy) and food thickness (Krishnamurthy et al., 2008). Infrared has been shown to destroy or inactivate many different microorganisms, such as yeasts, molds, and bacteria, in foods such as oysters (Sakai and Hanzawa, 1994), cereal grains (Jun and Irudayaraj, 2003; Krishnamurthy et al., 2008), Japanese noodles (Sakai and Hanzawa, 1994), meats (Sakai and Hanzawa, 1994; Huang, 2004; Muriana et al., 2004), and onions (Gabel et al., 2004). As with other methods of

pasteurization, spores have been found to be more resistant to pasteurization than vegetative cells.

Infrared has been shown to inactivate microorganisms through thermal denaturation (Sakai and Hanzawa, 1994; Krishnamurthy et al., 2008). In a study comparing FIR pasteurization to pasteurization by thermal conduction, pasteurization by FIR was shown to result in fewer viable *E. coli* and *S. aureus* cells in a phosphate-buffered saline solution. It was also shown to destroy more bacteria on an agar plate than conventional heating methods (Sakai and Hanzawa, 1994). FIR has been shown to be effective for surface pasteurization even when most of the food is below lethal temperatures because it heats the surface of the food (Sakai and Hanzawa, 1994). NIR has been shown to be more effective than FIR for certain bacteria (Hamakana et al., 2006), although using wavelengths that the microorganisms to be inactivated are particularly sensitive to results in a greater lethal rate than using a broader spectrum (Jun and Irudayaraj, 2003).

#### 2.3.4.2. Thawing

As with pasteurization, the possibilities of using IR for thawing have not been extensively studied. A few studies have used IR to thaw small packages of prepared meals, frozen fish pastes (Sakai and Hanzawa, 1994), and frozen tuna (Sakai and Hanzawa, 1994; Liu et al., 1999). IR heating was usually used in combination with another heat transfer method, such as an auxiliary heater to increase the rate of thawing or forced air convection to prevent the sample from overheating. These studies found that thawing with IR causes less overheating of the corners and surfaces of foods as compared to foods thawed by

conventional methods such as microwaving. Water and ice have similar absorption IR coefficients, so heating is relatively uniform throughout the thawing process (Sakai and Hanzawa, 1994). Other advantages of IR thawing include lower drip loss and less discoloration of meats (Sakai and Hanzawa, 1994). However, IR thawing appears to be best for relatively thin foods. Thicker foods will thaw through conduction of heat from the surface rather than from IR energy due to the relatively short penetration of IR waves into the food. Because of this, IR thawing time of thicker foods is rather long. An auxiliary heating source may be used to decrease the thawing time if the food is thick: Liu et al. (1999) found that using an emitter below the sample in addition to an emitter above the sample reduced thawing time of 3 cm thick tuna slabs from about 1 hour to 30 minutes. Another disadvantage to IR thawing is excessive surface heating if the emitter temperature is too high or if the food is placed too close to the emitter (Liu et al., 1999). The extent of surface heating may be controlled by using forced air convection to cool the surface of the food during thawing with IR (Sakai and Hanzawa, 1994).

#### 2.3.4.3. Drying

Infrared drying offers several advantages over conventional drying methods. It has been shown to have better temperature control and lower processing time and costs than either freeze-drying or hot-air drying (Sakai and Hanzawa, 1994; Chua and Chou, 2003). Proper selection of IR parameters (wavelength, drying time, etc.) resulted in little color change of foods such as carrot (Baysal et al., 2003), onion, potato, and pineapple (Tan et al., 2001). Using intermittent exposure to IR helped prevent color change during drying even in

heat-sensitive foods (Chua and Chou, 2003). In addition, there was less loss of volatile compounds (Sakai and Hanzawa, 1994) and better rehydration in vegetables dried with IR than with the other drying methods (Sakai and Hanzawa, 1994, Baysal et al., 2003).

There is also evidence that products dried by IR may have better texture and flavor when compared to the same foods dried by conventional drying methods. Horse mackerel that had been dried by IR received higher sensory scores than horse mackerel dried by hot air or freeze-dried (Sakai and Hanzawa, 1994). A study on breadcrumbs dried by IR vs. hot air, microwaves, and a combination of IR and microwaves found that breadcrumbs dried by IR tended to have greater water-holding capacity as compared to breadcrumbs dried by hot air. Greater water-holding capacity caused the breadcrumbs to be less prone to staling and resulted in better taste and softer crumb. The same study found that IR drying was good for surface moisture removal (Tireki et al., 2006).

It should be noted that the food to be dried should not be thicker than the depth to which radiation penetrates. If the food is thicker than the penetration depth, other drying methods should be considered (Sandu, 1986). Thick foods or foods dried in a deep bed, such as grain or rice, will not dry evenly when dried by IR (Das et al., 2004). For this reason, IR is often used in combination with other heating sources, such as microwaves (Baysal et al., 2003; Tireki et al., 2006) or hot air (Chou and Chua, 2001; Hebbar et al., 2004) to improve drying while still obtaining the benefits of drying with IR.

#### 2.3.4.4. Baking and roasting

The majority of research on using IR to process foods has focused on baking and roasting. This research has provided valuable knowledge on how foods behave when exposed to IR waves. Foods studied include meats, vegetables, and baked goods. Cooking these foods using IR heat results in numerous advantages over conventional cooking methods, such as effective heat transfer (Skjöldebrand et al., 1988; Olsson et al., 2005), reduced energy requirements (Sakai and Hanzawa, 1994; Carnahan et al., 2002), and shorter cooking times (Krishnamurthy et al., 2008).

There are several studies that have reported successful cooking of meat by IR. One study examined pork cooked by IR waves in a two-stage frying process (Dagerskog 1979a). The first stage used a peak wavelength of 3.5-3.8  $\mu\text{m}$  to provide surface heat transfer and brown the outside, while the second stage used a peak wavelength of 1.0  $\mu\text{m}$  to provide deep heating and cook the inside. The final moisture content and sensory qualities of the meat products were found to be higher than those from samples cooked conventionally (Dagerskog, 1979a). Other studies also found that the wavelength of the IR radiation used has an effect on product quality. A study by Sheridan and Shilton (1999) used MIR and FIR to cook ground beef patties with various amounts of added fat. The results of this study indicated that the energy used to cook the patties using FIR was much less than for MIR. In addition, there was slightly less fat and water loss from meat cooked with FIR than MIR, resulting in juicier patties. In general, FIR had a longer cook time than MIR, but cook time with FIR shortened with increasing fat content until it was comparable with MIR cook times at 50% fat content. Sheridan and Shilton (1999) hypothesized that both thermal conductivity

and fat and water convection within the meat was responsible for heat transfer in the meat. Increased fat content would increase heat transfer within the meat, decreasing cook time. Fat content did not affect MIR cooking time (Sheridan and Shilton, 1999). Another study examining the quality of various foods cooked by NIR and FIR found that beef patties cooked by FIR had less charring than NIR. Fresh beef patties had higher yield when cooked by FIR than by NIR; frozen patties had no significant difference in yield loss (Carnahan et al., 2002). Roast beef hash, ham slices, and sausage links have also been successfully cooked by IR (Dagerskog, 1979a).

Infrared radiation has also been used to bake bread and other cereal products. Using IR to bake foods tends to result in baked products with thinner crusts and finer or softer crumb structures than conventional heating methods (Lentz et al., 1995; Martínez-Bustos et al., 1999; Olsson et al., 2005). A study using NIR heating to finish par-baked bread found that NIR heating produced less total moisture loss and lower moisture loss rate than impingement and conventional oven. The lower moisture loss was attributed to the fact that the desired crumb temperature, 70 to 80°C, was reached more quickly with IR vs. impingement and conventional oven. NIR heating also produced surface color more quickly than conventional baking (Olsson et al., 2005). Flatbreads, such as wheat flour tortillas (Martínez-Bustos et al., 1999) and pitas (Carnahan et al., 2002), have also been studied. Both the pitas and tortillas had similar texture and color to their conventionally baked counterparts (Martínez-Bustos et al., 1999; Carnahan et al., 2002). Further studies on the IR heating of baked goods include pizza crust (Unklesbay and Unklesbay, 1985; Lentz et al., 1995), cookies (Wade, 1987), and toaster strudel and pizza rolls (Lentz et al., 1995). Infrared

heating was found to reduce baking time in all of these products (Wade, 1987; Lentz et al., 1995). Other products that have been successfully cooked by IR include green bell pepper (Carnahan et al., 2002), and rice crackers, oysters and eggs (Sakai and Hanzawa, 1994). In addition, sweet potatoes, coffee, chestnuts, and green tea have all been successfully roasted by IR (Sakai and Hanzawa, 1994). Roasting conditions are easily maintained under IR heating and the taste of the roasted products is comparable to or better than conventionally roasted products (Sakai and Hanzawa, 1994).

Using IR heating to cook foods gives several advantages over other cooking methods. IR heating gives high heat transfer capacity, heat penetration directly into the product, and fast regulation response (Dagerskog, 1979a; Sandu, 1986). Therefore, cooking times are typically much shorter with IR heating (Sheridan and Shilton, 1999; Martínez-Bustos et al., 1999). Infrared frying is also very energy efficient compared to traditional heating methods (Sakai and Hanzawa, 1994; Carnahan et al., 2002; Krishnamurthy et al., 2008), as long as the appropriate wavelength band is chosen for the food (Sandu, 1986; Martínez-Bustos et al., 1999). Energy consumption and thus energy efficiency depends on the operating conditions of the oven (temperature, air velocity, humidity) and the thermal properties of the food (heat capacity, thermal conductivity, thermal diffusivity) (Baik et al., 1999). Intermittent radiation (radiating, then resting food, or using a different radiation flux) can be also used to reduce energy costs and produce higher-quality food (Sandu, 1986). Part of the lower energy cost from IR heating is due to the fact that the air around the food is not heated, reducing oven temperature and humidity (Sheridan and Shilton, 1999). A high heat flux can be directed into the food and evenly applied over the surface, resulting in a lower energy requirement.

Because the air surrounding the food does not need to be heated, IR cooking equipment can be more compact with more precise temperature control (Sheridan and Shilton, 1999).

Infrared radiation is generally viewed as an advantageous cooking method but there are also several major disadvantages when using IR. Unless the IR wavelengths emitted are wavelengths best absorbed by the particular food, heating may be very inefficient (Sheridan and Shilton, 1999). Inefficient heating can cause excessive surface heating and crust formation. The best IR wavelength range for any food, or the range which gives the greatest penetration depth, depends on the optical properties of the food, which change depending on degree of baking and the wavelength used (Skjöldebrand et al., 1988). Few studies have been done on the optical properties of any food and the optical properties that have been found are only applicable to the specific food studied. There is currently no universal formula to calculate the optical properties of any food. Determining the correct IR wavelength range to produce a quality food product requires a “cook and look” method, which is time-consuming and can be expensive. The lack of available optical property data is major disadvantage of using IR to cook foods.

#### *2.3.5. Infrared frying*

The use of IR in frying has been studied by several researchers (August, 1991; Petelle et al., 1995; Durance and Liu, 1997; Fosb et al., 1998; Komai and Imamura, 2005). Many of the studies have examined heating of foods by radiant heat without oil in an attempt to produce a product comparable to that of a fried product, such as potato chips (Durance and Liu, 1997; Petelle et al., 1995; Fosb et al., 1998) or other vegetable chips (Fosb et al., 1998),

French fries (Lloyd, 2003), and pastry products (Lentz et al., 1995; Komai and Imamura, 2005). The foods cooked by radiant heating, such as potato chips (August, 1991), were often reported as dry and tough in comparison to the fried products. However, Lloyd (2003) developed a process to finish frozen, partially-fried French fries in an IR oven that was able to produce French fries that had similar acceptability to fully-fried French fries. It is possible that partially frying food before cooking with IR improves the palatability of the finished product. Another issue in using IR to produce fried-like products is that the required heat flux and times for foods are reported on a per-food basis and cannot be easily adapted for different foods. More research on the overall process of cooking by IR needs to be completed to properly utilize IR as part of a frying process.

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## **Chapter 3: General Materials and Methods**

This chapter discusses infrared (IR) oven design and setup, measurement of heat flux in the oven, oscillatory testing on wheat and gluten-free (GF) dough, and a method of scoring all donuts in comparison to the wheat control. Materials and methods used for producing and testing all donuts are discussed in their respective chapters.

### 3.1. IR oven setup

The IR oven had five pairs of emitters placed above and below a continuous belt (Figure 3.1). The emitters were 500 W quartz-halogen glass bulbs (type T3, General Electric, Cleveland, OH) containing a tungsten filament with a 120 mm lighted length. Emitters were placed with the filament perpendicular to the movement of the belt. Heat flux from the emitters was controlled by varying the voltage to the emitters; each emitter was set to 115 VAC, the maximum power. Metal reflector plates were positioned 5 mm above the top emitters and 5 mm below the bottom emitters to increase the heat flux delivered to the food. A stainless-steel mesh belt was used in the oven, allowing energy from the bottom emitters to cook the underside of the donuts as they traveled along the belt. The speed of the belt was controlled by setting the DC voltage to the belt drive motor. A voltage-time curve was constructed from data gathered from preliminary experiments. The equation relating voltage to residence time was found to be:

$$t = 5117V^{-1.10} \quad (R^2=0.9997) \quad (3.1)$$

where  $t$  is residence time in seconds and  $V$  is voltage in volts. This allowed the voltage settings to be converted to IR-finishing time measurements. Emitter heights ( $h_1$ ,  $h_2$ , etc.) were taken to be the distance from the belt to the bottom of the top emitters. The distance

from the belt to the bottom emitters was held constant at 25 mm. The distances between each set of emitters were also held constant (Figure 3.1).

### **3.2. Heat flux measurements**

Heat flux provided by the emitters in the oven was measured using a water-cooled radiometer (model 9000, Vatell Inc., Blacksburg, VA.). The top set of oven emitters were rotated 90 degrees so they were perpendicular to the belt. This enabled the radiometer to measure the flux of the emitters as it traveled along the belt. The bottom set of emitters was covered by a metal sheet to enable the radiometer to measure only the flux from the top set of emitters. The radiometer was attached to a metal stand and adjusted so that the flux sensor was level with the center of the emitters. The stand with the radiometer was placed on the belt of the IR oven and allowed to travel through the oven, measuring the flux from the emitters as it did so. The residence time of the radiometer in the oven was 106 s. Flux measurements were taken with the emitters set at four different distances from the radiometer (Table 3.1). All measurements were conducted in triplicate.

### **3.3. Oscillatory testing**

Oscillatory testing was conducted using a StressTech rheometer operating in controlled stress mode. A smooth cup 26.5 mm in diameter and 65 mm in height, and a vane 13.55 mm diameter and 37.1 mm in height were used in the testing. The machine was calibrated before each use. Wheat and GF dough were prepared using the formulations used for the wheat donuts and the Trial GF8 formulation, respectively (Melito, 2009). The dough

was prepared in the same manner as for the donuts, but was not proofed before testing. A 30 g sample of dough was placed in the cup. The cup was placed into the apparatus and the vane was lowered slowly into the dough until the top of the vane was level with the surface of the dough. The dough was then allowed to rest for five minutes at 27 °C.

The samples were first tested for the linear viscoelastic region (LVR) by using a stress sweep of 0.1 to 1000 Pa at a frequency of 1.0 Hz. The wheat dough was used for these tests, as it was the softer dough. A temperature ramp was then performed to examine the changes in complex modulus ( $G^*$ ), storage modulus ( $G'$ ), loss modulus ( $G''$ ), and phase angle during baking. The temperature of the cup was increased from 27 °C to 100 °C over a period of 5 minutes, then decreased from 100 °C to 80 °C over a period of 10 minutes. This temperature ramp was found to cause the dough to have a similar temperature profile to the temperature profile found during frying. Measurements were collected in triplicate.

### **3.4. Donut scoring matrix**

To determine which GF and par-fried, IR-finished donuts were most instrumentally and sensorially similar to the wheat control, data for each par-fried, IR-finished donut were scored on the basis of statistical similarity to the wheat control. The GF par-fried, IR-finished donuts were also scored based on the GF control to show which GF par-fried, IR-finished donuts were most similar to the GF control. This scoring system was developed to more easily compare and draw conclusions from the data collected.

There were two separate scores calculated for each donut for each control used as a scoring basis. The first score calculated was the overall score, which included all 15

instrumental measurements: percent mass change, percent volume change, percent density change, core temperature,  $L^*$ ,  $a^*$ ,  $b^*$ , percent moisture, percent fat, force to puncture the crust, hardness 1 (H1), hardness 2 (H2), cohesiveness, springiness, and chewiness. For each measurement, if the par-fried, IR-finished donut was statistically similar to the wheat control, a score of 1 was given; if the two were significantly different, a score of 0 was given. The only exceptions to this scoring system were with moisture and fat content. Because a lower fat content was desirable, the par-fried, IR-finished donuts received a score of 1 if the fat content was significantly lower than the wheat control and 0 otherwise. A relatively high moisture content was also desirable, as moisture content and fat content have been shown to be negatively correlated (Shih et al., 2001; Kassama and Ngadi, 2005; Tan and Mittal, 2006). The par-fried, IR-finished donuts received a score of 1 if the moisture content was statistically similar or greater than the moisture content of the wheat control and 0 otherwise. The scores for each measurement were then totaled for a final overall score. The maximum possible score was 15.

Though this overall score gave a good idea of which par-fried, IR-finished donuts were most similar to the wheat control, some of the instrumental measurements were considered more important than others in determining the degree of similarity to the wheat control. For example, the similarity of the mechanical measurements (force to puncture crust, H1, H2, etc.) was considered more important than the similarity of final core temperatures. Therefore, a second score was calculated using only the results of percent volume change,  $L^*$ , percent fat, force to puncture the crust, H1, H2, cohesiveness,

springiness, and chewiness. Scoring was carried out in the same manner as detailed in the paragraph above. The maximum possible score was 9.

### **3.5. Statistical analysis**

All data for the donut scoring matrix were analyzed using SAS 9.1.3 (SAS Institute Inc., Cary, NC). Analyses of variance were performed using the ANOVA procedure in SAS. Analyses of variance were run on both the three individual data groups (wheat par-fried, IR-finished donuts; GF fully-fried donuts; and GF par-fried, IR-finished donuts) and all data combined. Instrumental and sensory data were run separately. Tukey's HSD test was used to determine differences ( $p \leq 0.05$ ) among data groups. Correlations between instrumental results were also determined using SAS.

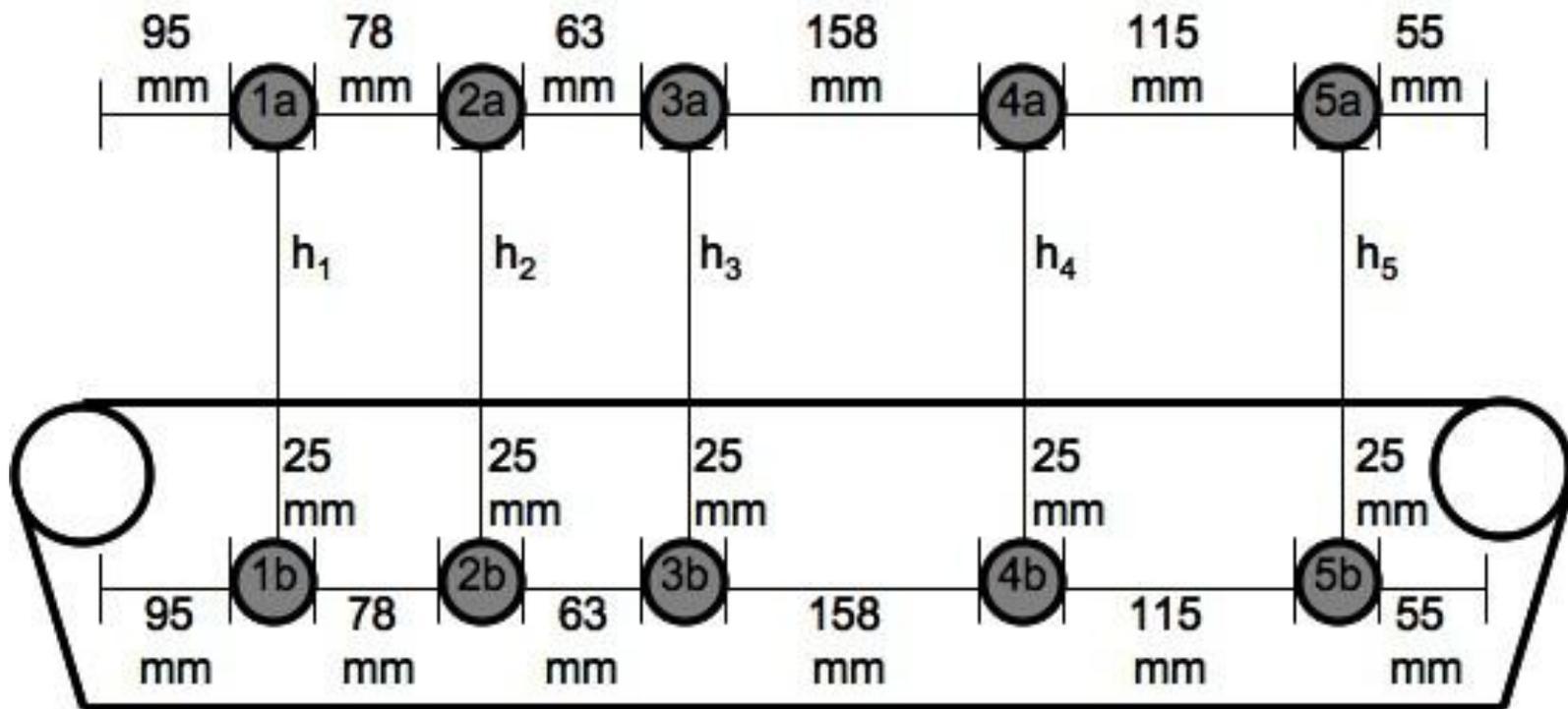
### **3.5. References**

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**Figure 3.1. Infrared oven emitter spacing and heights**

Note: Small gray circles above and below the belt denote the emitters. The belt in the diagram moves in a clockwise direction.

**Table 3.1. Emitter settings for heat flux measurements**

<b>Trial</b>	<b>Emitter distances (mm)</b>	<b>Oven residence time (s)</b>
1	$h_1: 55, h_2: 55, h_3: 55, h_4: 55, h_5: 55$	106
2	$h_1: 60, h_2: 60, h_3: 60, h_4: 60, h_5: 60$	106
3	$h_1: 50, h_2: 50, h_3: 60, h_4: 70, h_5: 70$	106
4	$h_1: 70, h_2: 70, h_3: 60, h_4: 50, h_5: 50$	106

Note: Emitter distances are the distance from the radiometer sensor face to the edge of the emitter.

## **Chapter 4: Process parameters for producing partially-fried, infrared-finished donuts**

#### 4.1. Abstract

There is an increasing demand for lower-fat versions of fried products due to rising health concerns of obesity and obesity-related diseases. Infrared (IR) radiation is able to simulate the heat flux created during the frying process, creating a product with a fried-like texture but a lower fat content. The objective of this study was to determine the process parameters needed to produce partially- (par-) fried, IR-finished yeast donuts that have instrumental and sensorial properties similar to fully-fried yeast donuts. Donuts were par-fried for 64 s and finished in an IR oven. Two different IR cooking times (45 s or 53 s) and four different distance combinations from the IR emitters to the food were tested. Mass, volume, and density changes, percent moisture and fat, crust color, and mechanical properties of the par-fried, IR-finished donuts were compared to a fully-fried control. Sensory testing was also performed using a 9-point hedonic scale (1: dislike extremely, 9: like extremely) to measure overall acceptance, aroma, taste, and texture/mouthfeel.

Statistical analysis ( $\alpha=0.05$ ) showed that all par-fried, IR-finished donuts had a significantly lower fat content (25.6%-30.6%) than the control (33.7%). Several IR-finished donuts had significantly firmer crust and crumb than the control. Setting the emitters with a height gradient from 70 mm to 50 mm or a constant height of 60 mm above the belt in the IR oven and using either IR-finishing time produced donuts that were the most instrumentally similar to the control. Overall acceptance scores of the par-fried, IR-finished donuts showed no significant differences from the control, 5.28-5.85 versus 5.83, respectively. In general, all sensory scores of the par-fried, IR-finished donuts were similar to fully-fried donuts. The only exception was a lower appearance score for one group of par-fried, IR-finished donut

compared to the control, 5.69 versus 6.57, respectively. The lower score may be due to the paler crust color of the donut as compared to the other donuts. Based on these results, infrared radiation may be used to finish par-fried donuts, yielding a product similar to a fully-fried donut but with significantly lower fat content.

## 4.2. Introduction

Fried foods are enjoyed worldwide due to their palatable texture and taste (Guallar-Castillón et al., 2007). Americans in particular consume large amounts of fried food, whether it is with a meal, such as chicken nuggets, French fries, and other fast-food products, or for a snack, such as potato chips. However, fried foods tend to have high fat and saturated fat content and are energy dense rather than nutrient dense. The rising prevalence of overweight and obesity in America is often attributed to the increased consumption of fast foods and fried foods (Nawar, 1998). With 66% of the American population considered overweight and 50% of those who are overweight considered obese (National Center for Health Statistics, 2006), obesity-related diseases such as cardiovascular disease, hypertension, and Type II diabetes, have become a major health concern (Nicklas et al., 2001). This has caused many consumers to become more health conscious, resulting in an increased demand for foods with the same texture and taste of fried foods but with a lower calorie and fat content.

There are several ways to lower fat content in deep-fried foods. One method is to change or add ingredients of the food to reduce oil uptake during and after frying. Ingredients that have decreased hydrophobicity, such as rice flour, or physically block oil from entering the food during cooking, such as methylcellulose, have been used to produce deep-fried foods with significantly lower oil content than foods made without these additions or substitutions (Annapure et al., 1999; García et al., 2004). Another method to reduce fat content is to partially fry the food and finish cooking using another method, such as convective or infrared (IR) heating. Provided that the correct processing parameters are

used, using this method can yield products with the crisp, crunchy crust and soft interior of a fully-fried product, but with a significantly lower fat content than the fully-fried product.

To develop a method to lower fat content in fried foods, it is important to understand how heat and mass are transferred during frying, particularly if frying is partially or completely replaced with another heating method. Frying is a common process that produces foods with a crisp, crunchy crust and a soft interior. This is largely due to the heating profile of foods during frying. After a food is placed in a deep fryer, the heat flux provided to the food rapidly increases to a peak of about  $30,000 \text{ W/m}^2$ , then decreases as cooking progresses. Moisture present on the surface of the food vaporizes and evaporates, drying the surface and causing crust formation. As cooking progresses, the crust continues to dry and thicken (Farkas and Hubbard, 2000). The drying results in a crust with a porous structure, allowing oil to enter the food and ultimately increasing the fat content of the food (Mellema, 2003).

Infrared heating as a replacement for deep-frying has not been extensively studied; it has mainly been used for pasteurization, drying, thawing and baking (Sakai and Hanzawa, 1994; Krishnamurthy, 2008). Infrared heating is of particular interest because of its ability to provide a high heat flux that can be easily and rapidly controlled. This allows the heat flux profile found in frying to be duplicated. Lloyd (2003) developed a process that used IR heating to reproduce the heat flux of frying. This process was able to produce French fries that were instrumentally and sensorially comparable to fully-fried French fries. In addition, the par-fried, IR-finished French fries had significantly lower fat content than fully-fried French fries: 13.0% versus 19.2%, respectively (Lloyd, 2003).

Because IR heating has been successfully used to create a fried-like texture and taste in potatoes, it is desirable to investigate the use of IR heating to cook other fried products, such as donuts. Donuts, which are traditionally deep-fried, are a popular breakfast and snack food. However, they tend to be high in fat. The fat content of yeast donuts has been reported to range from 10% to 36% (Tan and Mittal, 2006); fat provides 50% of the total calories in several popular brands of donuts (Krispy Kreme, 2007; Calorie-count, 2007). Entenmann's<sup>®</sup> glazed donuts have about 15 g of fat per 64 g serving (23 % fat) (Calorie-count, 2007) and Krispy Kreme<sup>®</sup> glazed donuts have about 12 g of fat per 52 g serving (23% fat) (Krispy Kreme, 2007). Most of the fat in donuts is from oil absorbed during frying. Research on fat reduction in donuts has generally focused on donut composition with little work done on changing processing. The objective of this study was to determine the combination of par-frying and IR parameters that produced the highest quality wheat donut, as compared to a traditionally fried wheat donut, by instrumental and sensorial analysis. Developing IR processing parameters to produce donuts allows for the production of a healthier food item. Comparing donuts produced by both heating treatments allows for an increased understanding of the impact of IR heating on the physical and sensorial properties of foods.

### **4.3. Materials and Methods**

#### *4.3.1. Donut preparation*

Donuts were formulated (Table 4.1) using an adaptation of a recipe from Sultan (1969). All ingredients were purchased from a local supermarket (Harris Teeter, Raleigh, NC).

Dough was prepared by hand-mixing the sugar, salt, nonfat dry milk powder, and shortening in a mixing bowl. Yeast and the water for the yeast (35°C) were mixed together separately and allowed to sit for 5 minutes. Egg was added to the shortening and combined with the dry ingredients, followed by the water. Vanilla extract was then added and blended in. In a separate beaker, the wheat flour was combined with baking powder, then blended into the other ingredients until moistened. Lastly, the yeast mixture was added. The mixture was kneaded to form a dough, covered lightly in wheat flour to prevent sticking, and rolled out on waxed paper to a thickness of 9 mm. The dough was then cut into squares approximately 50 mm on each side and allowed to proof (30 minutes, 27°C).

#### *4.3.2. Donut frying*

Proofed donuts were fried in a deep-fryer (Rival, model 3, Arpt, KS) containing 1.5 L of vegetable oil (soybean oil, ConAgra) heated to 182°C. Fully-fried control donuts were fried for 70 s on each side for a total of 140 s of frying time, then removed from the fryer and allowed to cool on paper towels. Par-fried donuts were fried for 32 s on each side for a total of 64 s of frying time, then immediately transferred to the conveyor belt of an IR oven (Melito, 2009). Emitter heights and residence times varied for each trial (Table 4.2). The average thickness of the donuts entering the IR oven was about 25 mm. Donuts were immediately removed from the conveyor belt at the end of IR heating and placed on paper towels.

### *4.3.3. Instrumental measurements*

#### 4.3.3.1. Temperature measurement

Temperature measurements were taken with a thermocouple (Omega model HH21) by placing the probe into the center of each donut immediately after cooking was completed. The probe was inserted into at least three points in the donut to obtain an accurate temperature measurement.

After temperature measurements were completed, donuts were allowed to cool on paper towels for approximately 30 minutes. Mass and bulk volume measurements were performed immediately after the donuts had cooled. Donuts used for color and texture analysis were placed in Ziploc bags and stored at 23°C for 24 hours. Donuts used for moisture and fat analysis were placed in Ziploc bags and stored in a commercial freezer (Frigidaire) at -30°C. All trials were run in triplicate.

#### 4.3.3.2. Donut mass and volume measurement

Donuts were weighted before and 30 minutes after frying to the nearest 0.01 g. Percent mass change was then calculated (Eqn. 4.1). Donut bulk volume was measured using the rapeseed displacement method (AACC International, 2000). Bulk volume measurements were performed on both finished donuts and unproofed dough samples to determine percent volume change (Eqn. 4.2). Bulk density before and after frying was calculated from the resulting mass and volume measurements to determine percent density change (Eqn. 4.3).

$$\% \Delta m = \left( \frac{m_f - m_i}{m_i} \right) 100\% \quad (4.1)$$

$$\% \Delta V = \left( \frac{V_f - V_i}{V_i} \right) 100\% \quad (4.2)$$

$$\% \Delta \rho = \left( \frac{\frac{m_f}{V_f} - \frac{m_i}{V_i}}{\frac{m_i}{V_i}} \right) 100\% \quad (4.3)$$

where  $m_f$  and  $V_f$  are the final mass (g) and bulk volume (mL), respectively, of the donut,  $m_i$  and  $V_i$  are the initial mass (g) and bulk volume (mL), respectively, of the donut, and  $\Delta m$ ,  $\Delta V$ , and  $\Delta \rho$  are the mass (g), bulk volume (mL), and bulk density change (g/mL) of the donut, respectively.

#### 4.3.3.3. Donut crust color measurement

Crust color of the cooled donuts was measured 24 hours after cooking using a colorimeter (HunterLab, model D25LDP9000). The colorimeter was calibrated with black and white plates before each use. Donuts were placed in Pyrex petri dishes (Corning) and set on the viewport of the colorimeter.  $L^*$  (light to dark),  $a^*$  (red to green), and  $b^*$  (yellow to blue) values were recorded for each donut. At least three measurements were taken per sample to obtain representative color values.

#### 4.3.3.4. Donut moisture and fat content measurements

Donuts used for moisture and fat content were removed from the freezer and allowed to reach room temperature before sample preparation. Donuts were ground in a coffee grinder (Braun KSM2, 2.5 oz capacity). Two donuts (approximately 60 g of sample) were ground together for each sample. About 8 g of each ground sample were weighed out into aluminum dishes (Fisherbrand cat. no. 08-732-5C) and dried in a forced air oven (Fisher Isotemp forced draft oven) at 105°C for to constant weight ( $\pm 0.02$  g; approximately 3.5 hours) (Rimac-Brncic et al., 2004).

Approximately 3 g of each dried sample were weighed into 33 mm x 94 mm cellulose thimbles (Whatman) for fat extraction. Fat content was determined by soxhlet extraction (Bouchon et al., 2003).

#### 4.3.3.5. Donut mechanical measurements

Mechanical measurements were performed on a Universal Testing Machine (Instron model 5542, Norwood, MA). Because sensory testing was performed on the donuts approximately 24 hours after cooking and because most donuts are not sold right after cooking is completed, mechanical analysis was performed 24 hours after cooking to obtain results that were more indicative of what panelists, and consumers in general, would be sampling. The force to puncture the crust was measured with a one-cycle punch test using a 3 mm diameter probe with a crosshead speed of 100 mm/s (Vélez-Ruiz and Sosa-Morales, 2003). Crumb properties were determined using a modification of the method used by Tan and Mittal (2006). A cylinder 8 mm in diameter was cut from the center of each donut. The

crust was removed from either end of the cylinder and the sample was trimmed to 16 mm in height. Hardness 1 and 2 (H1 and H2, or the force to compress the cylinder to 50% of the original height for the first and second compressions, respectively), cohesiveness (area under first force curve divided by area under second force curve), springiness (time to peak force on the second curve divided by time to peak force on the first curve), and chewiness (H1 multiplied by cohesiveness multiplied by springiness) were then measured on the cylinders with a 2-cycle compression test (compressing the sample to 8 mm each cycle) using a 1 kN load cell at a crosshead speed of 100 mm/s.

#### *4.3.4. Sensory testing*

Sensory testing was conducted on the North Carolina State University campus and was approved by the University's Institutional Review Board. Panelists were students, faculty, and staff of the university. Panelists were recruited by fliers advertising panel dates and free treats for participation. Panelist participation was strictly voluntary. Only individuals with wheat allergy or sensitivity were not allowed to participate in the panels, as a sample containing wheat was present in all sensory panels.

Because there were eight different groups of par-fried, IR-finished donuts, testing all of the par-fried, IR-finished donuts was considered impractical due to possible panelist fatigue. Therefore, donuts chosen for sensory testing were selected to cover the range of instrumental results measured for all parameters. Five different donuts were used in sensory testing. Four of the donuts were made using the parameters for Trials 1, 2, 4, and 8 (Table

4.2) and the fifth donut, the control, was a fully-fried wheat donut. A total of 99 panelists (71 females and 28 males) between the ages of 18 and 65 participated in testing.

All donuts tested were made the day before the panel, cooled, placed in Ziploc bags, and stored overnight at room temperature. Each sample was assigned a randomly generated 3-digit code.

All donut samples were served warm to address product limitations and consumer preferences. Sensory data from the donuts tested were later compared to sensory data from gluten-free donuts that were also served warm. It was necessary to present all donuts in the same manner to prevent confounding effects from donut presentation. Gluten-free baked products stale very rapidly even with stabilizers and preservatives. Because of this, many manufacturers instruct consumers to reheat the product for a short time (less than 1 minute) before eating to increase the palatability of the product. In addition, certain donuts, such as those produced by Krispy Kreme<sup>®</sup>, are meant to be eaten warm and sold with reheating instructions. Beignets, or fried pastry served with powdered sugar, are similar in formulation to the donuts produced and are also served warm. Therefore, it was decided that the donuts should be served to the panelists in the manner of beignets: warm (54°C internal temperature) with confectioner's sugar sprinkled on top.

During the panel, donuts were reheated on aluminum foil-covered metal baking trays for 2.5 minutes in a convection oven heated to 163°C, then transferred to a warming oven heated to 60°C. Donuts were allowed to remain in the warming oven for a maximum of 30 minutes; donuts remaining in the oven after 30 minutes were discarded. Samples were prepared by slicing each donut in half and placing one half cut side down on a divided,

prenumbered Styrofoam tray. Each tray had 5 sections; the sections were labeled with sample codes in a random order and one sample was placed in each section. After the donuts were placed on the tray, they were sprinkled with confectioner's sugar and immediately given to a panelist or placed in the warming oven for a maximum of 5 minutes before discarding. Preliminary testing was performed to ensure that the donuts did not cool significantly during sampling.

Panelists were asked to evaluate each sample using a 9-point hedonic scale, with 1 being "dislike extremely", and 9 being "like extremely". Overall acceptance was rated first, followed by appearance, aroma, flavor, and mouthfeel/texture. Panelists were also asked to comment on what they liked and disliked about each sample. In addition, panelists were asked several demographic questions: age, gender, shopping responsibility, donut consumption and purchase frequency, and factors that affected donut purchases. Panelist responses were collected and analyzed via Compusense *five* (Compusense Inc., Ontario, Canada).

#### 4.3.5. *Statistical analysis*

All data were analyzed using SAS 9.1.3 (SAS Institute Inc., Cary, NC). Analyses of variance were performed using the ANOVA procedure in SAS. Instrumental and sensory data were run separately. Tukey's HSD test was used to determine differences ( $p \leq 0.05$ ) among data groups. Correlations between instrumental results were also determined using SAS.

## 4.4. Results and Discussion

### 4.4.1. Mass, volume, and density changes

All par-fried, IR-finished donuts had significantly ( $p \leq 0.05$ ) lower change in mass than the control (Table 4.3). During frying, moisture is lost from the donut due to evaporation while oil is absorbed into the crust (Bouchon et al., 2003; Shih et al., 2005). As frying time increases, oil uptake and moisture evaporation increase (Tan and Mittal, 2006). Donuts that are fried for a shorter period of time have been shown to have lower oil uptake and moisture loss than donuts fried for a longer period of time at the same temperature (Vélez-Ruiz and Sosa-Morales, 2003). Because mass change is dependent on oil uptake and moisture loss, lower moisture loss and oil uptake results in lower mass change. Since the par-fried donuts were fried for only 64 s compared to the control, which was fried for 160 s, they had lower oil uptake and higher moisture content than the control. Therefore, the shorter frying time was likely the cause of the smaller change in mass of the par-fried, IR-finished donuts. No trends were found between change in mass and IR oven parameters.

All par-fried, IR-finished donuts had statistically similar ( $p \leq 0.05$ ) volume and density changes (Table 4.3) to the control (34% and -22%, respectively), indicating that IR-finishing most likely did not adversely affect final volume. Setting the emitters at 70, 70, 60, 50, and 50 mm above the belt gave the largest percent volume increase and percent density decrease, 61% and -34%, respectively, for an IR residence time of 53 s. Setting the emitters at 50, 50, 60, 70, and 70 mm above the belt gave the lowest percent volume increase and percent density decrease, 14% and -8.0%, respectively, for an IR residence time of 53 s. Percent volume and density changes did not appear to be correlated with IR oven parameters.

However, finished volume and density had a relatively high standard deviation, probably due to variable humidity during proofing, so there may be confounding factors in these results.

#### *4.4.2. Core temperature*

The core temperatures (Table 4.3) of the par-fried, IR-finished donuts (72.2 to 90.8°C) were statistically similar to the control (94.1°C), with the exception of the par-fried, IR-finished donuts from Trial 2 (73.7°C) and Trial 6 (72.2°C). Wheat starch gelatinizes at 70°C (Lelievre, 1973), so an internal temperature at or above the gelatinization temperature indicated completion of cooking. Core temperature increased with increased IR oven residence time. However, this increase was only significant ( $p \leq 0.05$ ) in donuts from Trial 5 (90.8°C) and Trial 6 (72.2°C). Core temperature was also affected by heat flux provided in the first half of IR-finishing: as the heat flux increased, core temperature generally increased.

#### *4.4.3. Oil and moisture content*

In general, moisture content (Table 4.3) of the par-fried, IR-finished donuts was significantly ( $p \leq 0.05$ ) higher than the control. The donuts that did not have higher moisture content than the control (23.3%) were the donuts from Trial 5 (23.1%). All other par-fried, IR finished donuts had moisture contents ranging from 24.9% to 26.1%. Donuts from Trial 5 were exposed to a relatively high flux throughout cooking (13.1 to 24.3 kW/m<sup>2</sup>) and the highest flux in the first half of IR-finishing (18.9 to 24.3 kW/m<sup>2</sup>) (Figure 4.1). In addition, they had a longer IR residence time (53 s). The high heat flux combined with a longer IR-finishing time could have caused increased surface drying, resulting in a higher rate of

moisture migration and evaporation and thus lower moisture content. Donuts from Trial 6 also had a relatively low moisture content; these donuts were made with the same emitter settings as the donuts in Trial 5 but a lower IR residence time (45 s). The lower residence time may have reduced the extent of drying, resulting in higher moisture content.

All par-fried, IR-finished donuts had significantly ( $p \leq 0.05$ ) lower fat content (Table 4.3) than the control, 25.6% to 30.6% compared to 33.7%, respectively. Although the par-fried, IR-finished donuts were all fried for the same period of time and it was assumed that no oil was gained or lost in the IR oven, the donuts did not have statistically similar fat contents. However, oil was observed to be continually dripping off of the donuts during IR-fining, although a quantitative measure of this drip loss was not conducted. In addition, fat content of the donuts generally decreased with increased heat flux in the second half of IR-fining. A high heat flux in the second half of IR-fining may have kept the oil on the surface of the crust hotter than a lower flux, decreasing the viscosity of the oil enough such that it could easily drip off of the donut as the donuts traveled along the belt. It is recommended that the relationship between IR heat flux and fat content be further investigated to provide a more thorough explanation for these results.

#### 4.4.4. Crust color

The majority of surface browning occurred during IR-fining, as indicated by the significantly ( $p \leq 0.05$ ) higher  $L^*$  value of the donut that was par-fried without being finished by IR (Table 4.3). The  $L^*$  value of the donuts that were par-fried but not IR-finished was 55.5, compared to the par-fried, IR-finished donuts that had  $L^*$  values ranging from 33.4 to

45.0. The extent of crust darkening depended on IR oven residence time (Figure 4.2): for each emitter setting, donuts made with a lower residence time (45 s) had higher L\* values, indicating that they were lighter. Although this difference was not statistically significant, there was a visual (qualitative) difference in crust color. The b\* values of the par-fried, IR-finished donuts also followed this trend (Figure 4.4), while the a\* values decreased with increased IR oven residence time (Figure 4.3). Again, this difference was generally not statistically significant. L\* values of the par-fried, IR-finished donuts were positively correlated to the b\* values ( $R^2=0.83$ ,  $p<0.0001$ )

The total amount of flux provided by the emitters (Figure 4.1) also affected crust color values. Generally, as the amount of flux increased, the L\* and b\* values decreased while the a\* values increased. Heat flux provided by the first three emitters (the first half of cooking in the IR oven) (Figure 4.1) appeared to affect crust color, particularly the L\* and b\* values. In general, as the overall heat flux provided by these three emitters increased, the L\* and b\* values decreased. The data showed that crust color was determined not only by the overall heat flux but also by when in the cooking process that flux was provided. In general, increased heat flux and IR oven residence time resulted in increased crust darkening. Red and yellow hues increased with increased overall heat flux and increased IR oven residence time, respectively.

#### 4.4.5. *Mechanical properties*

Mechanical properties (Table 4.4) of the par-fried, IR-finished donuts depended on IR treatment. In general, the control donut had a softer crust and crumb than the par-fried, IR-

finished donuts, although the force to puncture the crust was statistically similar ( $p \leq 0.05$ ) to the control (0.774 N) for donuts from Trial 3 (1.36 N), Trial 4 (1.08 N), Trial 6 (1.42 N), Trial 7 (1.44), and Trial 8 (1.18). Infrared radiation generally does not penetrate farther than about 18 mm into the food (Krishnamurthy et al., 2008). This results in a concentration of IR energy near the food's surface, resulting in the surface of the food heating more quickly during IR heating than during frying. Faster surface heating causes faster surface drying, which produces a harder crust. Crust hardness was highest in Trials 1, 2, 5, and 6; donuts from these trials were exposed to a relatively high heat flux (22.6 to 24.5 kW/m<sup>2</sup> for Trials 1 and 2; 18.9 to 24.3 kW/m<sup>2</sup> for Trials 5 and 6) in the first half of IR-finishing (Figure 4.1). Donuts in Trials 1 and 2 were also exposed to a relatively high heat flux in the second half of IR-finishing (15.1 to 15.8 kW/m<sup>2</sup>). The higher heat flux most likely produced the harder crust in these donuts.

Donuts from Trial 3, Trial 4, and Trial 7 had statistically similar crumb H1 values (3.73 N, 2.81 N, and 3.60 N, respectively) to the control (2.63 N). Donuts from Trial 4 (2.64) and Trial 7 (2.91 N) also had statistically similar H2 values to the control (2.11 N). All other par-fried, IR-finished donuts had significantly ( $p \leq 0.05$ ) harder crumb (higher H1 and H2 values) than the control. In general, as the H1 and H2 values increased, the force to puncture the crust increased, indicating that donuts with a harder crust generally had a harder crumb. Crust and crumb hardness also increased with decreased fat content. Fat tenderizes the crumb of baked goods (Bennion and Scheule, 2004), so as fat content decreased, crumb hardness increased. A high core temperature indicates increased heating, which resulted in a dryer, firmer crumb.

The cohesiveness and chewiness of the par-fried, IR-finished donuts were not significantly different ( $p \leq 0.05$ ) from the control, with the exception of the cohesiveness of the donuts from Trial 6 (0.405 compared to 0.573 for the control). Cohesiveness and chewiness of the par-fried, IR-finished donuts ranged from 0.423 to 0.564 and 1.71 to 4.13, respectively, while the cohesiveness and chewiness of the control was 0.573 and 5.01, respectively. The springiness of all par-fried, IR-finished donuts (0.926 to 1.64) was lower than the control (3.48), indicating that the par-fried, IR-finished donuts recovered more slowly from deformation produced by compression. Springiness was found to be positively correlated with chewiness ( $R^2=0.80$ ,  $p < 0.0001$ ). Springiness was used to calculate chewiness, so this correlation was expected. It is possible that the decreased springiness in the par-fried, IR-finished donuts was due to the IR-finishing process.

#### *4.4.6. Sensory evaluation*

All donuts had statistically similar ( $p \leq 0.05$ ) sensory scores (Table 4.5), with the exception of the appearance score of Trial 1 donuts. The appearance score of these donuts (5.28) was significantly lower than the appearance score of the control (5.83). The lower appearance score may have resulted from uneven crust color caused by excessive crust browning. This resulted in a patchy or mottled crust color. Par-fried, IR-finished donuts generally received lower scores for all attributes tested than the control, but the differences were not significant. There were also no significant differences among the scores of the par-fried, IR-finished donuts, aside from the lower appearance score of Trial 1 donuts. These scores indicated that par-fried, IR-finished donuts were as well liked as the control donut.

With overall acceptance scores ranging between 5.28 and 5.85 (neither like nor dislike to like slightly), all par-fried, IR-finished donuts were considered acceptable to the panelists. Panelists commented that donuts were bland or not sweet enough. Applying a glaze or a heavier coating of powdered sugar to the donuts may improve overall acceptance scores of all donuts.

#### **4.5. Conclusions**

All par-fried, IR-finished donuts had significantly lower change in mass than the control, likely caused by the shorter frying time used for the par-fried, IR-finished donuts. Par-fried, IR-finished donuts generally had statistically similar volume and density changes and core temperature to the control, indicating that IR-finishing most likely did not adversely affect final volume or temperature. Moisture content was generally higher and fat content was lower in the par-fried, IR-finished donuts than in the control. Crust color of the par-fried, IR-finished donuts was affected by total amount of flux provided by the emitters and IR oven residence time. The  $L^*$  values of the par-fried, IR-finished donuts were generally similar to the control, but  $a^*$  and  $b^*$  values were significantly different. Par-fried, IR-finished donuts generally had a firmer crust and crumb than the control, possibly due to higher heat flux in the crust region during cooking and a lower fat content. The springiness of the par-fried, IR-finished donuts was lower than the control, although the cohesiveness and chewiness were not significantly different from the control. Sensory scores of all donuts indicated that they were considered acceptable to the panelists. Par-fried, IR-finished donuts generally had statistically similar sensory scores to the control. Based on the instrumental

and sensory results, the IR parameters of the par-frying, IR-finishing process may be adjusted to produce wheat donuts similar to a fully-fried donut but with significantly lower fat content.

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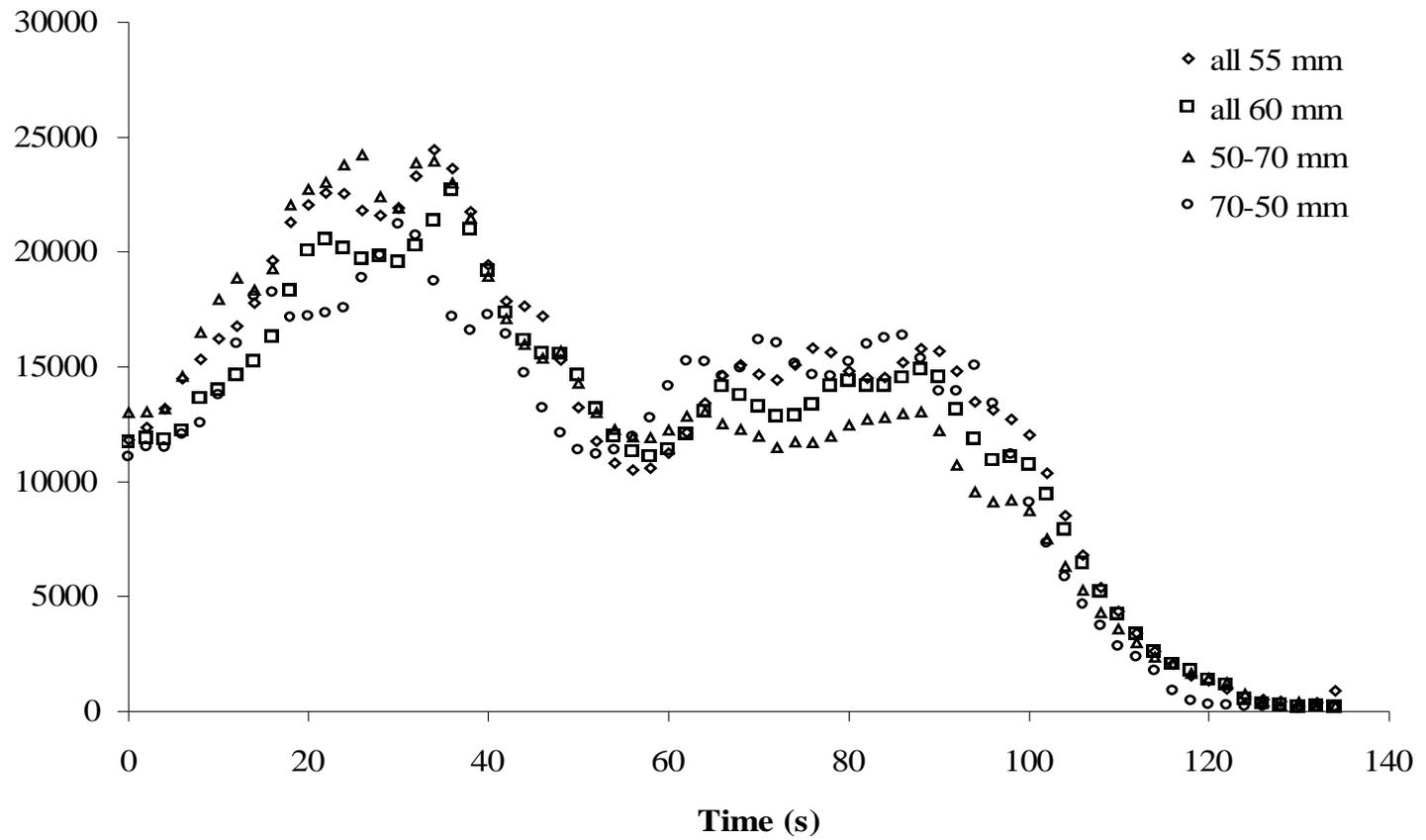
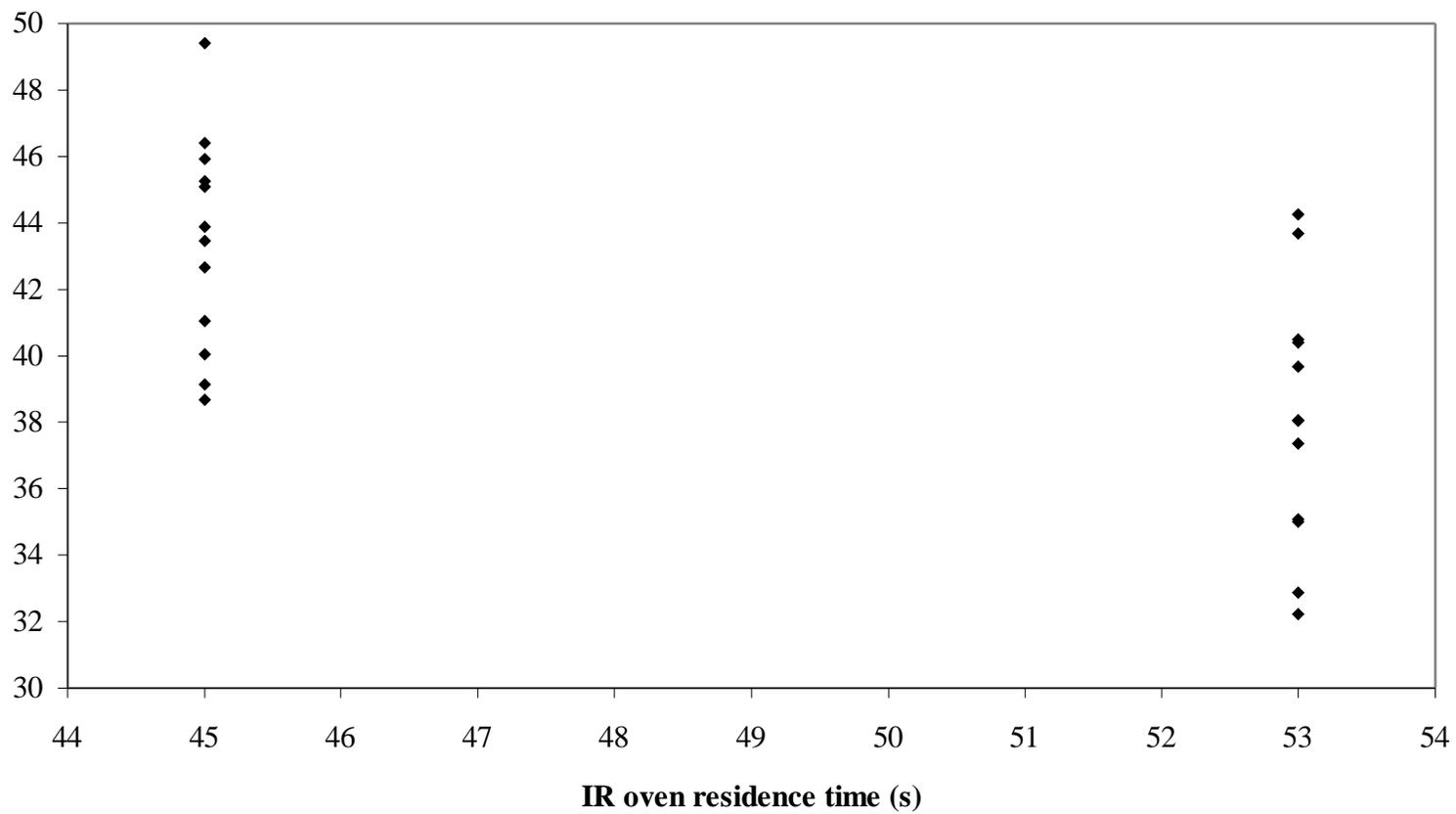
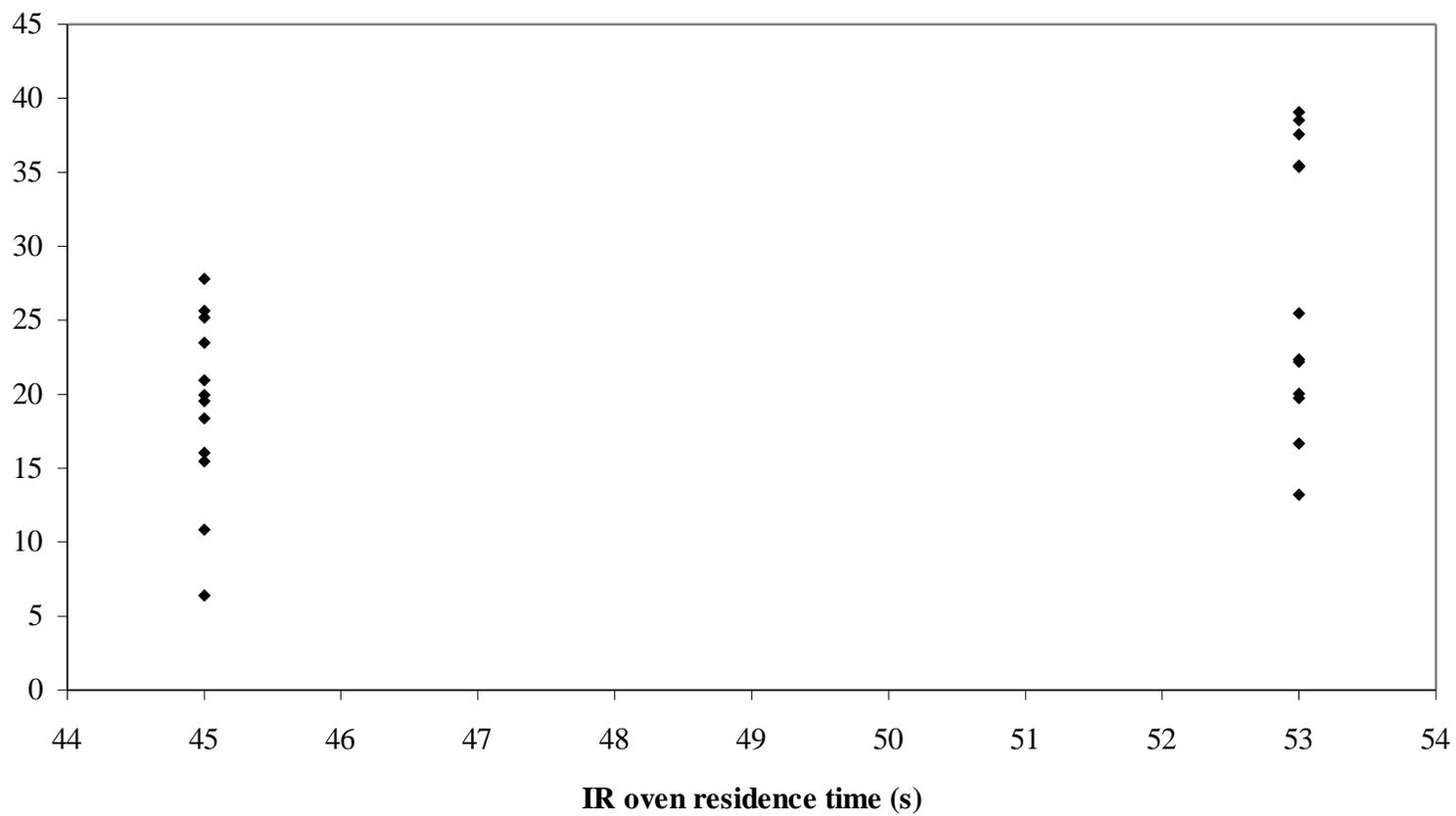


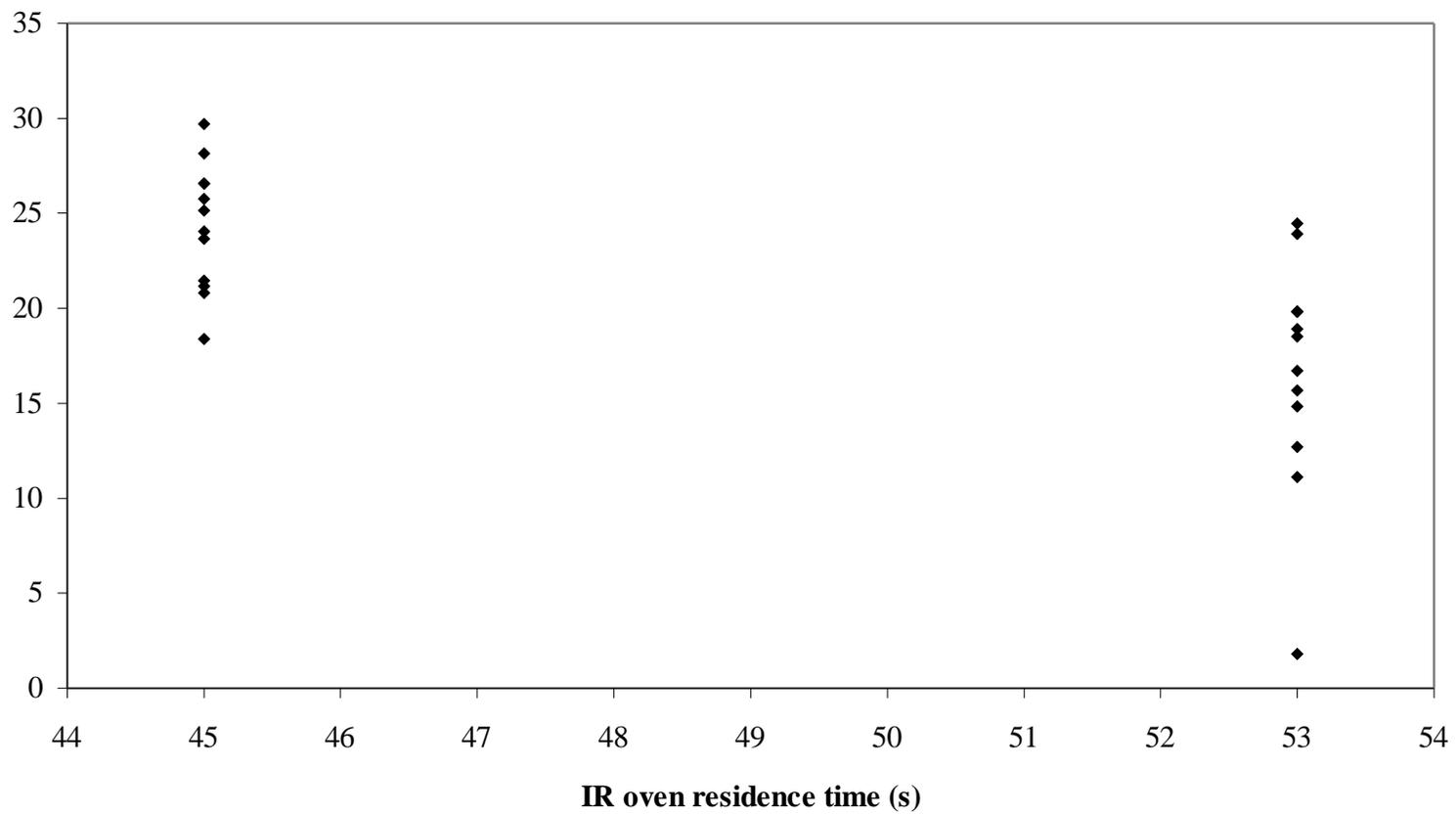
Figure 4.1. Heat flux profiles for emitter settings



**Figure 4.2. Trend in L\* values of wheat par-fried, IR-finished donuts**



**Figure 4.3. Trend in a\* values of wheat par-fried, IR-finished donuts**



**Figure 4.4. Trend in b\* values of wheat par-fried, IR-finished donuts**

**Table 4.1. Wheat donut formulation**

<b>Ingredient</b>	<b>Weight (g)</b>	<b>% weight (wheat flour basis)</b>
Flour	302.4	100%
Water	113.4	38%
Shortening	56.7	19%
Egg	37.8	13%
Water for yeast	37.8	13%
Sugar	18.9	6.3%
Nonfat dry milk powder	18.9	6.3%
Yeast	9.00	3.0%
Salt	4.72	1.6%
Vanilla extract	4.72	1.6%
Baking powder	4.72	1.6%

**Table 4.2. IR oven settings for wheat donuts**

<b>Trial</b>	<b>Emitter heights (mm)</b>	<b>Residence time (s)</b>
1	h <sub>1</sub> : 55, h <sub>2</sub> : 55, h <sub>3</sub> : 55, h <sub>4</sub> : 55, h <sub>5</sub> : 55	53
2	h <sub>1</sub> : 55, h <sub>2</sub> : 55, h <sub>3</sub> : 55, h <sub>4</sub> : 55, h <sub>5</sub> : 55	45
3	h <sub>1</sub> : 60, h <sub>2</sub> : 60, h <sub>3</sub> : 60, h <sub>4</sub> : 60, h <sub>5</sub> : 60	53
4	h <sub>1</sub> : 60, h <sub>2</sub> : 60, h <sub>3</sub> : 60, h <sub>4</sub> : 60, h <sub>5</sub> : 60	45
5	h <sub>1</sub> : 50, h <sub>2</sub> : 50, h <sub>3</sub> : 60, h <sub>4</sub> : 70, h <sub>5</sub> : 70	53
6	h <sub>1</sub> : 50, h <sub>2</sub> : 50, h <sub>3</sub> : 60, h <sub>4</sub> : 70, h <sub>5</sub> : 70	45
7	h <sub>1</sub> : 70, h <sub>2</sub> : 70, h <sub>3</sub> : 60, h <sub>4</sub> : 50, h <sub>5</sub> : 50	53
8	h <sub>1</sub> : 70, h <sub>2</sub> : 70, h <sub>3</sub> : 60, h <sub>4</sub> : 50, h <sub>5</sub> : 50	45

**Table 4.3. Mass, volume, and density change, final temperature, crust color, and moisture and fat content of par-fried, IR-finished donuts as compared to control donuts**

<b>Trial</b>	<b>Mass change (%)</b>	<b>Volume change (%)</b>	<b>Density change (%)</b>	<b>Final core temp (°C)</b>
1	3.07%±0.41% (d)	28%±11% (b)	-19%±7.1% (abc)	81.5±0.4 (ab)
2	4.31%±0.76% (bcd)	18%±6.7% (b)	-11%±5.4% (a)	73.7±0.8 (b)
3	4.43%±0.36% (bcd)	18%±5.6% (b)	-12%±4.6% (ab)	88.0±0.4 (a)
4	6.73%±1.17% (b)	31%±4.8% (ab)	-18%±2.2% (abc)	83.0±1.2 (ab)
5	4.52%±1.04% (bcd)	14%±1.7% (b)	-8.0%±1.7% (a)	90.8±1.0 (a)
6	3.61%±1.09% (cd)	44%±8.2% (ab)	-28%±3.3% (bc)	72.2±1.1 (b)
7	4.54%±0.98% (bcd)	61%±20% (a)	-34%±8.5% (c)	81.9±1.0 (ab)
8	3.74%±0.47% (cd)	34%±17% (ab)	-22%±9.3% (abc)	83.0±0.5 (ab)
CW	10.9%±1.96% (a)	43%±14% (ab)	-22%±6.9% (abc)	94.1±2.0 (a)
WPF	6.39%±0.73% (bc)	33%±2.4% (ab)	-20%±1.3% (abc)	73.4±0.7 (b)

<b>Trial</b>	<b>L*</b>	<b>Crust color</b>		<b>Moisture content (%)</b>	<b>Fat content (%)</b>
		<b>a*</b>	<b>b*</b>		
1	39.7±4.4 (bc)	36.1±1.2 (a)	17.1±2.5 (cd)	25.1%±0.03% (bc)	26.1%±0.14% (e)
2	42.2±3.3 (b)	16.6±1.5 (cd)	23.5±2.0 (bc)	25.5%±0.10% (bc)	26.3%±0.41% (e)
3	38.4±1.2 (bc)	17.4±4.5 (cd)	20.4±3.0 (c)	25.4%±1.12% (bc)	27.2%±0.19% (d)
4	45.0±5.3 (b)	12.4±6.9 (cd)	25.4±6.1 (abc)	25.5%±0.03% (bc)	30.6%±0.20% (b)
5	33.4±1.5 (c)	32.5±10.8 (ab)	8.5±5.9 (d)	23.1%±0.21% (d)	29.0%±0.37% (c)
6	41.7±2.0 (bc)	25.6±2.2 (abc)	22.9±3.1 (bc)	24.9%±0.11% (c)	27.5%±0.06% (d)
7	40.9±3.1 (bc)	22.5±2.9 (bcd)	20.0±4.4 (c)	25.5%±0.08% (bc)	26.0%±0.09% (e)
8	44.8±1.3 (b)	21.9±3.0 (bcd)	25.3±1.5 (abc)	26.1%±0.09% (ab)	25.6%±0.23% (e)
CW	44.3±1.6 (b)	10.5±0.2 (de)	35.3±0.3 (a)	23.3%±0.11% (d)	33.7%±0.55% (a)
WPF	55.5±2.7 (a)	-1.0±0.5 (e)	31.4±0.7 (ab)	26.9%±0.06% (a)	27.7%±0.34% (d)

Note: Trial number indicates the heating treatment for the corresponding number in Table 4.2. CW is the fully-fried wheat control donut and WPF is the donut that was par-fried only. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Table 4.4. Mechanical properties of par-fried, IR-finished donuts as compared to control donuts**

<b>Trial</b>	<b>Force to puncture crust (N)</b>	<b>H1 (N)</b>	<b>H2 (N)</b>	<b>Cohesiveness</b>	<b>Springiness</b>	<b>Chewiness</b>
1	1.66±0.52 (ab)	5.16±0.17 (a)	4.49±0.37 (a)	0.495±0.056 (ab)	1.595±0.52 (b)	4.13±1.77 (a)
2	1.71±0.10 (ab)	5.21±0.59 (a)	4.26±0.30 (ab)	0.423±0.017 (ab)	0.957±0.16 (b)	2.25±0.08 (a)
3	1.36±0.12 (abc)	3.73±0.28 (bc)	3.28±0.22 (bc)	0.564±0.035 (ab)	1.568±0.75 (b)	3.30±1.55 (a)
4	1.08±0.19 (bc)	2.81±0.27 (c)	2.64±0.32 (cd)	0.536±0.026 (ab)	1.349±0.29 (b)	2.10±0.26 (a)
5	1.85±0.30 (a)	4.51±0.35 (ab)	4.13±0.36 (ab)	0.524±0.083 (ab)	1.367±0.18 (b)	2.85±0.38 (a)
6	1.42±0.20 (abc)	5.12±0.36 (a)	4.27±0.16 (ab)	0.405±0.093 (b)	0.926±0.16 (b)	2.42±0.40 (a)
7	1.44±0.20 (abc)	3.60±0.38 (bc)	2.91±0.32 (cd)	0.522±0.049 (ab)	1.643±0.32 (b)	2.83±0.73 (a)
8	1.18±0.19 (abc)	4.47±0.82 (ab)	3.33±0.75 (bc)	0.466±0.068 (ab)	1.284±0.46 (b)	1.71±0.54 (a)
CW	0.77±0.03 (c)	2.63±0.38 (c)	2.11±0.16 (d)	0.573±0.028 (a)	3.482±1.35 (a)	5.01±2.84 (a)

Note: Trial number indicates the heating treatment for the corresponding number in Table 4.2. CW is the fully-fried wheat control donut. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Table 4.5. Sensorial properties of selected par-fried, IR-finished donuts as compared to control donuts**

<b>Trial</b>	<b>Overall acceptance</b>	<b>Appearance</b>	<b>Aroma</b>	<b>Texture</b>	<b>Mouthfeel/ Taste</b>
1	5.28±1.74 (a)	5.69±1.61 (b)	5.97±1.31 (a)	5.41±1.65 (a)	5.16±1.82 (a)
2	5.85±1.53 (a)	6.32±1.40 (a)	6.13±1.28 (a)	5.77±1.55 (a)	5.63±1.76 (a)
4	5.63±1.56 (a)	6.36±1.47 (a)	5.89±1.50 (a)	5.60±1.71 (a)	5.37±1.71 (a)
8	5.43±1.71 (a)	6.55±1.37 (a)	5.95±1.42 (a)	5.44±1.83 (a)	5.18±1.86 (a)
CW	5.83±1.48 (a)	6.57±1.45 (a)	6.16±1.45 (a)	5.77±1.58 (a)	5.80±1.82 (a)

Note: Trial number indicates the heating treatment for the corresponding number in Table 4.2. CW is the fully-fried wheat control donut. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Chapter 5: Physical properties of gluten-free  
donuts made with xanthan gum and  
pregelatinized rice flour**

## 5.1. Abstract

Gluten intolerance and wheat allergy are becoming more prevalent in the American population. Up to 1% of Americans are considered gluten intolerant and wheat is considered one of the eight major allergens. Treatment for either condition is complete avoidance of wheat and gluten-containing products. Several studies have been done on gluten-free (GF) breads but little work has been done on GF fried foods, such as donuts. The objective of this study was to examine the instrumental and sensorial properties of several formulations of GF yeast donuts in comparison to wheat yeast donuts. Four different formulations of GF donuts were tested, each formulation using a different combination of GF flours (commercial GF flour and rice flour) and hydrocolloids (pregelatinized rice flour and xanthan gum). Donuts were fried with and without a methylcellulose coating (0.5 g methylcellulose in 50 g water), which was brushed on before proofing. Mass, volume, and density changes, percent moisture and fat, crust color, and crust and crumb rheological properties of the GF donuts were compared to a control (wheat yeast donut). Sensory testing was also performed using a 9-point hedonic scale (1: dislike extremely, 9: like extremely) to measure overall acceptance, aroma, taste, and texture/mouthfeel.

Statistical analysis ( $\alpha=0.05$ ) showed that 6 out of 8 of the GF donuts had a significantly lower fat content (26.3%-32.2%) than the control (33.7%). Donuts made with a higher ratio of commercial GF flour to rice flour (3:1) were more instrumentally similar to the control than donuts made with an equal ratio of commercial GF flour to rice flour (1:1), regardless of the hydrocolloid used. This was especially true with regard to mechanical properties. Donuts made with a 3:1 ratio of flours had crust color and crust and crumb

hardness similar to that of the control while donuts with 1:1 ratio of flours had significantly lighter crust color and were significantly harder than the control. However, the fat content of donuts made with a 3:1 ratio of flours (31.2-32.7%) was significantly higher than fat contents of donuts made with a 1:1 ratio of flour (26.3-27.2%). All GF donuts received significantly lower overall acceptance scores (4.33-4.68) than the control (6.37), indicating that the GF donuts were not as well liked as the control, possibly due to their dryness. Although the GF donuts were not as sensorially acceptable as wheat donuts, they were instrumentally similar to and had a lower fat content than the wheat control.

## 5.2. Introduction

Food allergies and intolerances are a health concern both in America and worldwide. Gluten intolerance, affecting about 1% of the American population, is an inability to break down wheat gluten proteins, as well as similar proteins found in rye, barley and possibly oats. Consuming these proteins results in the gradual deterioration of the intestinal villi, causing malabsorption of nutrients and other health problems (Schober et al., 2003). Wheat allergy also indicates sensitivity to wheat proteins. When a person with a wheat allergy consumes wheat, there is an IgE-mediated response, stimulating a histamine release and causing a variety of symptoms such as nausea, GI distress, hives, and anaphylaxis. Treatment for both gluten intolerance and wheat allergy is a lifelong avoidance of wheat and wheat-containing products such as commercial soups and sauces. People who are gluten intolerant must also avoid products containing gluten (Hischenhuber et al., 2006). The need to avoid wheat and gluten-containing products has resulted in a demand for commercial wheat- and gluten-free (GF) products. Currently, there are some GF analogs to commonly consumed products, such as bread, cereals, and cookies; however, the texture and taste of these products differs from wheat products and the acceptability is widely variable.

Fried foods are enjoyed worldwide due to their palatable texture and taste (Guallar-Castillón et al., 2007). Americans in particular consume large amounts of fried food, whether it is with a meal, such as chicken nuggets, French fries, and other fast-food products, or for a snack, such as potato chips. However, many fried foods are either breaded or are made from dough containing wheat flour and must be avoided by people with wheat allergy or gluten intolerance. Considerable research has been done on formulating and improving

GF breads, but few studies have examined GF fried products. The studies that are available on fried GF foods have noted that GF flours have significantly lower oil uptake than wheat flour due to differences in the flour proteins (Mohamed et al., 1998; Altunakar et al., 2004; Shih et al., 2004). It was noted that GF flours could be used in battered, fried products or in fried doughs to lower the fat content of the finished product (Mohamed et al., 1998; Shih et al., 2001; Shih and Daigle, 2002; Shih et al., 2005). Hydrocolloids, typically used in GF products to improve the texture and structure, have also been shown to lower fat content in fried foods when incorporated into the product (Shih and Daigle, 2002; Shih et al., 2005) or used as a coating on the surface (Shih and Daigle, 2002; García et al., 2004; Shih et al., 2005). Hydrocolloids reduce oil uptake during frying by forming an oil barrier. This oil barrier mechanism works by either decreasing the hydrophobicity of the surface or by physically blocking oil from entering the food during cooking (Annapure et al., 1999; García et al., 2004).

As the percentage of Americans classified as overweight or obese increases, consumers are becoming increasingly health conscious. This has caused an increased demand for lower-fat alternatives to commonly consumed high-fat fried foods. Hydrocolloids and GF flours have already been shown to lower the fat content of fried foods (Annapure et al., 1999; Shih et al., 2001; Mellema, 2003; Shih et al., 2005). Using GF flours and hydrocolloids as a replacement for wheat flour in a fried product such as donuts allows people with wheat and gluten sensitivities to enjoy a common food. It may also provide a product with a significantly lower fat content than a similar product made with wheat flour. The objective of this study was to quantify the effects of different hydrocolloids mixed with

different GF flours on the physical properties and sensory aspects of GF donuts, as measured by instrumental and sensorial analysis, and to determine which formulation is most comparable to wheat donuts.

### **5.3. Materials and Methods**

#### *5.3.1. Donut preparation*

Donuts were formulated (Table 5.1) using an adaptation of a recipe from Sultan (1969). The recipe was adapted for a GF flour formulation by decreasing the amount of vanilla to 1.57 g, increasing the total amount of flour (a combination of commercial GF flour, rice flour, and pregelatinized rice flour) to 350 g, and adding 3.52 g of xanthan gum to the formulation as a gluten replacer. Pregelatinized rice flour was obtained from Sage Foods (Los Angeles, CA). Xanthan gum and methylcellulose were obtained from TIC Gums (Belcamp, MD). All other ingredients were purchased from a local supermarket (Harris Teeter, Raleigh, NC).

Dough was prepared by hand-mixing the sugar, salt, nonfat dry milk powder, and shortening in a mixing bowl. Yeast and the water for the yeast (35°C) were mixed together separately and allowed to sit for 5 minutes. Egg was added to the shortening and combined with the dry ingredients, followed by the water. Vanilla extract was then added and blended in. In a separate beaker, the GF flours (Table 5.1) and xanthan gum were combined with the baking powder, then blended into the other ingredients until moistened. Lastly, the yeast mixture was added. The mixture was kneaded to form a dough, covered lightly in rice flour to prevent sticking, and rolled out on waxed paper to a thickness of 9 mm. The dough was

then cut into squares approximately 50 mm on each side. A methylcellulose wash, made by mixing 0.50 g methylcellulose with 50.0 g water using an immersion blender, was applied with a pastry brush to the top and sides of the donuts made with formulations GF2, GF4, GF6, and GF8. Donuts were then allowed to proof (30 minutes, 27°C).

### 5.3.2. *Donut frying*

Proofed donuts were fried in a deep-fryer (Rival, model 3, Arpt, KS) containing 1.5 L of vegetable oil (soybean oil, ConAgra) heated to 182°C. Wheat control donuts were fried for 70 s on each side for a total of 140 s of frying time, then removed from the fryer and allowed to cool on paper towels. GF donuts were fried for 65 s on each side for a total of 130 s of frying time, then removed from the fryer and allowed to cool on paper towels. GF donuts were fried for a shorter time than the wheat control because preliminary experiments showed donuts were overcooked and had excessive surface browning at frying times longer than 130 s.

### 5.3.3. *Instrumental measurements*

#### 5.3.3.1. Temperature measurement

Temperature measurements were taken with a thermocouple (Omega model HH21) by placing the probe into the center of each donut immediately after cooking was completed. The probe was inserted into at least three points in the donut to obtain an accurate temperature measurement.

After temperature measurements were completed, donuts were allowed to cool on paper towels for approximately 30 minutes. Mass and bulk volume measurements were performed immediately after the donuts had cooled. Donuts used for color and texture analysis were placed in Ziploc bags and stored at 23°C for 24 hours. Donuts used for moisture and fat analysis were placed in Ziploc bags and stored in a commercial freezer (Frigidaire) at -30°C. All trials were run in triplicate.

#### 5.3.3.2. Donut mass and volume measurement

Donuts were weighted before and 30 minutes after frying to the nearest 0.01 g. Percent mass change was then calculated (Eqn. 5.1). Donut bulk volume was measured using the rapeseed displacement method (AACC International, 2000). Bulk volume measurements were performed on both finished donuts and unproofed dough samples to determine percent volume change (Eqn. 5.2). Bulk density before and after frying was calculated from the resulting mass and volume measurements to determine percent density change (Eqn. 5.3).

$$\% \Delta m = \left( \frac{m_f - m_i}{m_i} \right) 100\% \quad (5.1)$$

$$\% \Delta V = \left( \frac{V_f - V_i}{V_i} \right) 100\% \quad (5.2)$$

$$\% \Delta \rho = \left( \frac{\frac{m_f}{V_f} - \frac{m_i}{V_i}}{\frac{m_i}{V_i}} \right) 100\% \quad (5.3)$$

where  $m_f$  and  $V_f$  are the final mass (g) and bulk volume (mL), respectively, of the donut,  $m_i$  and  $V_i$  are the initial mass (g) and bulk volume (mL), respectively, of the donut, and  $\Delta m$ ,  $\Delta V$ , and  $\Delta \rho$  are the mass (g), bulk volume (mL), and bulk density change (g/mL) of the donut, respectively.

#### 5.3.3.3. Donut crust color measurement

Crust color of the cooled donuts was measured 24 hours after cooking using a colorimeter (HunterLab, model D25LDP9000). The colorimeter was calibrated with black and white plates before each use. Donuts were placed in Pyrex petri dishes (Corning) and set on the viewport of the colorimeter.  $L^*$  (light to dark),  $a^*$  (red to green), and  $b^*$  (yellow to blue) values were recorded for each donut. At least three measurements were taken per sample to obtain representative color values.

#### 5.3.3.4. Donut moisture and fat content measurements

Donuts used for moisture and fat content were removed from the freezer and allowed to reach room temperature before sample preparation. Donuts were ground in a coffee grinder (Braun KSM2, 2.5 oz capacity). Two donuts (approximately 60 g of sample) were ground together for each sample. About 8 g of each ground sample were weighed out into aluminum dishes (Fisherbrand cat. no. 08-732-5C) and dried in a forced air oven (Fisher Isotemp forced draft oven) at 105°C for to constant weight ( $\pm 0.02$  g; approximately 3.5 hours) (Rimac-Brncic et al., 2004).

Approximately 3 g of each dried sample were weighed into 33 mm x 94 mm cellulose thimbles (Whatman) for fat extraction. Fat content was determined by soxhlet extraction (Bouchon et al., 2003).

#### 5.3.3.5. Donut mechanical measurements

Mechanical measurements were performed on a Universal Testing Machine (Instron model 5542, Norwood, MA). Because sensory testing was performed on the donuts approximately 24 hours after cooking and because most donuts are not sold right after cooking is completed, mechanical analysis was performed 24 hours after cooking to obtain results that were more indicative of what panelists, and consumers in general, would be sampling. The force to puncture the crust was measured with a one-cycle punch test using a 3 mm diameter probe with a crosshead speed of 100 mm/s (Vélez-Ruiz and Sosa-Morales, 2003). Crumb properties were determined using a modification of the method used by Tan and Mittal (2006). A cylinder 8 mm in diameter was cut from the center of each donut. The crust was removed from either end of the cylinder and the sample was trimmed to 16 mm in height. Hardness 1 and 2 (H1 and H2, or the force to compress the cylinder to 50% of the original height for the first and second compressions, respectively), cohesiveness (area under first force curve divided by area under second force curve), springiness (time to peak force on the second curve divided by time to peak force on the first curve), and chewiness (H1 multiplied by cohesiveness multiplied by springiness) were then measured on the cylinders with a 2-cycle compression test (compressing the sample to 8 mm each cycle) using a 1 kN load cell at a crosshead speed of 100 mm/s.

#### 5.3.4. *Sensory testing*

Sensory testing was conducted on the North Carolina State University campus and was approved by the University's Institutional Review Board. Panelists were students, faculty, and staff of the university. Panelists were recruited by fliers advertising panel dates and free treats for participation. Panelist participation was strictly voluntary. Only individuals with wheat allergy or sensitivity were not allowed to participate in the panels, as a sample containing wheat was present in all sensory panels.

Because there were eight different formulations of GF donuts, testing all of the donuts was considered impractical due to possible panelist fatigue. Therefore, donuts chosen for sensory testing were selected to cover the range of instrumental results measured for all parameters. Five different donuts were used in sensory testing. Four of the donuts were made using the parameters of formulations GF1, GF3, GF5, and GF7 (Table 5.2) and the fifth donut, the control, was a fully-fried wheat donut. A total of 100 panelists (63 females and 37 males) between the ages of 18 and 65 participated in testing.

All donuts tested were made the day before the panel, cooled, placed in Ziploc bags, and stored overnight at room temperature. Each sample was assigned a randomly generated 3-digit code.

All donut samples were served warm to address product limitations and consumer preferences. Gluten-free baked products stale very rapidly even with stabilizers and preservatives. Because of this, many manufacturers instruct consumers to reheat the product for a short time (less than 1 minute) before eating to increase the palatability of the product. In addition, certain donuts, such as those produced by Krispy Kreme<sup>®</sup>, are meant to be eaten

warm and sold with reheating instructions. Beignets, or fried pastry served with powdered sugar, are similar in formulation to the GF donuts produced and are also served warm. Therefore, it was decided that the donuts should be served to the panelists in the manner of beignets: warm (54°C internal temperature) with confectioner's sugar sprinkled on top.

During the panel, donuts were reheated on aluminum foil-covered metal baking trays for 2.5 minutes in a convection oven heated to 163°C, then transferred to a warming oven heated to 60°C. Donuts were allowed to remain in the warming oven for a maximum of 30 minutes; donuts remaining in the oven after 30 minutes were discarded. Samples were prepared by slicing each donut in half and placing one half cut side down on a divided, prenumbered Styrofoam tray. Each tray had 5 sections; the sections were labeled with sample codes in a random order and one sample was placed in each section. After the donuts were placed on the tray, they were sprinkled with confectioner's sugar and immediately given to a panelist or placed in the warming oven for a maximum of 5 minutes before discarding. Preliminary testing was performed to ensure that the donuts did not cool significantly during sampling.

Panelists were asked to evaluate each sample using a 9-point hedonic scale, with 1 being "dislike extremely", and 9 being "like extremely". Overall acceptance was rated first, followed by appearance, aroma, flavor, and mouthfeel/texture. Panelists were also asked to comment on what they liked and disliked about each sample. In addition, panelists were asked several demographic questions: age, gender, shopping responsibility, donut consumption and purchase frequency, and factors that affected donut purchases. Panelist

responses were collected and analyzed via Compusense *five* (Compusense Inc., Ontario, Canada).

#### 5.3.5. *Statistical analysis*

All data were analyzed using SAS 9.1.3 (SAS Institute Inc., Cary, NC). Analyses of variance were performed using the ANOVA procedure in SAS. Instrumental and sensorial data were run separately. Tukey's HSD test was used to determine differences ( $p \leq 0.05$ ) among data groups. Correlations between instrumental results were also determined using SAS.

### **5.4. Results and Discussion**

#### 5.4.1. *Mass, volume, and density changes*

All GF donuts, with the exception of donuts from Trial GF1 (9.8%) had a significantly lower ( $p \leq 0.05$ ) change in mass (Table 5.3) than the wheat control (10.9%). During frying, moisture is lost from the donut due to evaporation while oil is absorbed into the crust (Bouchon et al., 2003). As frying time increases, oil uptake and moisture evaporation increase (Tan and Mittal, 2006). Donuts that are fried for a shorter period of time have been shown to have less oil uptake and moisture loss than donuts fried for a longer period of time at the same temperature (Vélez-Ruiz and Sosa-Morales, 2003). Because mass change is dependent on oil uptake and moisture loss, lower moisture loss and oil uptake result in lower mass change. GF donuts were fried for 130 s while the wheat control was

fried for 140 s. It is unlikely that the small difference in frying times caused the significantly different changes in mass between the GF and wheat donuts.

A more likely cause of the different changes in mass was the difference in formulation between the GF and wheat donuts. Donuts made with rice flour and pregelatinized rice flour (Shih et al., 2001; Shih and Daigle, 2002), and foods fried with a methylcellulose coating (García et al., 2004) have been shown to have lower oil uptake, so a lower percent mass change was expected for the GF donuts. The percent mass change of GF donuts made with a 1:1 ratio of commercial GF flour to rice flour was lower, although not significantly so, than the percent mass change of GF donuts made with a 3:1 ratio of commercial GF flour to rice flour, indicating that GF donuts made with a 1:1 ratio of commercial GF flour to rice flour lost less moisture and absorbed less oil during frying. Pregelatinized rice flour, with the exception of donuts from Trial GF5 (1.3%) and Trial GF7 (1.7%), reduced percent mass change in the GF donuts, although the difference was only significant for donuts from Trial GF1 (9.8%) and Trial GF3 (4.5%). Pregelatinized rice flour has been shown to increase moisture content and reduce oil uptake in wheat (Shih et al., 2001) and rice flour donuts (Shih and Daigle, 2002). Adding a methylcellulose coating to the GF donuts also decreased percent mass change, although the difference was not significant. Methylcellulose has been shown to have oil barrier properties, which prevents oil from being absorbed during frying (García et al., 2004) and reduces the percent mass change. Mass change was found to be positively correlated to volume change ( $p < 0.0001$ )

With the exception of donuts from Trial GF7 (23%) all GF donuts had comparable ( $p \leq 0.05$ ) or greater volume change (Table 5.3) to the wheat control (34%). These results

were contrary to other studies that found GF baked goods to have lower volume than their wheat counterparts (Cato et al., 2004; Gallagher et al., 2004; Schober et al., 2005; Sciarini et al., 2008). However, the majority of studies on GF baked goods that report volume changes focus on GF breads. The large volume to surface area ratio in a loaf of bread creates a much larger dependence on the presence of gluten for volume increase during baking. It is possible that the smaller volume to surface area ratio in the donuts allowed rapid starch gelatinization after expansion during cooking. The rapid starch gelatinization would prevent a structural collapse and a reduction in volume.

The volume change of GF donuts ranged from 23% to 128%. Gluten-free donuts made with a 3:1 ratio of commercial GF flour to rice flour had a larger volume increase than GF donuts made with a 1:1 ratio of commercial GF flour to rice flour. Change in GF donut volume and density generally decreased with addition of pregelatinized rice flour. Pregelatinized rice flour is a thickener (Shih and Daigle, 2002) and may have increased the viscosity of the dough to the point where gas bubbles evolved by baking powder or yeast could not readily expand during cooking, resulting in decreased final volume and increased final density. The presence of a methylcellulose coating did not appear to be correlated with volume or density change. Finished volume and density had a relatively high standard deviation, possibly due to variable humidity during proofing conditions, so there may be confounding factors in these results.

#### 5.4.2. *Core temperature*

The core temperatures (Table 5.3) of GF donuts (80.2 to 94.9°C) were statistically similar ( $p \leq 0.05$ ) to the wheat control (83.0°C). Rice flour gelatinizes at about 55°C and the gelatinization temperature is only slightly increased with the addition of other flours (Sciarini et al., 2008); an internal temperature at or above gelatinization temperature indicates completion of cooking. Core temperature did not appear to be correlated to presence of methylcellulose coating, addition of pregelatinized rice flour, or ratio of commercial GF flour to rice flour.

#### 5.4.3. *Oil and moisture content*

All GF donuts, with the exception of donuts from Trial GF3 (22.2%), had moisture content (Table 5.3) comparable to or higher than ( $p \leq 0.05$ ) the wheat control (23.3%). In general, GF donuts made with a 1:1 ratio of commercial GF flour to rice flour had higher moisture content (23.2% to 24.8%) than GF donuts made with a 3:1 ratio of commercial GF flour to rice flour (22.2% to 23.6%). This result was contrary to the hypothesis that the reverse would be true because of the low water-holding capacity of rice flour (Shih et al., 2001, Shih et al., 2004, Shih et al., 2005). Shih et al. (2001) found that increased rice flour decreased final moisture content in donuts made with a mixture of wheat and rice flour. Addition of pregelatinized rice flour to the GF donut formulation did not result in GF donuts with significantly higher moisture content, regardless of flour ratio. This is contrary to the results of Shih et al. (2001) and Shih and Daigle (2002). Pregelatinized rice flour has a high water-holding capacity (Shih et al., 2001), so it was hypothesized that donuts made with

pregelatinized rice flour would have a higher moisture content than donuts made without. However, the differences in moisture content between GF donuts made with and without pregelatinized rice flour, although significant, were relatively small, only about 1%, so it is difficult to determine the true effect of pregelatinized rice flour on moisture content of GF donuts.

All GF donuts made with a 1:1 ratio of commercial GF flour to rice flour had significantly lower ( $p \leq 0.05$ ) fat content (Table 5.3) than the wheat control (33.7%). Fat content of GF donuts made with a 1:1 ratio of commercial GF flour to rice flour ranged from 26.3% to 27.5%. Gluten-free donuts made with a 3:1 ratio of commercial GF flour to rice flour had higher fat contents, ranging from 31.2% to 33.7%. Donuts from Trial GF1 (33.7%) and Trial GF2 (32.7%) had fat content similar to that of the wheat control while donuts from Trial GF3 (31.2%) and Trial GF4 (32.2%) had significantly lower fat content than the wheat control, although both of these groups of donuts had significantly higher fat content than donuts made with a 1:1 ratio of commercial GF flour to rice flour. Rice flour has been found by many researchers to lower oil uptake in fried foods (Mukprasirt et al., 2001; Shih et al., 2001; Shih et al., 2004; Shih et al., 2005). The proteins in rice flour resist oil uptake during frying, resulting in foods with lower fat content compared to foods made with other types of flour (Jackson et al., 2006). Addition of pregelatinized rice flour to the GF donut formulation lowered the fat content of GF donuts made with a 3:1 ratio of commercial GF flour to rice flour, but did not have a significant effect on GF donuts made with a 1:1 ratio of commercial GF flour to rice flour. Pregelatinized rice flour has been shown to lower the fat content of donuts (Shih et al., 2001; Shih and Daigle, 2002) and rice-based batters (Shih et al., 2005).

Addition of a methylcellulose coating to the GF donuts did not appear to significantly reduce fat content, contrary to the findings of several researchers (Pinthus et al., 1993; García et al., 2002; Shih and Daigle, 2002; García et al., 2004). However, without a plasticizer, methylcellulose coatings tend to crack during frying, negating the oil barrier-forming properties of the methylcellulose (García et al., 2004). It is likely that the methylcellulose coating cracked during frying due to the expansion of the donuts.

#### 5.4.4. Crust color

Crust color of GF donuts (Table 5.3) varied with formulation. Donuts from Trial GF6 (55.1) and Trial GF8 (42.8) had higher ( $p \leq 0.05$ )  $L^*$  values than the wheat control (44.3); all other donuts had comparable  $L^*$  values. Donuts made with a methylcellulose coating tended to have higher  $L^*$  values than donuts made without the methylcellulose coating, with the exception of donuts from Trial GF3 (42.5) and Trial GF4 (42.3). The  $a^*$  values (-10.1 to 22.1) of the GF donuts were generally similar to the wheat control (10.5); however, the  $b^*$  values (7.5 to 39.6) of the GF donuts were generally lower than the wheat control (35.3). Adding a methylcellulose coating to the GF donuts did not appear to significantly affect  $a^*$  and  $b^*$  values ( $p \leq 0.05$ ). The  $L^*$  and  $a^*$  values of the GF donuts were found to be positively correlated ( $R^2 = -0.79$ ,  $p < 0.0001$ ). In general, GF donuts made with a 3:1 ratio of commercial GF flour to rice flour had lower  $L^*$  and  $a^*$  values than GF donuts made with a 1:1 ratio of commercial GF flour to rice flour. The commercial GF flour had twice as much protein per gram as the rice flour, which likely resulted in increased Maillard browning products and darker crust color. The  $b^*$  values of the GF donuts did not appear to be affected by the ratio

of flour used. The presence of pregelatinized rice flour in the GF formulation did not appear to significantly affect L\* or a\*, although using pregelatinized rice flour decreased b\* values, especially when a methylcellulose coating was used. Gallagher et al. (2004) also reported decreased b\* values in GF bread made with modified rice starch.

#### 5.4.5. *Mechanical properties*

All GF donuts had significantly ( $p \leq 0.05$ ) harder crust and crumb than the wheat control (Table 5.4). Gluten-free flours, particularly rice flour, generally do not have the water-binding or network forming abilities that wheat flour, containing gluten, does (Shih et al., 2001, Shih et al., 2004, Shih et al., 2005). The lower water-binding ability resulted in rapid moisture loss from the GF donuts during frying, increasing the rate of crust drying and resulting in a harder crust. Similar results have been reported for breaded okra (Shih et al., 2005).

The force to puncture the crust of the GF donuts (Table 5.4) ranged from 0.898 N to 2.98 N and was generally lower for donuts made with a 3:1 commercial GF flour to rice flour ratio. The most likely cause of this result was the higher oil uptake of donuts made with a 3:1 commercial GF to rice flour ratio. Fat tenderizes the structure of baked goods (Bennion and Scheule, 2004) and most of the oil absorbed from deep-frying is located in the crust (Farkas et al., 1996). Increased oil uptake during frying would therefore result in a relatively softer crust. The presence of the methylcellulose coating on the GF donuts also decreased crust hardness. With the exception of donuts from Trial GF4, GF donuts prepared with a methylcellulose coating (Trial GF2, Trial GF6, and Trial GF8) had a softer crust than GF

donuts prepared without the coating (Trial GF1, Trial GF5, and Trial GF7), although the difference in crust hardness was only significant in the donuts made with a 1:1 ratio of commercial GF flour to rice flour. Methylcellulose gels at high temperature and forms a moisture barrier, preventing moisture from leaving the crust during cooking (García et al., 2004) and resulting in a softer crust.

Although all GF donuts had higher H1 and H2 values (Table 5.4) than the wheat control, only donuts from Trial GF5 (5.91 N), Trial GF6 (6.47 N), and Trial GF7 (6.60 N) had significantly ( $p \leq 0.05$ ) higher H1 values than the wheat control (2.63 N). Donuts from Trial GF5 (4.37 N), Trial GF6 (5.23 N), and Trial GF7 (5.20 N) also had significantly higher H2 values than the wheat control (2.11 N). Hardness 1 and H2 values of the GF donuts were found to be positively correlated ( $R^2=0.89$ ,  $p < 0.0001$ ). All GF donuts made with a 1:1 ratio of commercial GF flour to rice flour had a significantly lower ( $p \leq 0.05$ ) fat content than the wheat control, while GF donuts made with a 3:1 ratio of commercial GF flour to rice flour had a fat content comparable to or slightly lower than the wheat control. The lower fat content of the GF donuts made with a higher ratio of rice flour to commercial GF flour could be partially responsible for the increased crumb hardness. Fat tenderizes the crumb of baked goods, so as fat content decreases, crumb hardness increases. Crumb hardness (H1 and H2) was found to be negatively correlated with fat content ( $p < 0.0001$ ) and positively correlated with moisture content ( $p < 0.0001$ ).

Gluten-free donuts made with a 1:1 ratio of commercial GF flour to rice flour were generally harder than GF donuts made with a 3:1 ratio of commercial GF flour to rice flour. This was most likely due to the low water-binding abilities of rice flour, which allowed

significant moisture migration from the crumb to the crust during storage (Gallagher et al., 2003). Rice breads were shown to be significantly firmer after several days of storage than wheat bread (Kadan et al., 2001) or breads made with GF flours with higher water-holding capacity (Kadan et al., 2001; Sciarini et al., 2008). Adding a methylcellulose coating to the GF donuts did not appear to be correlated with crumb hardness. Because the coating was applied only to the surface of the donuts, it is unlikely that it would affect crumb hardness.

With the exception of the cohesiveness of the Trial GF8 donuts (0.472), the cohesiveness (Table 5.4) of all GF donuts (0.294 to 0.472) was significantly lower ( $p \leq 0.05$ ) than the wheat control (0.573), indicating that the GF donuts were more crumbly than the wheat control. This result was expected, as the lack of structure provided by gluten causes a crumbly, brittle crumb texture (Gallagher et al., 2004). Springiness and chewiness of GF donuts (Table 5.4) were not significantly different from the wheat control, with the exception of the springiness of donuts from Trial GF1 (0.864 compared to 3.48 for the control). Springiness and chewiness of GF donuts ranged from 0.864 to 2.43 and 0.978 to 4.23, respectively, while springiness and chewiness of the wheat control was 3.48 and 5.01, respectively. Springiness and chewiness were found to be positively correlated ( $R^2=0.83$ ,  $p < 0.0001$ ). Springiness was used to calculate chewiness, so this correlation was expected.

#### *5.4.6. Sensory evaluation*

No significant differences ( $p \leq 0.05$ ) were found among the scores of the GF donuts (Table 5.5), indicating that all of the GF donuts were similarly liked. However, all GF donuts had significantly lower ( $p \leq 0.05$ ) sensory scores than the wheat control, indicating that

they were all liked less than the wheat control for every attribute tested. With overall acceptance scores ranging between 4.27 and 4.68 (dislike slightly to neither like nor dislike), the GF donuts were not nearly as acceptable to the panelists as the wheat control (overall acceptance of 6.37). Panelists commented that all donuts were bland or not sweet enough. Applying a glaze or a heavier coating of powdered sugar to the donuts may improve the overall acceptance scores of all donuts. In addition, many panelists commented that the GF donuts were dry and had a heavy texture, and a few panelists commented on the grittiness of the GF donuts. The grittiness was most likely due to residual rice flour on the surface of the donut used to keep the dough from sticking while the donuts were rolled out. Gluten-free products in general tend to be drier than wheat products, as many GF flours do not have the water-holding capacity of wheat flour (Shih et al., 2006; Sabanis and Tzia, 2009). The heavy texture comments most likely arose from the comparison of the GF donuts to the wheat control, which had a much softer and less dense crumb texture. The GF donuts had a relatively low volume, making the GF donut crumb denser than the wheat donut crumb. It is suggested that further investigation on gluten replacement and donut formulation be investigated to improve the texture and mouthfeel of the GF donuts.

## **5.5. Conclusions**

All GF donuts had significantly lower change in mass than the wheat control, likely caused by a combination of shorter frying time and the use of rice flour and pregelatinized rice flour used in the GF donut formulations. Volume and density changes of GF donuts were generally statistically similar to the wheat control, which was contrary to the findings of

other studies and possibly due to the relatively small volume to surface area ratio of the GF donuts. Core temperatures of all GF donuts were comparable to the core temperature of the wheat control.

Moisture content of GF donuts was generally comparable to or higher than the wheat control. Fat content of GF donuts was comparable to or lower than the wheat control. Fat content was lowest in GF donuts made with a 1:1 commercial GF flour to rice flour ratio. Gluten-free donuts made with a 3:1 commercial GF flour to rice flour ratio had lower fat content than the wheat control if pregelatinized rice flour was included in the formulation, otherwise, they had comparable fat content to the wheat control. The methylcellulose coating was not found to affect fat content.

Generally,  $L^*$  and  $a^*$  values of the GF donuts were similar to the wheat control, while  $b^*$  values of the GF donuts were lower than the wheat control. The methylcellulose coating generally increased  $L^*$  values, while the inclusion of pregelatinized rice flour in the GF donut formulation decreased  $b^*$  values. Gluten-free donuts generally had a firmer crust and crumb than the wheat control, although the difference was not always significant. Gluten-free donuts made with a 3:1 commercial GF flour to rice flour ratio had a softer crust and crumb than GF donuts made with a 1:1 commercial GF flour to rice flour ratio. The relatively high crust and crumb firmness was likely due to a combination of the lack of water-binding gluten and a lower fat content. Crust hardness of GF donuts decreased with the presence of a methylcellulose coating. Cohesiveness of GF donuts was lower than the wheat control, although springiness and chewiness were not significantly different from the

wheat control. Lower cohesiveness in the GF donuts was expected, as the lack of gluten generally results in a more crumbly, brittle crumb.

Sensory scores of all GF donuts were comparable to each other. All GF donuts received significantly lower sensory scores than the wheat control. Based on the instrumental and sensory results, the GF formulations detailed in this study may be used to produce donuts that are lower in fat than and instrumentally comparable to wheat donuts. However, the GF donuts are generally not as sensorially acceptable as the wheat control, even though they may have been instrumentally comparable.

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**Table 5.1. GF donut formulation**

<b>Ingredient</b>	<b>Weight (g)</b>	<b>% weight (flour basis)</b>
Salt	4.72	100%
Sugar	18.9	32%
Nonfat dry milk powder	18.9	16%
Shortening	56.7	11%
Egg	37.8	11%
Water	113.4	5.4%
Vanilla extract	1.57	5.4%
Yeast	9.00	2.6%
Warm water	37.8	1.3%
Flour	350.0	1.3%
Xanthan gum	3.52	1.0%
Baking powder	4.72	0.4%

**Table 5.2. Formulation changes for GF fully-fried donuts**

<b>Trial</b>	<b>Commercial GF flour (g)</b>	<b>Rice flour (g)</b>	<b>PGRF (g)</b>	<b>Methylcellulose wash used?</b>
GF1	262.5	87.5	--	No
GF2	262.5	87.5	--	Yes
GF3	262.5	77.0	10.50	No
GF4	262.5	77.0	10.50	Yes
GF5	175.0	175.0	--	No
GF6	175.0	175.0	--	Yes
GF7	175.0	164.5	10.50	No
GF8	175.0	164.5	10.50	Yes

Note: PGRF is pregelatinized rice flour. The sum of the weights of the commercial GF flour, rice flour, and pregelatinized flour total 350.0 g, the weight of the flour listed in Table 5.1.

**Table 5.3. Mass, volume, and density changed, final temperature, crust color, and moisture and fat content of GF donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Mass change (%)</b>	<b>Volume change (%)</b>	<b>Density change (%)</b>	<b>Final core temp (°C)</b>
GF1	9.84±0.71% (a)	128±5.3% (a)	-52±1.2% (e)	94.9±5.9 (a)
GF2	4.12±0.69% (b)	87±4.4% (b)	-44±1.4% (de)	85.7±4.6 (a)
GF3	4.54±2.63% (b)	46±4.7% (cd)	-28±4.2% (bc)	85.8±5.9 (a)
GF4	2.02±1.30% (bc)	87±7.1% (b)	-45±1.8% (de)	86.5±6.3 (a)
GF5	1.29±1.52% (bc)	61±0.1% (c)	-37±0.9% (cd)	87.0±2.3 (a)
GF6	0.70±1.74% (bc)	29±4.8% (de)	-22±1.8% (ab)	87.3±9.8 (a)
GF7	1.67±0.81% (bc)	23±3.8% (e)	-17±3.0% (a)	84.8±10.6 (a)
GF8	-0.68±1.67% (c)	29±6.8% (de)	-23±3.6% (ab)	80.2±7.8 (a)
CW	10.9±1.96% (a)	43±14% (cd)	-22±6.9% (ab)	94.1±2.7 (a)

<b>Trial</b>	<b>L*</b>	<b>Crust color</b>		<b>Moisture content (%)</b>	<b>Fat content (%)</b>
		<b>a*</b>	<b>b*</b>		
GF1	41.6±2.4 (d)	11.8±1.7 (ab)	24.0±3.6 (bc)	23.2±0.05% (e)	33.7±0.25% (a)
GF2	50.0±3.5 (ab)	9.9±7.9 (ab)	39.6±3.6 (a)	23.6±0.04% (d)	32.7±0.10% (ab)
GF3	42.5±0.2 (cd)	20.5±2.4 (a)	17.5±3.1 (cd)	22.2±0.09% (f)	31.2±0.68% (c)
GF4	42.3±0.7 (cd)	22.1±3.1 (a)	7.5±2.3 (d)	23.2±0.05% (e)	32.2±0.17% (bc)
GF5	44.4±3.3 (bcd)	13.0±3.6 (ab)	24.9±8.5 (bc)	23.9±0.02% (c)	27.5±0.29% (d)
GF6	55.1±3.0 (a)	-10.1±4.8 (c)	38.5±1.9 (a)	24.3±0.01% (b)	26.6±0.68% (d)
GF7	49.1±2.5 (abc)	2.1±3.6 (bc)	13.4±4.8 (cd)	24.8±0.06% (a)	26.3±0.15% (d)
GF8	52.8±2.6 (a)	2.2±7.5 (bc)	11.8±3.1 (d)	23.2±0.13% (e)	27.2±0.03% (d)
CW	44.3±1.6 (bcd)	10.5±0.2 (ab)	35.3±0.3 (ab)	23.3±0.11% (e)	33.7±0.55% (a)

Note: Trial number indicates the formulation for the corresponding number in Table 5.2. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Table 5.4. Mechanical properties of GF donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Force to puncture crust (N)</b>	<b>H1 (N)</b>	<b>H2 (N)</b>	<b>Cohesiveness</b>	<b>Springiness</b>	<b>Chewiness</b>
GF1	1.32±0.25 (bc)	3.68±0.22 (c)	2.71±0.16 (c)	0.294±0.034 (cd)	0.864±0.22 (b)	0.978±0.13 (a)
GF2	1.07±0.10 (bc)	4.47±0.98 (bc)	2.70±0.76 (c)	0.339±0.017 (cd)	1.44±0.37 (ab)	2.13±1.11 (a)
GF3	1.16±0.12 (bc)	3.38±0.66 (c)	2.87±0.64 (bc)	0.318±0.054 (cd)	1.02±0.24 (ab)	1.11±0.31 (a)
GF4	1.29±0.16 (bc)	4.64±0.82 (abc)	3.01±0.55 (bc)	0.276±0.064 (d)	1.10±0.37 (ab)	2.74±1.68 (a)
GF5	2.98±0.37 (a)	5.91±1.42 (ab)	4.37±0.84 (ab)	0.412±0.052 (bc)	1.59±0.22 (ab)	3.74±0.31 (a)
GF6	0.90±0.33 (bc)	6.47±0.21 (ab)	5.23±0.71 (a)	0.392±0.043 (bcd)	1.22±0.12 (ab)	3.05±0.28 (a)
GF7	2.57±0.21 (a)	6.60±0.42 (a)	5.20±0.38 (a)	0.367±0.059 (bcd)	2.43±2.23 (ab)	4.23±2.92 (a)
GF8	1.51±0.27 (b)	4.46±0.56 (bc)	3.69±0.42 (abc)	0.472±0.025 (ab)	1.87±0.42 (ab)	3.57±1.35 (a)
CW	0.77±0.03 (c)	2.63±0.38 (c)	2.11±0.16 (c)	0.573±0.028 (a)	3.48±1.35 (a)	5.01±2.84 (a)

Note: Trial number indicates the formulation for the corresponding number in Table 5.2. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Table 5.5. Sensorial properties of selected GF donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Overall acceptance</b>	<b>Appearance</b>	<b>Aroma</b>	<b>Texture</b>	<b>Mouthfeel/ Taste</b>
GF1	4.68±1.78 (b)	5.71±1.64 (b)	5.81±1.43 (b)	4.80±1.87 (b)	4.01±1.83 (b)
GF3	4.54±1.69 (b)	5.53±1.67 (b)	5.72±1.39 (b)	4.65±1.83 (b)	3.68±1.90 (b)
GF5	4.27±1.63 (b)	5.22±1.44 (b)	5.60±1.24 (b)	4.37±1.63 (b)	3.64±1.73 (b)
GF7	4.33±1.57 (b)	5.48±1.59 (b)	5.54±1.36 (b)	4.38±1.71 (b)	3.55±1.79 (b)
CW	6.37±1.54 (a)	7.09±1.23 (a)	6.47±1.22 (a)	6.41±1.56 (a)	6.50±1.64 (a)

Note: Trial number indicates the formulation for the corresponding number in Table 5.2. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Chapter 6: Process parameters for producing  
gluten-free partially-fried infrared-finished  
donuts**

## 6.1. Abstract

Due to rising health concerns, demand for both lower-fat fried products and gluten-free (GF) products have increased. Infrared (IR) radiation is able to simulate the heat flux created during the frying process, creating a product with a fried-like texture but a lower fat content. The objective of this study was to determine the process parameters needed to produce partially- (par-) fried, IR-finished GF yeast donuts that have similar instrumental and sensorial properties to fully-fried wheat yeast donuts but lower fat content. Gluten-free donuts were par-fried for 64 s and finished in an IR oven. Two different IR-finishing times (39 s or 45 s) and four different distance combinations from the emitters to the donuts were tested. Mass, volume, and density changes, percent moisture and fat, crust color, and crust and crumb rheological properties of the finished par-fried, IR-finished GF donuts were compared to a fully-fried wheat control and a fully-fried GF control. Sensory testing was also performed using a 9-point hedonic scale (1: dislike extremely, 9: like extremely) to measure overall acceptance, aroma, taste, and texture/mouthfeel. Statistical analysis ( $\alpha=0.05$ ) showed that all par-fried, IR-finished donuts had significantly lower fat content (23.7%-28.2%) than the wheat control (33.7%), although only a few GF donuts had lower fat content than the GF control (27.2%). Setting the emitters in either a height gradient from 70 mm to 50 mm or at a height of 60 mm above the belt of the IR oven and using an IR-finishing time of 39 s yielded donuts that were the most instrumentally similar to both the wheat and GF controls. All par-fried, IR-finished GF donuts received significantly lower overall acceptance scores (3.81-3.44) than the wheat control (6.94), most likely due to dry mouthfeel of the GF donuts. However, GF par-fried, infrared-finished donuts received

comparable overall acceptance scores to the GF control (4.33). Infrared radiation may be used to finish-fry par-fried GF donuts to produce donuts that are significantly lower in fat, yet instrumentally and sensorially similar to fully-fried GF donuts, as well as instrumentally similar to fully-fried wheat donuts.

## 6.2. Introduction

Fried foods are enjoyed worldwide for their palatable texture and taste (Guallar-Castillón et al., 2007). Americans in particular consume large amounts of fried food, whether it is with a meal, such as chicken nuggets, French fries, and other fast-food products, or for a snack, such as potato chips. However, fried foods tend to be high in fat and saturated fat, and are energy dense rather than nutrient dense. The rising prevalence of overweight and obesity in America is often attributed to the increased consumption of fast foods and fried foods (Nawar, 1998). With 66% of the American population considered overweight and 50% of those who are overweight considered obese (National Center for Health Statistics, 2006), obesity-related diseases such as cardiovascular disease, hypertension, and Type II diabetes, have become a major health concern (Nicklas et al., 2001). This has caused many consumers to become more health conscious, resulting in an increased demand for foods with the same texture and taste of fried foods but with a lower calorie and fat content.

It is important to understand how heat and mass are transferred during frying to develop a method to lower fat content in fried foods, particularly if frying is partially or completely replaced with another heating method. Frying is a common process that produces foods with a crisp, crunchy crust and a soft interior. This is largely due to the heating profile of foods during frying. After a food is placed in a deep fryer, the heat flux provided to the food rapidly increases to a peak of about  $30,000 \text{ W/m}^2$ , then decreases as cooking progresses. Moisture present on the surface of the food vaporizes and evaporates, drying the surface and causing crust formation. As cooking progresses, the crust continues to dry and thicken

(Farkas and Hubbard, 2000). The drying results in a crust with a porous structure, allowing oil to enter the food and ultimately increasing the fat content of the food (Mellema, 2003).

Infrared (IR) heating as a replacement for deep-frying has not been extensively studied; it has mainly been used for pasteurization, drying, thawing and baking (Sakai and Hanzawa, 1994; Krishnamurthy, 2008). Infrared heating is of particular interest because of its ability to provide a high heat flux that can easily be controlled. This allows the heat flux profile found in frying to be duplicated. Lloyd (2003) developed a process that used IR heating to reproduce the heat flux of frying. This process was able to produce French fries that were instrumentally and sensorially comparable to fully-fried French fries. In addition, the par-fried, IR-finished French fries had significantly lower fat content than fully-fried French fries: 13.0% versus 19.2%, respectively (Lloyd, 2003). It has also been shown to be able to produce wheat donuts with comparable instrumental and sensorial properties to fully-fried wheat donuts. The par-fried, IR-finished wheat donuts also had significantly lower fat content than fully-fried wheat donuts: 25.6-30.6% versus 33.7%, respectively (Melito, 2009).

Food allergies and intolerances are health concern both in America and worldwide. Gluten intolerance, affecting about 1% of the American population, is an inability to break down the gluten proteins found in wheat, as well as similar proteins found in rye, barley and possibly oats. Consuming these proteins results in the gradual deterioration of the intestinal villi, causing malabsorption of nutrients and other health problems (Schober et al., 2003). Wheat allergy also indicates sensitivity to wheat proteins. When a person with wheat allergy consumes wheat, there is an IgE-mediated response, stimulating a histamine release and causing a variety of symptoms such as nausea, GI distress, hives, and anaphylaxis.

Treatment for both gluten intolerance and wheat allergy is a lifelong avoidance of wheat and wheat-containing products. People who are gluten intolerant must also avoid products containing gluten (Hischenhuber et al., 2006). The need to avoid wheat and gluten-containing products has resulted in a demand for commercial wheat- and gluten-free (GF) products. Currently, there are some GF analogs to commonly consumed products, such as bread, cereals, and cookies; however, the texture and taste of these products differs from wheat products and the acceptability is widely variable.

Considerable research has been done on formulating and improving GF breads, but few studies have been done on other gluten-free products, particularly fried products such as breaded foods or deep-fried doughs. The studies that are available on fried GF foods have noted that GF flours have significantly lower oil uptake than wheat flour due to differences in the flour proteins (Mohamed et al., 1998; Altunakar et al., 2004; Shih et al., 2004). It was noted that GF flours could be used in battered, fried products or in fried doughs to lower the fat content of the finished product (Mohamed et al., 1998; Shih et al., 2001; Shih and Daigle, 2002; Shih et al., 2005). Hydrocolloids, typically used in GF products to improve the texture and structure, have also been shown to lower fat content in fried foods when incorporated into the product (Shih and Daigle, 2002; Shih et al., 2005) or used as a coating on the surface (Shih and Daigle, 2002; García et al., 2004; Shih et al., 2005). Hydrocolloids reduce oil uptake during frying by forming an oil barrier. This oil barrier mechanism works by either decreasing the hydrophobicity of the surface or by physically blocking oil from entering the food during cooking (Annapure et al., 1999; García et al., 2004).

Infrared heating has been successfully used to lower fat content while providing a fried-like texture and taste in both potatoes and wheat donuts (Lloyd, 2003; Melito, 2009). It was hypothesized that using IR to finish-fry GF donuts would produce GF donuts with similar instrumental and sensorial properties to fully-fried GF donuts. In addition, it may be possible to produce partially- (par-) fried, IR-finished GF donuts that have comparable instrumental and sensorial properties to fully-fried wheat donuts. The objective of this study was to determine the combination of partial-frying and infrared parameters that produce the highest quality GF donut as compared to both fully-fried GF donuts and fully-fried wheat donuts by instrumental and sensorial analysis.

### **6.3. Materials and Methods**

#### *6.3.1. Donut preparation*

Donuts were formulated (Table 6.1) using an adaptation of a recipe from Sultan (1969). The recipe was adapted for a GF flour formulation by decreasing the amount of vanilla to 1.57 g, increasing the total amount of flour (a combination of commercial GF flour, rice flour, and pregelatinized rice flour) to 350 g, and adding 3.52 g of xanthan gum to the formulation as a gluten replacer. Pregelatinized rice flour was obtained from Sage Foods (Los Angeles, CA). Xanthan gum and methylcellulose were obtained from TIC Gums (Belcamp, MD). All other ingredients were purchased from a local supermarket (Harris Teeter, Raleigh, NC).

Dough was prepared by hand-mixing the sugar, salt, nonfat dry milk powder, and shortening in a mixing bowl. Yeast and the water for the yeast (35°C) were mixed together

separately and allowed to sit for 5 minutes. Egg was added to the shortening and combined with the dry ingredients, followed by the water. Vanilla extract was then added and blended in. In a separate beaker, the GF flours (Table 6.1) and xanthan gum were combined with the baking powder, then blended into the other ingredients until moistened. Lastly, the yeast mixture was added. The mixture was kneaded to form a dough, covered lightly in rice flour to prevent sticking, and rolled out on waxed paper to a thickness of 9 mm. The dough was then cut into squares approximately 50 mm on each side. A methylcellulose wash, made by mixing 0.50 g methylcellulose with 50.0 g water using an immersion blender, was applied with a pastry brush to the top and sides of the donuts. Donuts were then allowed to proof (30 minutes, 27°C).

### 6.3.2. *Donut frying*

Proofed donuts were fried in a deep-fryer (Rival, model 3, Arpt, KS) containing 1.5 L of vegetable oil (soybean oil, ConAgra) heated to 182°C. Fully-fried wheat control donuts were fried for 70 s on each side for a total of 140 s of frying time, then removed from the fryer and allowed to cool on paper towels. Gluten-free donuts were fried for 32 s on each side for a total of 64 s of frying time, then immediately transferred to the conveyor belt of an IR oven (Melito, 2009). Emitter heights and residence times varied for each trial (Table 6.2). The average thickness of the donuts entering the IR oven was about 25 mm. Donuts were immediately removed from the conveyor belt at the end of the residence time and placed on paper towels.

### 6.3.3. *Instrumental measurements*

#### 6.3.3.1. Temperature measurement

Temperature measurements were taken with a thermocouple (Omega model HH21) by placing the probe into the center of each donut immediately after cooking was completed. The probe was inserted into at least three points in the donut to obtain an accurate temperature measurement.

After temperature measurements were completed, donuts were allowed to cool on paper towels for approximately 30 minutes. Mass and bulk volume measurements were performed immediately after the donuts had cooled. Donuts used for color and texture analysis were placed in Ziploc bags and stored at 23°C for 24 hours. Donuts used for moisture and fat analysis were placed in Ziploc bags and stored in a commercial freezer (Frigidaire) at -30°C. All trials were run in triplicate.

#### 6.3.3.2. Donut mass and volume measurement

Donuts were weighted before and 30 minutes after frying to the nearest 0.01 g. Percent mass change was then calculated (Eqn. 6.1). Donut bulk volume was measured using the rapeseed displacement method (AACC International, 2000). Bulk volume measurements were performed on both finished donuts and unproofed dough samples to determine percent volume change (Eqn. 6.2). Bulk density before and after frying was calculated from the resulting mass and volume measurements to determine percent density change (Eqn. 6.3).

$$\% \Delta m = \left( \frac{m_f - m_i}{m_i} \right) 100\% \quad (6.1)$$

$$\% \Delta V = \left( \frac{V_f - V_i}{V_i} \right) 100\% \quad (6.2)$$

$$\% \Delta \rho = \left( \frac{\frac{m_f}{V_f} - \frac{m_i}{V_i}}{\frac{m_i}{V_i}} \right) 100\% \quad (6.3)$$

where  $m_f$  and  $V_f$  are the final mass (g) and bulk volume (mL), respectively, of the donut,  $m_i$  and  $V_i$  are the initial mass (g) and bulk volume (mL), respectively, of the donut, and  $\Delta m$ ,  $\Delta V$ , and  $\Delta \rho$  are the mass (g), bulk volume (mL), and bulk density change (g/mL) of the donut, respectively.

#### 6.3.3.3. Donut crust color measurement

Crust color of the cooled donuts was measured 24 hours after cooking using a colorimeter (HunterLab, model D25LDP9000). The colorimeter was calibrated with black and white plates before each use. Donuts were placed in Pyrex petri dishes (Corning) and set on the viewport of the colorimeter.  $L^*$  (light to dark),  $a^*$  (red to green), and  $b^*$  (yellow to blue) values were recorded for each donut. At least three measurements were taken per sample to obtain representative color values.

#### 6.3.3.4. Donut moisture and fat content measurements

Donuts used for moisture and fat content were removed from the freezer and allowed to reach room temperature before sample preparation. Donuts were ground in a coffee grinder (Braun KSM2, 2.5 oz capacity). Two donuts (approximately 60 g of sample) were ground together for each sample. About 8 g of each ground sample were weighed out into aluminum dishes (Fisherbrand cat. no. 08-732-5C) and dried in a forced air oven (Fisher Isotemp forced draft oven) at 105°C for to constant weight ( $\pm 0.02$  g; approximately 3.5 hours) (Rimac-Brncic et al., 2004).

Approximately 3 g of each dried sample were weighed into 33 mm x 94 mm cellulose thimbles (Whatman) for fat extraction. Fat content was determined by soxhlet extraction (Bouchon et al., 2003).

#### 6.3.3.5. Donut mechanical measurements

Mechanical measurements were performed on a Universal Testing Machine (Instron model 5542, Norwood, MA). Because sensory testing was performed on the donuts approximately 24 hours after cooking and because most donuts are not sold right after cooking is completed, mechanical analysis was performed 24 hours after cooking to obtain results that were more indicative of what panelists, and consumers in general, would be sampling. The force to puncture the crust was measured with a one-cycle punch test using a 3 mm diameter probe with a crosshead speed of 100 mm/s (Vélez-Ruiz and Sosa-Morales, 2003). Crumb properties were determined using a modification of the method used by Tan and Mittal (2006). A cylinder 8 mm in diameter was cut from the center of each donut. The

crust was removed from either end of the cylinder and the sample was trimmed to 16 mm in height. Hardness 1 and 2 (H1 and H2, or the force to compress the cylinder to 50% of the original height for the first and second compressions, respectively), cohesiveness (area under first force curve divided by area under second force curve), springiness (time to peak force on the second curve divided by time to peak force on the first curve), and chewiness (H1 multiplied by cohesiveness multiplied by springiness) were then measured on the cylinders with a 2-cycle compression test (compressing the sample to 8 mm each cycle) using a 1 kN load cell at a crosshead speed of 100 mm/s.

#### *6.3.4. Sensory testing*

Sensory testing was conducted on the North Carolina State University campus and was approved by the University's Institutional Review Board. Panelists were students, faculty, and staff of the university. Panelists were recruited by fliers advertising panel dates and free treats for participation. Panelist participation was strictly voluntary. Only individuals with wheat allergy or sensitivity were not allowed to participate in the panels, as a sample containing wheat was present in all sensory panels.

Because there were eight different groups of GF par-fried, IR-finished donuts, testing all of the donuts was considered impractical due to possible panelist fatigue. Therefore, donuts chosen for sensory testing were selected to cover the range of instrumental results measured for all parameters. Five different donuts were used in sensory testing. Four of the donuts were made using the parameters for Trials G2, G3, G7, and G8 (Table 6.2) and the

fifth donut, the control, was a fully-fried wheat donut. A total of 100 panelists (66 females and 34 males) between the ages of 18 and 65 participated in testing.

All donuts were made the day before the panel, cooled, placed in Ziploc bags, and stored overnight at room temperature. Each sample was assigned a randomly generated 3-digit code.

All donut samples were served warm to address product limitations and consumer preferences. Gluten-free baked products stale very rapidly even with stabilizers and preservatives. Because of this, many manufacturers instruct consumers to reheat the product for a short time (less than 1 minute) before eating to increase the palatability of the product. In addition, certain donuts, such as those produced by Krispy Kreme<sup>®</sup>, are meant to be eaten warm and sold with reheating instructions. Beignets, or fried pastry served with powdered sugar, are similar in formulation to the GF donuts produced and are also served warm. Therefore, it was decided that the donuts should be served to the panelists in the manner of beignets: warm (54°C internal temperature) with confectioner's sugar sprinkled on top.

During the panel, donuts were reheated on aluminum foil-covered metal baking trays for 2.5 minutes in a convection oven heated to 163°C, then transferred to a warming oven heated to 60°C. Donuts were allowed to remain in the warming oven for a maximum of 30 minutes; donuts remaining in the oven after 30 minutes were discarded. Samples were prepared by slicing each donut in half and placing one half cut side down on a divided, prenumbered Styrofoam tray. Each tray had 5 sections; the sections were labeled with sample codes in a random order and one sample was placed in each section. After the donuts were placed on the tray, they were sprinkled with confectioner's sugar and immediately

given to a panelist or placed in the warming oven for a maximum of 5 minutes before discarding. Preliminary testing was performed to ensure that the donuts did not cool significantly during sampling.

Panelists were asked to evaluate each sample using a 9-point hedonic scale, with 1 being “dislike extremely”, and 9 being “like extremely”. Overall acceptance was rated first, followed by appearance, aroma, flavor, and mouthfeel/texture. Panelists were also asked to comment on what they liked and disliked about each sample. In addition, panelists were asked several demographic questions: age, gender, shopping responsibility, donut consumption and purchase frequency, and factors that affected donut purchases. Panelist responses were collected and analyzed via Compusense *five* (Compusense Inc., Ontario, Canada).

#### 6.3.5. *Statistical analysis*

All data were analyzed using SAS 9.1.3 (SAS Institute Inc., Cary, NC). Analyses of variance were performed using the ANOVA procedure in SAS. Instrumental and sensorial data were run separately. Tukey’s HSD test was used to determine differences ( $p \leq 0.05$ ) among data groups. Correlations between instrumental results were also determined using SAS.

## 6.4. Results and Discussion

### 6.4.1. Mass, volume, and density changes

All of the GF par-fried, IR-finished donuts had a significantly lower ( $p \leq 0.05$ ) change in mass (Table 6.3) than the wheat control (10.9%). However, with the exception of the GF par-fried, IR-finished donuts from Trial G3 (-3.2%) and Trial G5 (-2.5%) which had significantly lower change in mass, the GF par-fried, IR-finished donuts had similar ( $p \leq 0.05$ ) change in mass as the GF control (-0.68%). The change in mass of GF par-fried, IR-finished donuts ranged between -1.0% and -3.2%.

During frying, moisture is lost from food due to evaporation while oil is absorbed into the crust (Bouchon et al., 2003; Shih et al., 2005). As frying time increases, oil uptake and moisture evaporation increase (Tan and Mittal, 2006). Donuts that are fried for a shorter period of time have been shown to have less oil uptake and moisture loss than donuts fried for a longer period of time at the same temperature (Vélez-Ruiz and Sosa-Morales, 2003). Because mass change is dependent on oil uptake and moisture loss, less moisture loss and lower oil uptake results in lower mass change. Since the GF par-fried, IR-finished donuts were fried for only 64 s compared to the control, which was fried for 160 s, they had lower oil uptake and higher moisture content than the control. In addition, donuts made with rice flour and pregelatinized rice flour (Shih et al., 2001; Shih and Daigle, 2002), and foods fried with a methylcellulose coating (García et al., 2004) have been shown to have lower oil uptake. No trends were found between percent mass change and IR oven parameters.

All GF par-fried, IR-finished donuts had comparable ( $p \leq 0.05$ ) change in volume (Table 6.3) to the wheat control (34%) and change in volume comparable to or greater than

the GF control (29%). The volume change of the GF par-fried, IR-finished donuts ranged from 22% to 65%. These results were contrary to the findings of other studies that reported GF baked goods having a lower volume than their wheat counterparts (Cato et al., 2004; Gallagher et al., 2004; Schober et al., 2007; Sciarini et al., 2008). However, the majority of studies on GF baked goods that report volume change focused on GF breads. The large volume to surface area ratio in a loaf of bread creates a much larger dependence on the presence of gluten for volume increase during baking. It is possible that the smaller volume to surface area ratio in the donuts allowed starch gelatinization to occur rapidly after expansion during cooking. This would prevent a structural collapse and a reduction in volume. In addition, many of the donuts finished by IR developed an air cell between the crust and the crumb. This air cell increased the final volume and thus the change in volume.

In general, as the overall heat flux provided by the IR oven increased (Figure 6.1), change in volume and density increased. The increased heat flux most likely resulted in a more rapid increase in internal temperature, causing the air cells in the crumb to expand more rapidly. A higher internal temperature would also result in more rapid starch gelatinization, setting the structure before the gas could escape and collapse the air cell. Infrared oven residence time did not appear to be correlated with volume or density change. Finished volume and density data had a relatively high standard deviation, probably due to the presence of the air cell between the crust and the crumb, so there may be confounding factors in these results.

#### 6.4.2. Core temperature

Core temperatures (Table 6.3) for all GF par-fried, IR-finished donuts (92.4 to 98.9°C) were statistically similar ( $p \leq 0.05$ ) to the wheat control (94.1°C) but significantly higher than the core temperature of the GF control (80.2°C). Rice flour gelatinizes at about 55°C and the gelatinization temperature is only slightly increased with the addition of other flours (Sciarini et al., 2008). An internal temperature at or above gelatinization temperature indicates completion of cooking. The core temperatures of the GF par-fried, IR-finished donuts was expected to be higher than that of the GF control due to the high intensity of the IR heat flux. The GF donuts entering the IR oven had not yet significantly changed in volume (quantitative data not collected), so their height was still similar to their original height, 9 mm. Near-infrared radiation has been shown to penetrate 1.8-3.8 mm into bread crumb (Skjöldebrand et al., 1988). The GF par-fried, IR-finished donuts were heated on both the top and bottom because there were emitters on both sides of the donut. Therefore, only the center of the donut crumb was heated through conduction rather than radiation. The crumb of the GF fully-fried donuts was heated mainly by conduction of heat from the crust. Conduction is a slower mode of heat transfer than radiation, so the GF fully-fried donut crumb did not heat as quickly during cooking as the par-fried, IR-finished donut crumb did, resulting in a lower core temperature.

Core temperatures of the GF par-fried, IR-finished donuts did not appear to be correlated with IR oven residence time. The core temperatures of all GF par-fried, IR-finished donuts were close to the boiling point of water, which is the maximum temperature possible until all available water evaporates. It is possible that the rate of heating in the GF

par-fried, IR-finished donuts was rapid enough to allow the core temperature to rise near the boiling point of water in 39 seconds, the shorter IR residence time. Comparing the core temperatures found in this study with core temperatures in donuts produced with IR oven residence times shorter than 39 s may show a correlation of IR residence time to core temperature. Core temperature did appear to be affected by the overall heat flux provided by IR cooking: as the heat flux provided by the IR oven increased, core temperature generally increased.

#### *6.4.3. Oil and moisture content*

All GF par-fried, IR-finished donuts had moisture content (Table 6.3) comparable to or higher than ( $p \leq 0.05$ ) both the wheat control (23.3%) and the GF control (23.2%). Moisture content of the GF par-fried, IR-finished donuts ranged from 23.1% to 25.9%. With the exception of the GF par-fried, IR-finished donuts from Trial G7 (23.1%) and Trial G8 (24.0%), IR oven residence time did not appear to significantly affect moisture content. The moisture content did appear to be affected by the heat flux provided by the first half of the IR cooking. Moisture content generally increased as the heat flux in the first half of IR cooking decreased. Again, donuts from Trial G7 and G8 were an exception to this trend. However, these donuts were exposed to the highest heat flux (15.2 to 16.4 kW/m<sup>2</sup>) in the second half of IR cooking, so it is possible that this higher flux caused the decreased moisture content in these donuts.

All GF par-fried, IR-finished donuts had significantly lower ( $p \leq 0.05$ ) fat content (Table 6.3) than the wheat control (33.7%). With the exception of the GF par-fried, IR-

finished donuts from Trial G6 (27.9%), Trial G7 (28.2%) and Trial G8 (27.8%), all of the GF par-fried, IR-finished donuts had a significantly lower fat content than the GF control (27.2%). However, the GF par-fried, IR-finished donuts from Trial G6 and Trial G8 had comparable fat content to the GF control; only the GF par-fried, IR-finished donuts from Trial G7 had significantly higher fat content. Fat content of the GF par-fried, IR-finished donuts ranged from 23.7% to 28.2%. Fat and moisture content were found to be negatively correlated ( $R^2=-0.90$ ,  $p<0.0001$ ). This result has been found by several researchers (Shih et al., 2001; Kassama and Ngadi, 2005; Tan and Mittal, 2006).

The lower fat content of the GF par-fried, IR-finished donuts as compared to fat content of the wheat donuts is likely due not only to the shorter frying time, which resulted in lower oil uptake, but also the rice flour, pregelatinized rice flour and methylcellulose coating used in the GF par-fried, IR-finished donut formulation. Rice flour has been shown to lower oil uptake in various fried foods (Mukprasirt et al., 2001; Shih et al., 2001; Shih et al., 2004; Shih et al., 2005). The proteins in rice flour resist oil uptake during frying, resulting in a product with lower fat content as compared to fried products made with other types of flour (Jackson et al., 2006). Pregelatinized rice flour has been shown to lower the fat content of donuts (Shih et al., 2001; Shih and Daigle, 2002) and rice-based batters (Shih et al., 2005). Methylcellulose coatings have also been shown to lower fat content of fried foods (Pinthus et al., 1993; García et al., 2002; Shih and Daigle, 2002; García et al., 2004).

The significantly lower ( $p\leq 0.05$ ) fat content of the GF par-fried, IR-finished donuts as compared to the GF control indicates that IR-finishing also played a role in lowering the fat content of the GF par-fried, IR-finished donuts. With the exception of the GF par-fried, IR-

finished donuts from Trial G7 (28.2%) and Trial G8 (27.8%), fat content decreased with increased IR oven residence time (39 to 45 s), although the difference was not significant except for the GF par-fried, IR-finished donuts in Trial G5 (25.1%) and Trial G6 (27.9%). In general, fat content decreased with increased overall heat flux and increased heat flux provided by the first half of IR cooking. It was hypothesized that all GF par-fried, IR-finished donuts would have the same fat content because they were all fried for the same period of time and it was assumed that no oil was gained or lost in the IR oven. However, they did not have statistically similar fat contents. It is possible that higher IR heat flux (Figure 6.1) kept the oil on the surface of the crust hotter than a lower flux, decreasing the viscosity of the oil enough so that it could easily drip off of the donuts as they traveled along the belt. Oil was observed to be continually dripping off of the donuts during IR-fining, although a quantitative measure of this drip loss was not conducted. It is recommended that the relationship between IR heat flux and fat content be further investigated to provide a more thorough explanation for these results.

#### *6.4.4. Crust color*

In general, crust color (Table 6.3) of the GF par-fried, IR-finished donuts was comparable ( $p \leq 0.05$ ) to crust color of the wheat control but darker than the GF control. Because the core temperatures of the GF par-fried, IR-finished donuts were significantly higher than that of the GF control, it may be assumed that the GF par-fried, IR-finished donuts were cooked to a greater extent than the GF control. The darker crust color of the GF par-fried, IR-finished donuts was likely from the higher heat flux experienced during IR-

finishing. A higher flux would increase the temperature of the donut surface, increasing the amount of Maillard products and producing a darker crust. The wheat control had a comparable core temperature to the GF par-fried, IR-finished donuts, so it may be assumed that the wheat donuts underwent a comparable amount of cooking as compared to the GF par-fried, IR-finished donuts. Correspondingly, the crust color of the GF par-fried, IR-finished donuts was similar to that of the wheat control.

The  $L^*$  values of the GF par-fried, IR-finished donuts ranged from 33.7 to 49.3, the  $a^*$  values ranged from -33.1 to 19.4, and the  $b^*$  values ranged from 21.4 to 35.3 (Table 6.3). Only the GF par-fried, IR-finished donuts from Trial G1 had significantly different (lower)  $L^*$  values than the wheat control (44.3). All GF par-fried, IR-finished donuts, except the donuts from Trial G4 (49.3), had significantly lower  $L^*$  values than the GF control (52.8). The GF par-fried, IR-finished donuts from Trial G5 and Trial G6 had significantly lower  $a^*$  values (-20.9 and -33.1, respectively) than both the wheat and GF controls (10.5 and 2.21, respectively); all other donuts had comparable  $a^*$  values to both controls. The GF par-fried, IR-finished donuts from Trial G1 (21.4) and Trial G3 (24.1) were the only GF par-fried, IR-finished donuts to have significantly different (lower)  $b^*$  values than the  $b^*$  value of the wheat control (35.3), while all of the GF par-fried, IR-finished donuts had significantly higher  $b^*$  values than that of the GF control (11.8). Using an infrared finishing process for products made with modified rice starches may counteract the decrease in  $b^*$  value seen by Gallagher et al. (2004).

The  $L^*$  values of the GF par-fried, IR-finished donuts decreased and the  $b^*$  values increased with increased IR oven residence time (Figures 6.2 and 6.4, respectively), with the

exception of the GF par-fried, IR-finished donuts from Trial G5 (44.7 and 32.1, respectively) and Trial G6 (43.1 and 30.1, respectively). The  $a^*$  values of the GF par-fried, IR-finished donuts decreased with increased IR oven residence time (Figure 6.3). In general, as the overall heat flux from the IR oven increased, the  $L^*$  values of the GF par-fried, IR-finished donuts decreased. The  $a^*$  values generally increased with increased heat flux provided by the second half of the IR cooking, with the exception of the GF par-fried, IR-finished donuts from Trial G7 (6.95) and Trial G8 (1.24). The overall heat flux or the heat flux provided in either the first or second half of IR cooking (Figure 6.1) did not appear to be correlated to the  $b^*$  values of the GF par-fried, IR-finished donuts. In general, increased heat flux and IR oven residence time resulted in increased crust darkening. Red and yellow hues increased with increased heat flux in the second half of IR cooking and increased IR oven residence time, respectively.

#### *6.4.5. Mechanical properties*

All GF par-fried, IR-finished donuts had significantly higher ( $p \leq 0.05$ ) force to puncture the crust (Table 6.4) than the wheat control (0.774 N), with the exception of donuts from Trial G2 (1.40 N) and Trial G8 (1.24 N). Gluten-free flours, particularly rice flour, generally do not have the water-binding or network forming abilities that wheat flour, containing gluten, does (Shih et al., 2001, Shih et al., 2004, Shih et al., 2005). The lower water-binding ability results in rapid moisture loss from the donut during frying, increasing the rate of crust drying and resulting in a harder crust. Similar results have been reported for breaded okra (Shih et al., 2005). However, with the exception of the donuts from Trial G3

(2.61 N), all GF par-fried, IR-finished donuts had comparable hardness to the GF control. Infrared finishing did not appear to increase crust hardness of GF donuts.

The force to puncture the crust of the GF par-fried, IR-finished donuts ranged from 1.24 N to 2.61 N. Gluten-free par-fried, IR-finished donuts made with a lower IR oven residence time had softer crust, although the difference was only significant for the GF par-fried, IR-finished donuts from Trial G3 (2.61 N) and Trial G4 (1.07). The longer IR oven residence time likely resulted in increased crust drying, forming a harder crust. Both overall heat flux and heat flux provided in either the first or second half of IR-finishing did not appear to be correlated to crust hardness. Crust hardness in GF par-fried, IR-finished donuts appeared to be much more dependent on IR oven residence time than on heat flux provided.

Crumb H1 and H2 values (Table 6.4) of the GF par-fried, IR-finished donuts ranged from 5.59 to 10.1 N and from 4.11 to 6.47 N, respectively. All GF par-fried, IR-finished donuts had significantly higher ( $p \leq 0.05$ ) H1 and H2 values than the wheat control (2.63 N and 2.11 N, respectively). One possible explanation of the increased crumb hardness of the GF par-fried, IR-finished donuts as compared to the wheat control is the lower fat content of the GF par-fried, IR-finished donuts. Fat tenderizes the crumb of baked goods (Bennion and Scheule, 2004), so as fat content decreases, crumb hardness increases. In addition, the lack of gluten in rice flour combined with its low water-binding abilities allowed significant moisture migration from the crumb to the crust during storage (Gallagher et al., 2003), resulting in significantly firmer crumb after several days of storage as compared to wheat (Kadan et al., 2001).

The GF par-fried, IR-finished donuts from Trial G5 (4.40 N) and Trial G8 (4.11 N) had comparable ( $p \leq 0.05$ ) H1 values to the GF control (4.46 N), while donuts from Trial G1 (4.61 N), Trial G5 (4.40 N), Trial G6 (4.42 N), and Trial G8 (4.11 N) had comparable ( $p \leq 0.05$ ) H2 values to the GF control (3.69 N). All other GF par-fried, IR-finished donuts had significantly higher H1 and H2 values than the GF control. Hardness 1 and H2 of the GF par-fried, IR-finished donuts were found to be correlated ( $R^2 = 0.89$ ,  $p < 0.0001$ ). Crumb hardness did not appear to be significantly affected by IR oven parameters.

The cohesiveness (Table 6.4) of all GF par-fried, IR-finished donuts (0.263 to 0.428) was significantly lower ( $p \leq 0.05$ ) than the wheat control (0.573), indicating that the GF par-fried, IR-finished donuts were more crumbly than the wheat control. This result was expected, as the lack of structure provided by gluten causes crumbly, brittle crumb textures in GF products (Gallagher et al., 2004). However, the GF par-fried, IR-finished donuts had comparable cohesiveness to the GF control (0.472), with the exception of donuts from Trial G2 (0.296), Trial G6 (0.263), and Trial G7 (0.282), which had lower cohesiveness. In general, as the overall heat flux provided by the IR oven increased (Figure 6.1), cohesiveness decreased, possibly due to increased moisture loss and crumb dryness at the higher flux. Infrared oven residence time did not appear to be correlated to cohesiveness.

Springiness and chewiness (Table 6.4) of the GF par-fried, IR-finished donuts ranged from 1.03 to 2.86 and 1.43 to 7.58, respectively. The springiness and chewiness of the GF par-fried, IR-finished donuts were not significantly different ( $p \leq 0.05$ ) from the GF control (1.87 and 3.57, respectively). With the exception of the springiness of the GF par-fried, IR-finished donuts from Trial G4 (2.86) and Trial G5 (2.27), all GF par-fried, IR-finished donuts

were significantly ( $p \leq 0.05$ ) less springy than the wheat control (3.48). However, all of the GF par-fried, IR-finished donuts had comparable chewiness to the wheat control (5.01). Springiness and chewiness decreased with decreased IR oven residence time, with the exception of donuts from Trial G3 and Trial G4, but the differences were not found to be significant.

#### 6.4.6. *Sensory evaluation*

Overall acceptance scores (Table 6.5) were significantly different ( $p \leq 0.05$ ) among the GF par-fried, IR-finished donuts, although there were no significant differences among the GF par-fried, IR-finished donuts for all other attribute scores (Table 6.5). The GF par-fried, IR-finished donuts from Trial G7 had lower overall acceptance scores than the other GF par-fried, IR-finished donuts (3.81 vs. 3.98-4.44, respectively), although this score was not significantly different from the overall acceptance scores of the GF par-fried, IR-finished donuts from Trial G3 and Trial G8. However, it was significantly lower than the GF par-fried, IR-finished donuts from Trial G2. The lower acceptability scores may have been due to the fact that the GF par-fried, IR-finished donuts from Trial G7 had a harder crumb than the other GF par-fried, IR-finished donuts. The harder crumb may have increased the perception of a dry, crumbly texture, resulting in lower sensory scores.

All GF par-fried, IR-finished donuts had significantly lower ( $p \leq 0.05$ ) sensory scores (Table 6.5) than the wheat control donut, indicating that they were all liked less than the wheat control for every attribute tested. With overall acceptance scores ranging between

3.81 and 4.44 (dislike slightly), the GF par-fried, IR-finished donuts were not nearly as acceptable to the panelists as the wheat control (overall acceptance of 6.94).

Panelists commented that all donuts were bland or not sweet enough. Applying a glaze or a heavier coating of powdered sugar to the donuts may improve the overall acceptance scores of all donuts. In addition, many panelists commented that the GF par-fried, IR-finished donuts were dry and had a heavy texture, and a few panelists commented on the grittiness of the GF par-fried, IR-finished donuts. The grittiness was most likely due to residual rice flour on the surface of the GF par-fried, IR-finished donuts used to keep the dough from sticking while the donuts were rolled out. Gluten-free products in general tend to be drier than wheat products, as GF flours generally do not have the water-holding capacity of wheat flour (Shih et al., 2006; Sabanis and Tzia, 2009). The comments on heavy texture most likely arose from the comparison of the GF donuts to the control, which had a much softer and less dense crumb texture. The GF par-fried, IR-finished donuts had a relatively low volume, making the crumb denser than the wheat crumb. It is suggested that further investigation on gluten replacement and donut formulation be investigated to improve the texture and mouthfeel of the GF par-fried, IR-finished donuts.

## **6.5. Conclusions**

All GF par-fried, IR-finished donuts had significantly lower change in mass than the wheat control, likely caused by the shorter frying time used for the par-fried, IR-finished donuts. However, change in mass of the GF par-fried, IR-finished donuts was generally comparable to change in mass of the GF control. Gluten-free par-fried, IR-finished donuts

had statistically similar volume and density changes to both the wheat and GF control, indicating that IR-finishing most likely does not adversely affect final volume. Core temperatures of all GF par-fried, IR-finished donuts were comparable to the wheat control but significantly higher than the GF control. Volume and density changes and core temperature increased with increased IR heat flux.

Moisture content was generally higher in the GF par-fried, IR-finished donuts than in both the wheat and GF control. Fat content of the GF par-fried, IR-finished donuts was significantly lower than the wheat control and generally comparable to or lower than the GF control. Fat content was likely impacted by both the flours used in the GF par-fried, IR-finished donuts and the shorter frying time used for these donuts.

Generally,  $L^*$ ,  $a^*$ , and  $b^*$  values of the GF par-fried, IR-finished donuts were similar to the wheat control. Gluten-free, par-fried, IR-finished donuts also had comparable  $a^*$  values to the GF control. However, the GF par-fried, IR-finished donuts had significantly lower  $L^*$  values and significantly higher  $b^*$  values than the GF control, indicating an increase in crust darkening. Crust color of the GF par-fried, IR-finished donuts was affected by total amount of flux provided by the emitters and IR oven residence time. Gluten-free par-fried, IR-finished donuts generally had a firmer crust and crumb than the wheat control but had comparable crust firmness to and a firmer crumb than the GF control. The relatively high crust and crumb firmness was likely due to a combination of the lack of water-binding gluten and a lower fat content in the GF par-fried, IR-finished donuts. Springiness and cohesiveness of the GF par-fried, IR-finished donuts were lower than the wheat control, although the chewiness was not significantly different from the wheat control. Springiness,

cohesiveness, and chewiness of the GF par-fried, IR-finished donuts were comparable to the GF control. Springiness, cohesiveness, and chewiness values did not appear to be affected by IR parameters.

Sensory scores of GF par-fried, IR-finished donuts were statistically similar to the GF control. However, all GF par-fried, IR-finished donuts had significantly lower sensory scores than the wheat control. Based on the instrumental and sensorial results, infrared radiation may be used in place of a full-frying process to yield a product similar to a GF fully-fried donut but with significantly lower fat content. However, the GF par-fried, IR-finished donuts were generally not as sensorially acceptable as the wheat control, even though they may have been instrumentally comparable.

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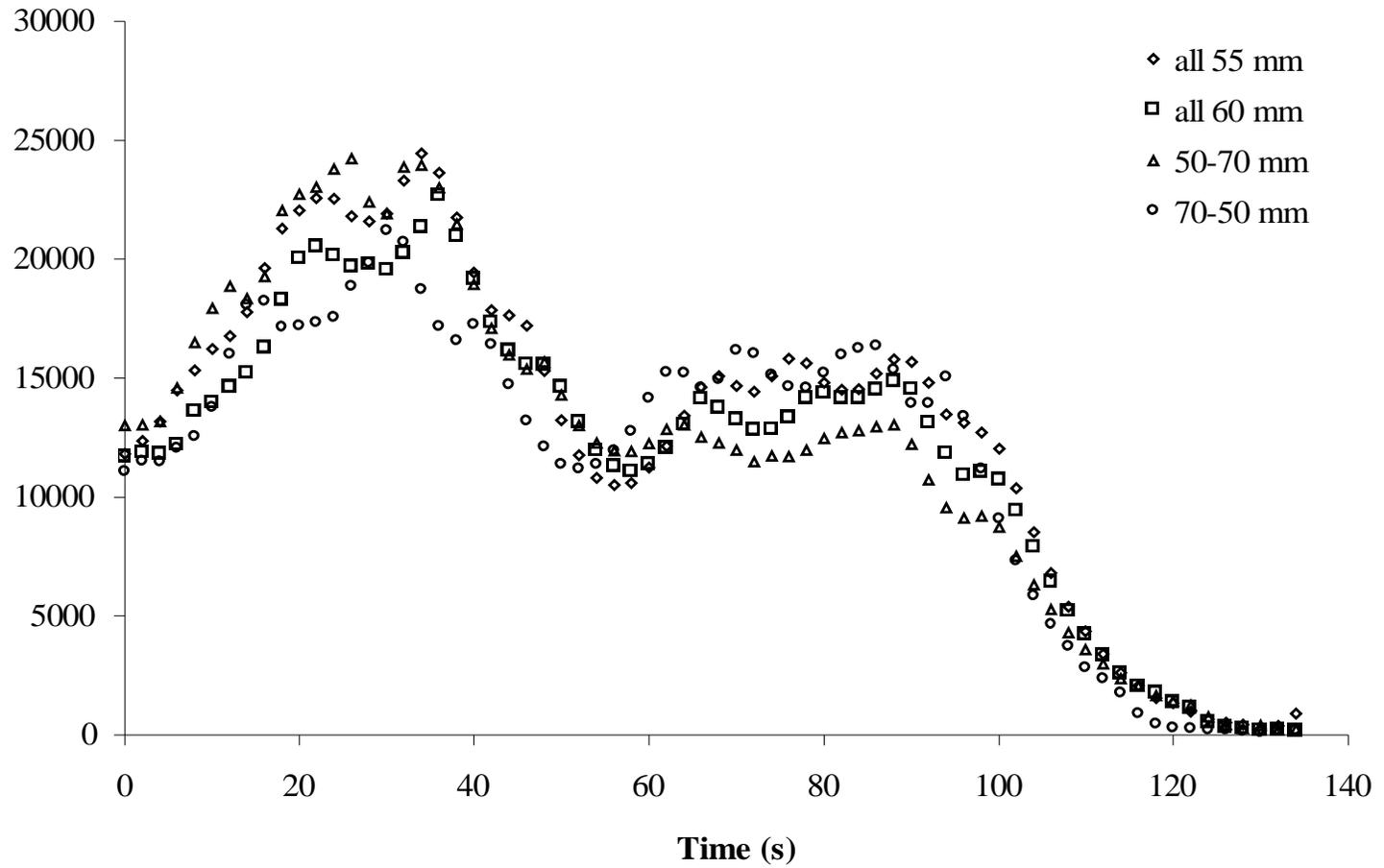
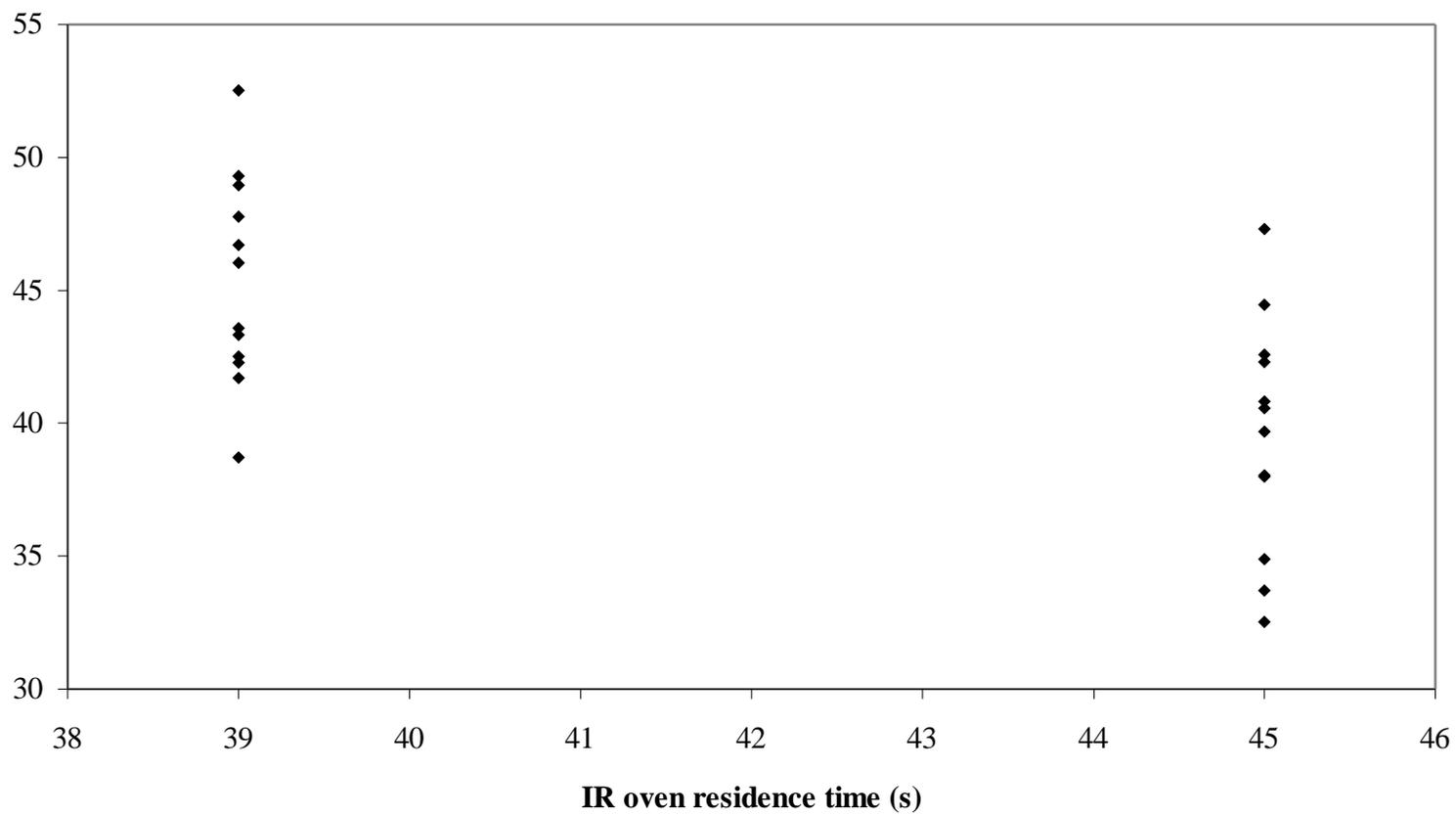
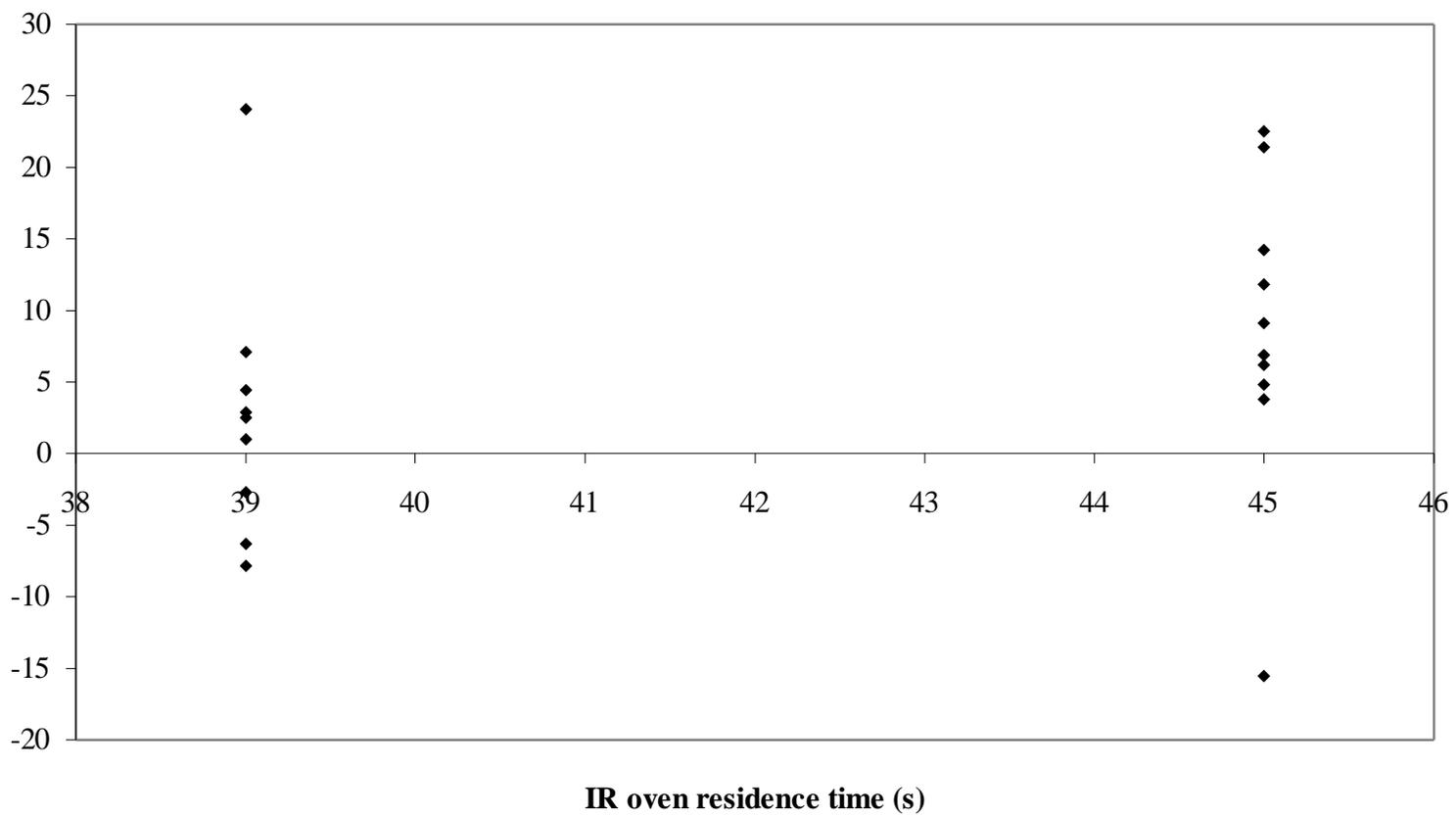


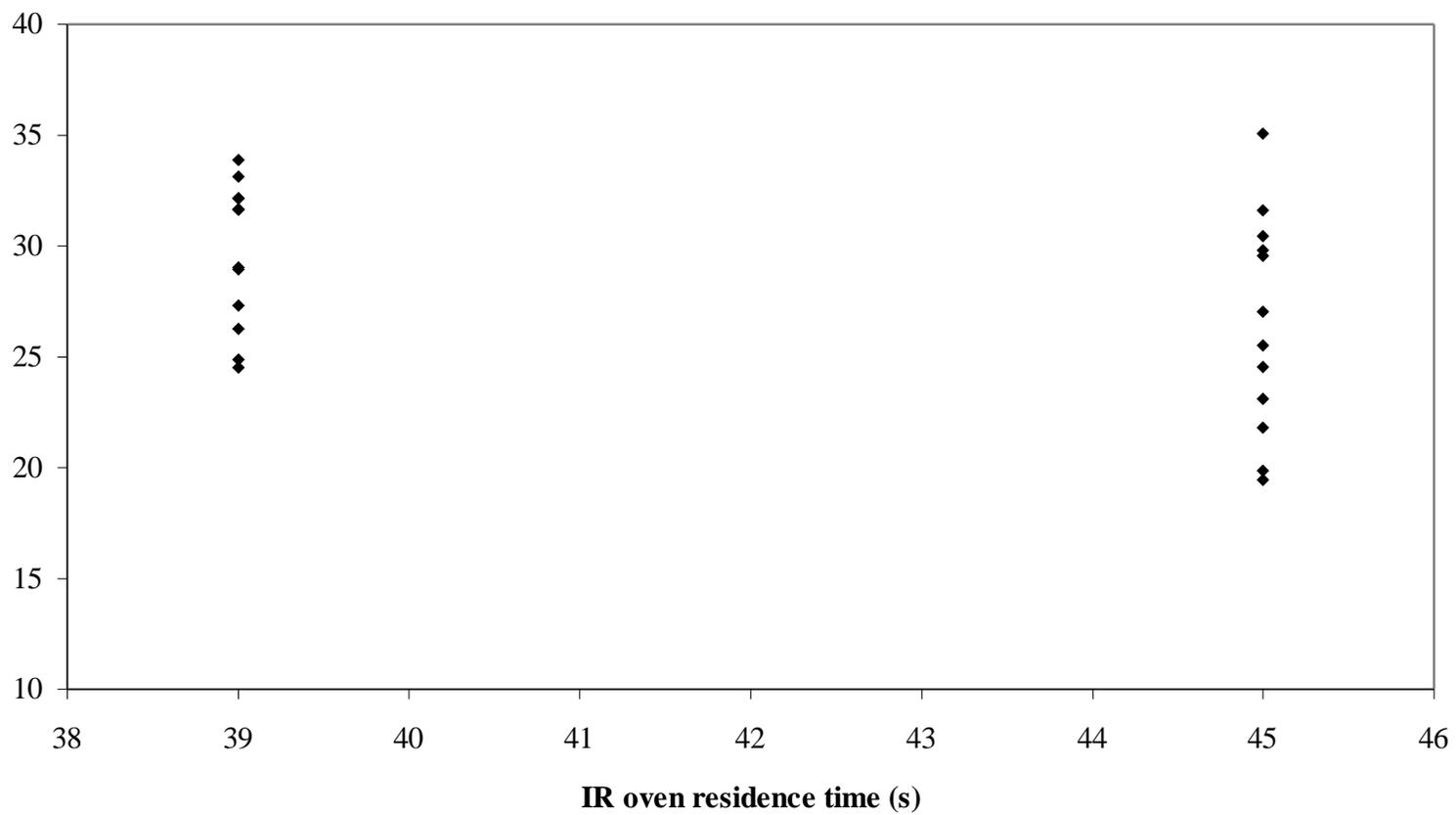
Figure 6.1. Heat flux profiles for emitter settings



**Figure 6.2. Trend in L\* values of GF par-fried, IR-finished donuts**



**Figure 6.3. Trend in a\* values of GF par-fried, IR-finished donuts**



**Figure 6.4. Trend in b\* values of GF par-fried, IR-finished donuts**

**Table 6.1. GF par-fried, IR-finished donut formulation**

<b>Ingredient</b>	<b>Weight (g)</b>	<b>% weight (total flour basis)</b>
Commercial GF flour	175.0	50%
Rice flour	164.5	47%
Water	113.4	32%
Shortening	56.70	16%
Egg	37.80	11%
Warm water	37.80	11%
Sugar	18.90	5.4%
Nonfat dry milk powder	18.90	5.4%
PGRF	10.50	3.0%
Yeast	9.00	2.6%
Salt	4.72	1.3%
Baking powder	4.72	1.3%
Xanthan gum	3.52	1.0%
Vanilla extract	1.57	0.45%

Note: Total flour weight is the sum of the weights of the commercial GF flour, the rice flour, and the pregelatinized rice flour.

**Table 6.2. IR oven settings for GF par-fried, IR-finished donuts**

<b>Trial</b>	<b>Emitter heights (mm)</b>	<b>Residence time (s)</b>
G1	$h_1: 55, h_2: 55, h_3: 55, h_4: 55, h_5: 55$	45
G2	$h_1: 55, h_2: 55, h_3: 55, h_4: 55, h_5: 55$	39
G3	$h_1: 60, h_2: 60, h_3: 60, h_4: 60, h_5: 60$	45
G4	$h_1: 60, h_2: 60, h_3: 60, h_4: 60, h_5: 60$	39
G5	$h_1: 50, h_2: 50, h_3: 60, h_4: 70, h_5: 70$	45
G6	$h_1: 50, h_2: 50, h_3: 60, h_4: 70, h_5: 70$	39
G7	$h_1: 70, h_2: 70, h_3: 60, h_4: 50, h_5: 50$	45
G8	$h_1: 70, h_2: 70, h_3: 60, h_4: 50, h_5: 50$	39

**Table 6.3. Mass, volume, and density change, final temperature, crust color, and moisture and fat content of GF par-fried, IR-finished donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Mass change (%)</b>	<b>Volume change (%)</b>	<b>Density change (%)</b>	<b>Final core temp (°C)</b>
G1	-2.41±1.15% (bc)	57%±0.9% (a)	-38%±0.4% (cd)	96.1±4.6 (a)
G2	-2.25±1.27% (bc)	65%±10.9% (a)	-41%±3.2% (d)	97.9±0.6 (a)
G3	-3.20±0.91% (c)	60%±5.3% (a)	-40%±2.4% (cd)	96.9±2.3 (a)
G4	-2.52±1.33% (bc)	40%±11.0% (abcd)	-30%±6.0% (abcd)	94.8±4.3 (a)
G5	-2.90±1.00% (c)	52%±8.9% (ab)	-36%±3.2% (cd)	95.7±3.2 (a)
G6	-1.00±1.25% (bc)	48%±5.6% (abc)	-33%±1.8% (bcd)	97.9±1.7 (a)
G7	-1.10±0.72% (bc)	22%±6.1% (d)	-19%±3.8% (a)	98.9±0.7 (a)
G8	-1.11±0.22% (bc)	26%±9.7% (cd)	-21%±5.8% (ab)	92.4±1.3 (a)
CW	10.86±1.96% (a)	43%±13.8% (abcd)	-22%±6.9% (ab)	94.1±2.7 (a)
CGF	-0.68±1.67% (bc)	29%±6.8% (bcd)	-23%±3.6% (ab)	80.2±7.8 (b)
GFPF	0.90±1.17% (b)	41%±6.2% (abcd)	-28%±3.9% (abc)	80.1±5.8 (b)

<b>Trial</b>	<b>Crust color</b>			<b>Moisture content (%)</b>	<b>Fat content (%)</b>
	<b>L*</b>	<b>a*</b>	<b>b*</b>		
G1	33.7±1.2 (e)	7.27±4.1 (ab)	21.4±1.9 (c)	25.7%±0.1% (b)	23.7%±0.12% (e)
G2	41.0±2.0 (d)	0.26±2.7 (b)	29.2±3.0 (abc)	25.7%±0.12% (b)	24.3%±0.14% (de)
G3	39.5±1.4 (de)	19.4±4.5 (a)	24.1±3.8 (bc)	25.9%±0.38% (b)	23.9%±0.38% (e)
G4	49.3±3.2 (ab)	6.89±16.1 (ab)	26.9±2.2 (abc)	25.8%±0.16% (b)	24.0%±0.12% (e)
G5	44.7±2.5 (bcd)	-20.9±4.7 (c)	32.1±2.8 (ab)	24.8%±0.04% (c)	25.1%±0.33% (d)
G6	43.1±0.7 (cd)	-33.1±1.0 (c)	30.1±4.7 (abc)	24.7%±0.09% (c)	27.9%±0.12% (bc)
G7	40.4±2.3 (d)	6.95±2.1 (ab)	28.3±3.2 (abc)	23.1%±0.20% (e)	28.2%±0.03% (b)
G8	47.8±1.1 (abc)	1.24±6.8 (ab)	32.3±0.7 (ab)	24.0%±0.33% (d)	27.8%±0.44% (bc)
CW	44.3±1.6 (bcd)	10.5±0.2 (ab)	35.3±0.3 (a)	23.3%±0.11% (e)	33.7%±0.55% (a)
CGF	52.8±2.6 (a)	2.21±7.5 (ab)	11.8±3.1 (d)	23.2%±0.13% (e)	27.2%±0.03% (c)
GFPF	49.7±2.9 (ab)	4.56±2.3 (ab)	30.4±4.1 (ab)	27.0%±0.14% (a)	23.8%±0.43% (e)

Note: Trial number indicates the heating treatment for the corresponding number in Table 6.2. CW is the fully-fried wheat control donut, CGF is the fully-fried GF control donut, and GFPF is the GF donut that was par-fried only. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Table 6.4. Mechanical properties of GF par-fried, IR-finished donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Force to puncture crust (N)</b>	<b>H1 (N)</b>	<b>H2 (N)</b>	<b>Cohesiveness</b>	<b>Springiness</b>	<b>Chewiness</b>
G1	1.64±0.32 (bc)	6.52±0.74 (de)	4.61±0.08 (bc)	0.428±0.083 (bc)	1.63±0.21 (bc)	3.76±0.09 (b)
G2	1.40±0.30 (bcd)	8.45±0.93 (abc)	5.57±0.79 (ab)	0.296±0.036 (cde)	1.41±0.12 (bc)	2.95±0.07 (b)
G3	2.61±0.26 (a)	8.89±0.90 (ab)	6.47±0.77 (a)	0.346±0.056 (bcde)	1.29±0.11 (bc)	3.93±0.40 (ab)
G4	1.07±0.15 (cd)	7.48±0.88 (bcd)	5.55±0.58 (ab)	0.372±0.074 (bcde)	2.86±0.60 (ab)	7.58±1.62 (a)
G5	1.92±0.17 (ab)	5.90±0.47 (def)	4.40±0.43 (bc)	0.406±0.032 (bcd)	2.27±0.75 (abc)	3.30±1.70 (b)
G6	1.51±0.23 (bc)	6.81±0.07 (cde)	4.42±0.13 (bc)	0.263±0.043 (e)	1.03±0.44 (c)	1.43±0.57 (b)
G7	1.65±0.35 (bc)	10.1±0.25 (a)	6.46±0.42 (a)	0.282±0.021 (de)	1.49±0.07 (bc)	4.24±0.26 (ab)
G8	1.24±0.09 (bcd)	5.59±0.59 (ef)	4.11±0.39 (c)	0.342±0.049 (bcde)	1.43±0.30 (bc)	2.22±0.56 (b)
CW	0.77±0.03 (d)	2.63±0.38 (g)	2.11±0.16 (d)	0.573±0.028 (a)	3.48±1.35 (a)	5.01±2.84 (ab)
CGF	1.51±0.27 (bc)	4.46±0.56 (fg)	3.69±0.42 (c)	0.472±0.025 (ab)	1.87±0.42 (abc)	3.57±1.35 (b)

Note: Trial number indicates the heating treatment for the corresponding number in Table 6.2. CW is the fully-fried wheat control donut and CGF is the fully-fried GF control donut. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

**Table 6.5. Sensorial properties of selected GF par-fried, IR-finished donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Overall acceptance</b>	<b>Appearance</b>	<b>Aroma</b>	<b>Texture</b>	<b>Mouthfeel/ Taste</b>
G2	4.44±1.65 (b)	5.64±1.38 (b)	5.61±1.32 (b)	4.57±1.80 (b)	3.86±1.77 (b)
G3	4.22±1.58 (bc)	5.64±1.61 (b)	5.56±1.47 (b)	4.22±1.69 (b)	3.65±1.71 (b)
G7	3.81±1.59 (c)	5.26±1.72 (b)	5.18±1.55 (b)	3.95±1.57 (b)	3.28±1.53 (b)
G8	3.98±1.61 (bc)	5.60±1.50 (b)	5.47±1.49 (b)	4.11±1.82 (b)	3.45±1.71 (b)
CW	6.94±1.17 (a)	7.17±1.08 (a)	6.78±1.12 (a)	6.75±1.28 (a)	6.94±1.60 (a)

Note: Trial number indicates the heating treatment for the corresponding number in Table 6.2. CW is the fully-fried wheat control donut. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.

# **Chapter 7: General Results, Conclusions, and Future Work**

## 7.1. Oscillatory testing

After examining the mechanical data and sensory scores, it was clear that there were significant differences in the gluten-free (GF) and wheat donut crumb properties. To gain a better understanding of the differences between the wheat and GF crumb, oscillatory testing was performed on wheat and GF dough as it baked. The moduli (Figure 7.1) of the GF dough were significantly higher at all times during the testing. A higher modulus indicates a more solid material; these results indicated that the GF donuts were firmer than the wheat donuts. This agreed with the mechanical and sensorial data: the fully-fried GF donuts made with the dough formulation tested (GF8) had significantly higher force to puncture the crust (1.51 N vs. 0.77 N, respectively) and higher crumb hardness than the wheat control donut (4.46 N vs. 2.63 N, respectively, for hardness 1 (H1) and 3.69 N vs. 2.11 N, respectively for hardness 2 (H2)). In addition, many panelists remarked on the heaviness or denseness of the GF donuts compared to the wheat donuts, indicating that the GF donuts were firmer sensorially as well as instrumentally.

The phase angle (Figure 7.2), which shows the degree of solid- or liquid-like behavior, was lower for the GF dough than the wheat dough at the start of testing. This indicated that the wheat dough showed less solid-like behavior than the GF dough. The viscosity of the GF dough was higher than the viscosity of the wheat dough at all times during testing (Figure 7.3), so it was expected that the phase angle of the GF dough would be lower than the phase angle of the wheat dough. The phase angle of both the wheat and GF doughs increased slowly until about 385 s. It was hypothesized that the onset of starch gelatinization at this time caused a more solid crumb structure to form, resulting in a sharp

decrease in phase angle. The core temperature of the donuts at this time during testing was approximately 75 °C, which above the temperature needed for gelatinization of both wheat and rice flour (Lelievre, 1973; Sciarini et al., 2008). Because the core temperature of the dough samples did not reach the gelatinization temperature needed for rice starch and wheat starch until 330 s and 360 s, respectively, after testing started, it likely that starch gelatinization began at the time when the phase angle began to decrease. After about 490 s, the phase angles of the two doughs became very similar and remained so for the remainder of the testing.

## **7.2. Donut comparison**

To determine the infrared (IR) finishing parameters that produce wheat and GF par-fried, IR-finished donuts most similar to fully-fried wheat control donuts, it was necessary to compare the degree of instrumental and sensorial similarity among the wheat and GF par-fried, IR-finished donuts. The instrumental degree of similarity for each wheat and GF par-fried, IR-finished donut (Table 7.1 and 7.3, respectively) was calculated using the scoring matrix detailed in the General Materials and Methods section (Melito, 2009). The GF fully-fried donuts were also scored to determine which formulation produced donuts most similar to the wheat control (Table 7.2).

The wheat par-fried, IR-finished donuts that received the best overall scores (Table 7.1) were the wheat par-fried, IR-finished donuts from Trial 3 (11), Trial 4 (13), Trial 7 (12) and Trial 8 (11). The same wheat par-fried, IR-finished donuts had the best scores for the selected measurements (Table 7.1): 7, 8, 8, and 6 for Trial 3, Trial 4, Trial 7, and Trial 8,

respectively. Out of these four trials, the trial that had parameters that produced wheat par-fried, IR-finished donuts most similar to the wheat control was Trial 4.

The four trials that produced wheat par-fried, IR-finished donuts most similar to the wheat control had IR parameters that gave a relatively low overall heat flux (14.1 kW/m<sup>2</sup> to 22.7 kW/m<sup>2</sup> for 53 s and 45 s for Trials 3 and 4, respectively; 15.2 kW/m<sup>2</sup> to 21.2 kW/m<sup>2</sup> for 53 s and 45 s for Trials 7 and 8, respectively) as well as a relatively low heat flux in the first half of IR cooking (20.5 kW/m<sup>2</sup> to 22.7 kW/m<sup>2</sup> for 26.5 s and 22.5 s for Trials 3 and 4, respectively; 17.2 kW/m<sup>2</sup> to 21.2 kW/m<sup>2</sup> for 26.5 s and 22.5 s for Trials 7 and 8, respectively). Because peak heat flux is reached very quickly during frying (Figure 7.4), the donuts may be assumed to have already reach peak heat flux when they were transferred to the IR oven. After peak heat flux is reached, heat flux to the donuts decreases (Figure 7.4). To simulate frying, a relatively low flux that decreases over time is needed during this point in the cooking. There did not appear to be a trend between IR residence time and either overall or selected scoring of the wheat par-fried, IR-finished donuts, indicating that variations in IR residence time (45 s to 53 s for wheat donuts; 39 s to 45 s for GF donuts) did not significantly affect the quality of the wheat par-fried, IR-finished donuts.

The GF fully-fried donuts that received the best overall scores (Table 7.2) were the GF fully-fried donuts from Trial GF1 (10), Trial GF2 (10), Trial GF3 (11), Trial GF4 (10), and Trial GF8 (10). Some of the same GF fully-fried donuts had the best scores for the selected measurements: 8, 7, and 7 for Trial GF3, Trial GF4, and Trial GF8, respectively (Table 7.2). Out of the trials with the highest scores for both overall and selected scoring, the trial that had parameters that produced GF fully-fried donuts most similar to the wheat

control was Trial GF3. In general, the GF fully-fried donuts made with a 3:1 ratio of commercial GF flour to rice flour had higher scores than GF fully-fried donuts made with a 1:1 ratio of commercial GF flour to rice flour. The GF fully-fried donuts made with a 1:1 ratio of commercial GF flour to rice flour did not score well on mechanical attributes: they were generally harder than either the wheat control or the GF fully-fried donuts made with a 3:1 ratio of commercial GF flour to rice flour (Melito, 2009). Mechanical attributes comprised a large part of both overall and selected scoring, so the differences between the wheat control and the GF fully-fried donuts made with a 1:1 ratio of commercial GF flour to rice flour with respect to these attributes was most likely the cause of the lower scores. The presence of pregelatinized rice flour in the GF donut formulation did not appear to affect Scoring 1 but Scoring 2 generally increased with the presence of pregelatinized rice flour. Again, this probably due to the influence of the mechanical attribute scores. Pregelatinized flour improves water-holding ability (Shih and Daigle, 2002), decreasing the dryness and crumbliness of the crumb and producing a texture more similar to that of wheat crumb. The methylcellulose coating appeared to have no significant effect on scoring.

Although Trial GF3 had the best overall and selected scores of all the GF fully-fried donuts, the formulation from Trial GF8 was chosen to be the formulation of the GF par-fried, IR-finished donuts. This choice was made for several reasons. First, although this trial did not have the highest overall or selected score, it still had a relatively high score. It also scored relatively well with respect to mechanical attributes. Finally, it had a relatively low fat content (27.2%); this fat content was significantly lower than all of the other top-scoring donuts. One of the main goals of these studies was to produce donuts with a significantly

lower fat content than the wheat control. Because the GF fully-fried donuts from Trial GF8 had a relatively low fat content but were still instrumentally and sensorially comparable to the wheat control, the formulation from Trial GF8 was chosen to be the formulation of the GF par-fried, IR-finished donuts.

The GF par-fried, IR-finished donuts that received the best overall scores (Table 7.3) were the GF par-fried, IR-finished donuts from Trial G4 (10) and Trial G8 (10). The same GF par-fried, IR-finished donuts had the best scores for the selected measurements (Table 7.3): 5 for both Trial G4 and Trial G8. Donuts from Trial G5 also scored 5. Out of these three trials, the GF par-fried, IR-finished donuts that were most similar to the wheat control were from Trial G4 and Trial G8. These two trials had IR parameters (Melito, 2009) that gave a relatively low heat flux throughout cooking (14.1 kW/m<sup>2</sup> to 22.7 kW/m<sup>2</sup> for 39.1 s for Trial G4 and 15.2 kW/m<sup>2</sup> to 21.2 kW/m<sup>2</sup> for 39.1 s for Trial G8) as well as a relatively low heat flux in the first half of IR cooking (20.5 kW/m<sup>2</sup> to 22.7 kW/m<sup>2</sup> for 19.55 s for Trial G4 and 17.2 kW/m<sup>2</sup> to 21.2 kW/m<sup>2</sup> for 19.55 s for Trial G8). Again, the donuts may be assumed to have already reached peak heat flux before they were transferred to the IR oven, so a relatively low flux that decreases over time was needed during this point in the cooking process. With the exception of Trial G5 and Trial G6, a shorter IR residence time (39 s) resulted in a higher score for both overall and selected scoring for GF par-fried, IR-finished donuts. It likely that the shorter IR residence time resulted in decreased drying of the GF par-fried, IR-finished donuts, reducing the crumbliness and dryness of the crumb and giving a crumb more similar to that of a wheat donut.

The GF par-fried, IR-finished donuts may also be compared to their fully-fried counterpart. Using the GF fully-fried donuts from Trial GF8 as a GF control, the GF par-fried, IR-finished donuts that received the best overall scores (Table 7.4) were the GF par-fried, IR-finished donuts from Trial G1 (9), Trial G4 (11), Trial G5 (9) and Trial G8 (12). The same GF par-fried, IR-finished donuts had the best scores for the selected measurements: 6, 7, 7, and 8 for Trial G1, Trial G4, Trial G5, and Trial G8, respectively (Table 7.4). Out of these four trials, the GF par-fried, IR-finished donuts that were most similar to the GF control were from Trial G8. Trials G8 had IR parameters that gave a relatively low overall heat flux as well as a relatively low heat flux in the first half of IR cooking (Figure 7.4). There did not appear to be any relationship between IR residence time and either overall or selected scoring, indicating that short differences in residence time (39 s vs. 45 s) did not affect scoring when using the GF control.

Scoring for GF par-fried, IR-finished donuts using the wheat control and the GF control may be combined to produce a combined score for both overall and selected scores (Table 7.4). The GF par-fried, IR-finished donuts that received the best combined overall scores (maximum of 30) were the GF par-fried, IR-finished donuts from Trial G4 (21), Trial G5 (17) and Trial G8 (22). The same GF par-fried, IR-finished donuts had the best scores for the combined selected measurements (maximum of 18): 12, 12, and 13 for Trial G4, Trial G5, and Trial G8, respectively. Out of these three trials, the GF par-fried, IR-finished donuts that had the highest overall and selected scores were those from Trial G8. Therefore, it may be said that the GF par-fried, IR-finished donuts from Trial G8 were the most instrumentally similar to both the GF and wheat controls.

The overall acceptance scores of all donuts were compared to those of the wheat control to determine donut similarity in terms of sensory data (Table 7.5). When all sensory data were analyzed together, only the wheat par-fried, IR-finished donuts from Trial 2 had statistically similar ( $p \leq 0.05$ ) overall acceptance scores to the wheat control, indicating that they were sensorially comparable to the wheat control. This result differs from the findings of Melito (2009) because the average overall acceptance scores of the wheat control donuts in the sensory trials using GF fully-fried and GF par-fried IR-finished donuts were half a point to one point higher on the hedonic scale than the overall acceptance score of the wheat control donuts in the sensory trial using wheat par-fried, IR-finished donuts (Melito, 2009). When all of the data for the wheat control donuts were combined, the overall acceptance score of the wheat control increased, causing the statistical analysis to yield different results. Both the GF fully-fried donuts and GF par-fried, IR-finished donuts tested received significantly lower ( $p \leq 0.05$ ) overall acceptance scores than the wheat control, indicating that they were not sensorially comparable to the wheat control.

Because the wheat fully-fried donuts were used as a control in each sensory panel, it was possible to analyze the results of all three sensory panels together and determine the similarity of the GF par-fried, IR-finished donuts tested to the GF control (Table 7.5). In this case, the GF control was considered to be the GF fully-fried donut made using the Trial GF7 formulation. This formulation was almost identical to the formulation of Trial GF8, the GF control used in all other analyses. However, the methylcellulose wash was not used in Trial GF7. The GF par-fried, IR-finished donuts tested were found to have comparable overall

acceptance scores to the GF control donut, with the exception of the GF par-fried, IR-finished donuts from Trial G7, which had a lower overall acceptance score.

Combining the instrumental and sensorial analyses led to several conclusions. First, the wheat par-fried, IR-finished donuts may be considered sensorially comparable to the wheat control but not necessarily instrumentally comparable. The wheat par-fried, IR-finished donuts that were most instrumentally comparable to the wheat control were those from Trial 4. It may be said that, of the wheat par-fried, IR-finished donuts, the Trial 4 donuts were most comparable to the wheat control. Next, several of the GF fully-fried donuts were shown to be somewhat instrumentally comparable to the wheat control, although they generally had overall and selected scores lower than the wheat par-fried, IR-finished donuts. The GF fully-fried donuts considered to be the most instrumentally comparable to the wheat control were those from Trial GF3. However, the GF fully-fried donuts were not sensorially comparable to the wheat control, most likely to their textural properties (drier, more crumbly crumb). Overall, GF fully-fried donuts were not comparable to the wheat control due to their significantly lower sensory scores, though they may have been instrumentally similar. The GF par-fried, IR-finished donuts were also not sensorially comparable to the wheat control, although several GF par-fried, IR-finished donuts were considered instrumentally comparable. The GF par-fried, IR-finished donuts from Trial G4 and Trial G8 were considered to be the most instrumentally comparable to the wheat control. Again, though they may have been instrumentally similar, the GF par-fried, IR-finished donuts may not be considered comparable to the wheat control because of their significantly

lower sensory scores. Finally, several GF par-fried, IR-finished donuts may be considered comparable to the GF control, as they have comparable instrumental and sensorial scores. The GF par-fried, IR-finished donuts most instrumentally similar to the GF control were those from Trial G8. The GF par-fried, IR-finished donuts were much more comparable to the GF control than the wheat control, based on the differences in instrumental and sensorial scoring. This result was expected; GF fully-fried donuts were not comparable to the wheat control, so it was highly unlikely that GF par-fried, IR-finished donuts would be comparable because the donut formulation was the same.

### **7.3. Conclusions**

It has been shown that the par-frying, IR-finishing process is able to produce wheat and GF donuts that were both instrumentally and sensorially similar to their fully-fried counterparts. This accomplished one of the main goals of the study. Another goal, the reduction of fat in the donuts by using the par-frying and IR-finishing process, was also achieved. By using this process, it was possible to lower the fat content of the donuts by 24% and 13% for the wheat and GF donuts, respectively. Unfortunately, it was not possible to produce GF donuts, either fully-fried or par-fried and IR-finished, that was sensorially comparable to a fully-fried wheat donut, although several of the GF donuts were considered instrumentally comparable. In particular, the mechanical and textural properties of wheat donuts were difficult to duplicate. Further work is necessary to refine the GF formulation and improve the mechanical and textural properties of the donut.

### **7.3. Future Work**

Further study on the par-frying, IR-finishing process is needed to expand the knowledge basis of the effects of IR-finishing on fried products. A study on how IR heat flux affects the final fat content of foods is highly recommended. It was assumed that the IR process did not add or remove oil from the food; however, the results of this study showed that assumption to be invalid. The fat content of both the wheat and GF par-fried, IR-finished donuts varied significantly with IR oven parameters. Since the par-fried, IR-finished donuts were fried for the same amount of time and the oil quality was kept constant, the only part of the process that varied was the IR oven parameters. Therefore, it was hypothesized that IR heat flux affects the final oil content. Further study is needed to support this hypothesis.

Study of how IR flux profile affects food properties of is also recommended. The emitter heights and spacings chosen for these experiments all provided the same general flux profile. Examining different flux profiles may provide insight on the effect of IR flux on foods. It is also recommended that the optical properties of various foods and food components be found. This will allow the wavelengths that are best absorbed by the food to be found, which will improve the efficiency of the process. It will also enable process modeling to find the IR residence time and arrangement of emitters that produce the highest-quality product.

The GF donut formulation should also be studied further. Several researchers have found that transglutaminase able to form cross-links in GF products, yielding a network similar to gluten (Gujral and Rosell, 2004; Moore et al., 2006; Marco and Rosell, 2008). It is

possible that this enzyme could improve the textural and mechanical properties of the GF donuts. Different hydrocolloids or GF flours may also be useful in improving GF donut properties. Further study on improving the volume of the GF donuts is also recommended. An increased volume would result in a less dense crumb, making the GF donuts more similar to the wheat control. In addition, there was an air cell that formed between the crust and crumb of the GF par-fried, IR-finished donuts, as discussed by Melito (2009). Determining the cause of and a method to prevent the air cell that was seen in the GF par-fried, IR-finished donuts would also help improve their quality.

Finally, optimizing both the wheat and GF donut formulations for IR cooking is also suggested. There may be a donut formulation that would yield higher-quality donuts when cooked by infrared than the formula used. The formula used was intended for donuts that were fully-fried. It is possible that a different combination of ingredients or ratio of ingredients could produce higher-quality par-fried, IR-finished donuts.

#### 7.4. References

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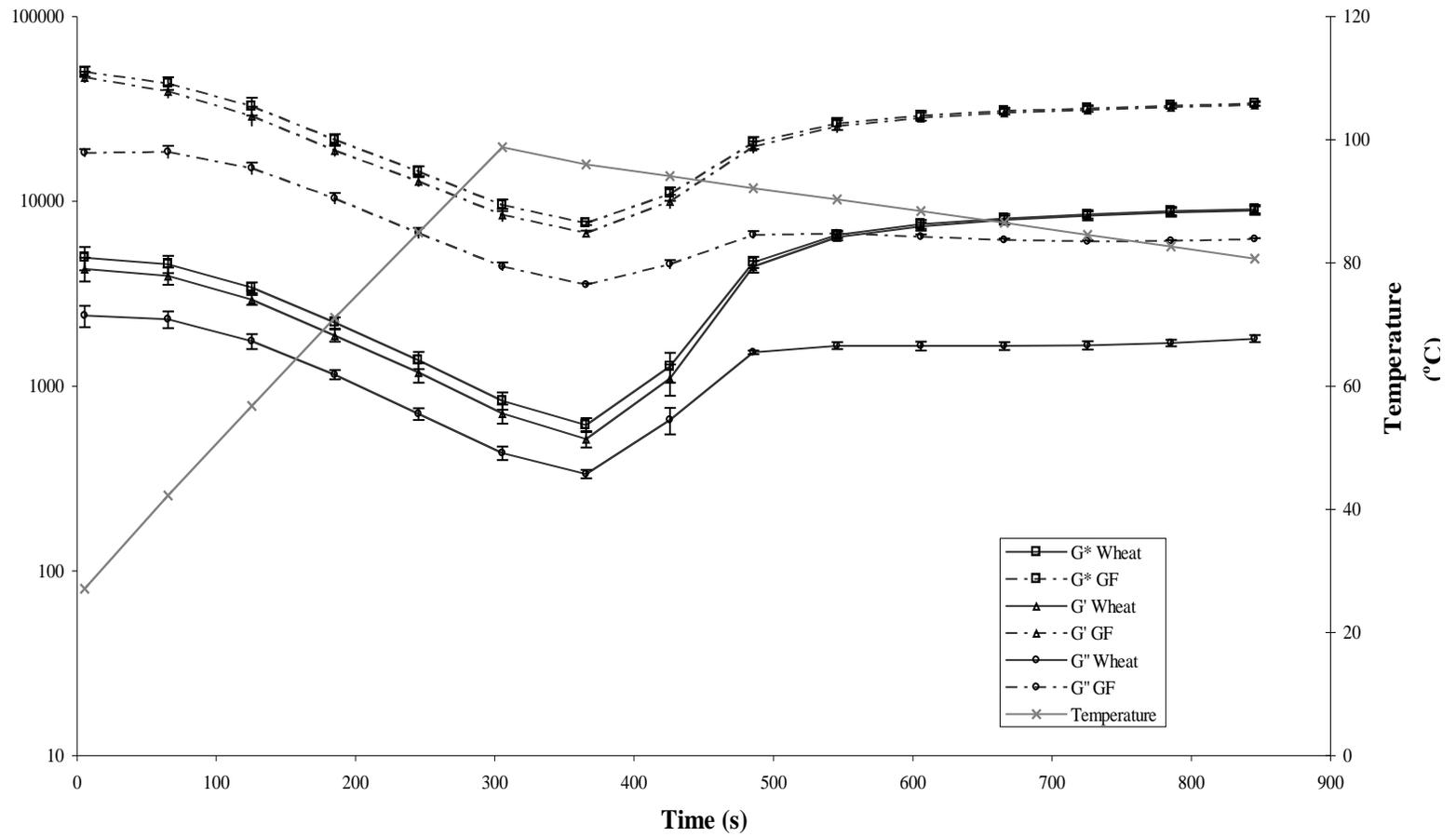
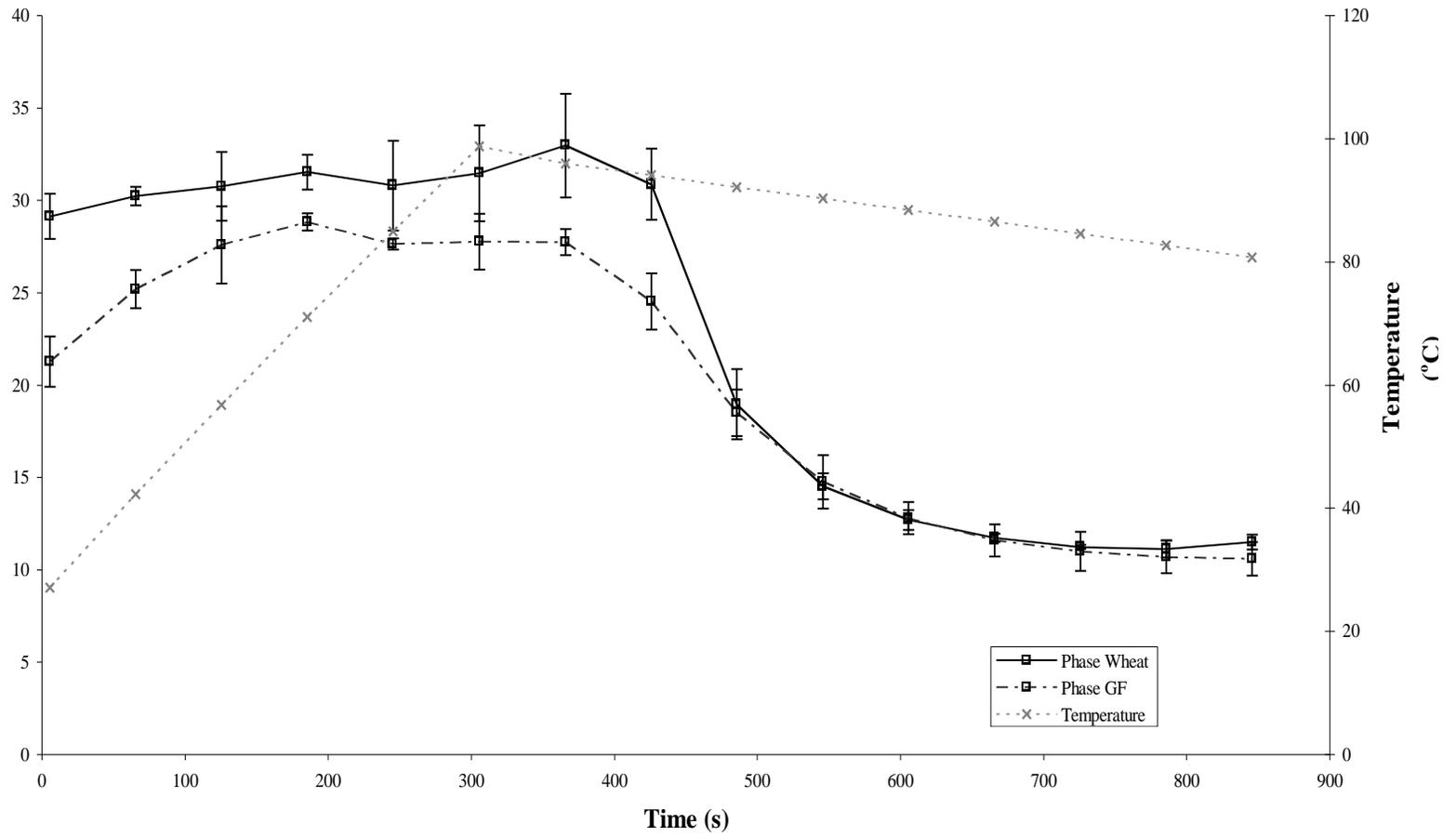
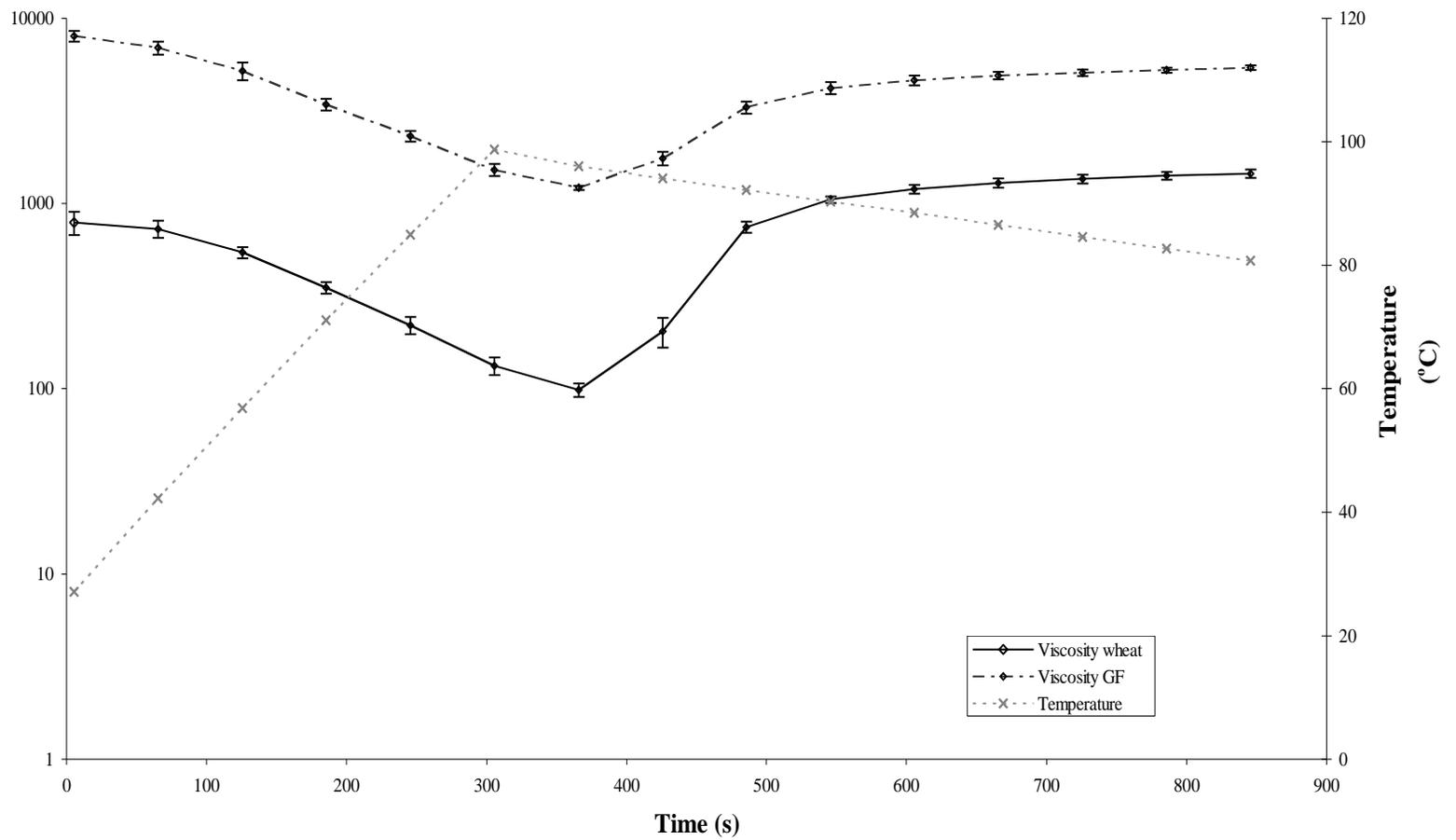


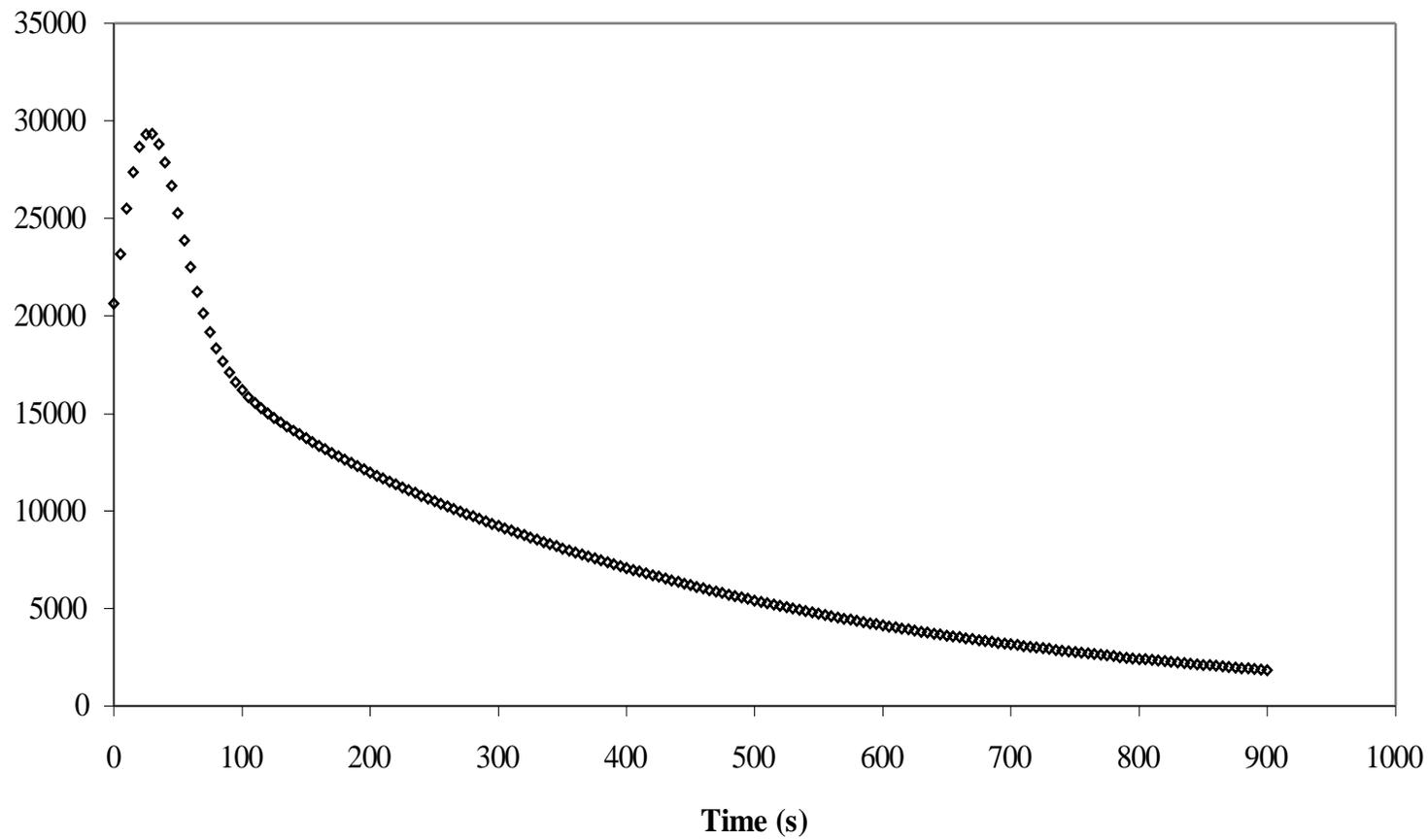
Figure 7.1. Oscillatory testing results: moduli and temperature vs. time



**Figure 7.2. Oscillatory testing results: phase angle and temperature vs. time**



**Figure 7.3. Oscillatory testing results: viscosity and temperature vs. time**



**Figure 7.4. Heat flux profile during frying**

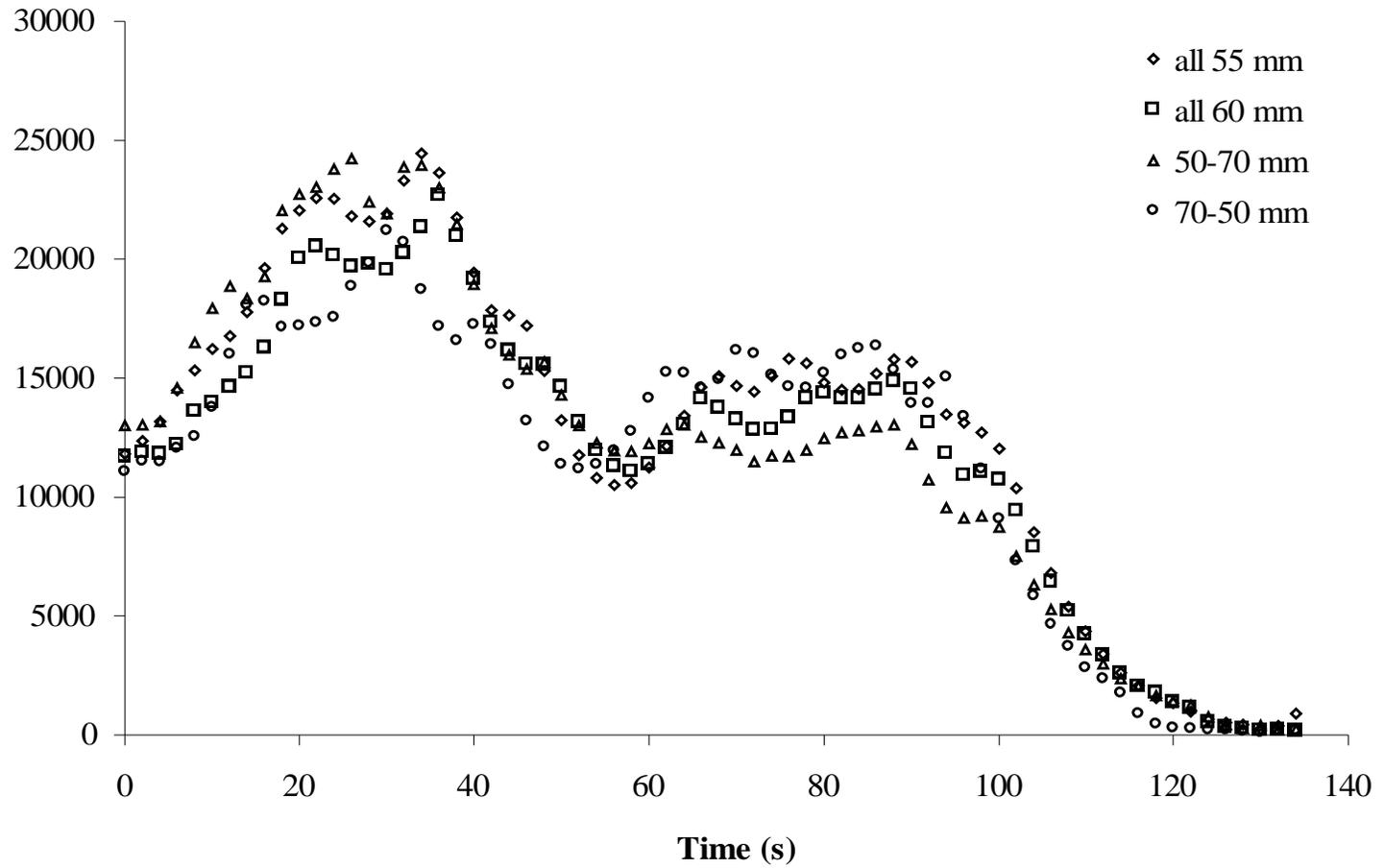


Figure 7.5. Heat flux profiles for emitter settings

**Table 7.1. Scoring results for wheat par-fried, IR-finished donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Scoring 1</b>	<b>Scoring 2</b>
1	8	5
2	8	5
3	11	7
4	13	8
5	7	4
6	7	5
7	12	8
8	11	6

Note: Trial number indicates the heating treatment for the corresponding number in Table 4.2. Scoring 1 includes all instrumental measurements (maximum possible score of 15). Scoring 2 includes change in volume, L\* value, fat content, force to puncture crust, H1, H2, cohesiveness, springiness, and chewiness (maximum possible score of 9).

**Table 7.2. Scoring results for GF fully-fried donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Scoring 1</b>	<b>Scoring 2</b>
GF1	10	5
GF2	10	6
GF3	11	8
GF4	10	7
GF5	9	5
GF6	9	5
GF7	8	4
GF8	10	7

Note: Trial number indicates the heating treatment for the corresponding number in Table 5.2. Scoring 1 includes all instrumental measurements (maximum possible score of 15). Scoring 2 includes change in volume, L\* value, fat content, force to puncture crust, H1, H2, cohesiveness, springiness, and chewiness (maximum possible score of 9).

**Table 7.3. Scoring results for GF par-fried, IR-finished donuts as compared to wheat control donuts**

<b>Trial</b>	<b>Scoring 1</b>	<b>Scoring 2</b>
G1	6	3
G2	8	4
G3	6	3
G4	10	5
G5	8	5
G6	8	4
G7	8	3
G8	10	5

Note: Trial number indicates the heating treatment for the corresponding number in Table 6.2. Scoring 1 includes all instrumental measurements (maximum possible score of 15). Scoring 2 includes change in volume, L\* value, fat content, force to puncture crust, H1, H2, cohesiveness, springiness, and chewiness (maximum possible score of 9).

**Table 7.4. Scoring results for GF par-fried, IR-finished donuts as compared to both GF and wheat control donuts**

<b>Trial</b>	<b>Scoring 1 (GF control)</b>	<b>Scoring 2 (GF control)</b>	<b>Scoring 1 (wheat control)</b>	<b>Scoring 2 (wheat control)</b>	<b>Combined Scoring 1</b>	<b>Combined Scoring 2</b>
G1	9	6	6	3	15	9
G2	7	4	8	4	15	8
G3	7	4	6	3	13	7
G4	11	7	10	5	21	12
G5	9	7	8	5	17	12
G6	8	5	8	4	16	9
G7	8	5	8	3	16	8
G8	12	8	10	5	22	13

Note: Trial number indicates the heating treatment for the corresponding number in Table 6.2. Scoring 1 includes all instrumental measurements (maximum possible score of 15). Scoring 2 includes change in volume, L\* value, fat content, force to puncture crust, H1, H2, cohesiveness, springiness, and chewiness (maximum possible score of 9). Combined scoring is the sum of the GF and wheat control scores for each trial. The maximum possible scores in the combined scoring are 30 for Scoring 1 and 18 for Scoring 2.

**Table 7.5. Analysis of sensory scores for all donuts tested**

<b>Trial</b>	<b>Overall acceptance</b>	<b>Appearance</b>	<b>Aroma</b>	<b>Texture</b>	<b>Mouthfeel/ Taste</b>
1	5.28±1.74 (bc)	5.69±1.61 (bc)	5.97±1.31 (abc)	5.41±1.65 (bcd)	5.16±1.82 (b)
2	5.85±1.53 (ab)	6.32±1.40 (ab)	6.13±1.28 (ab)	5.77±1.55 (ab)	5.63±1.76 (ab)
4	5.63±1.56 (b)	6.36±1.47 (ab)	5.89±1.50 (abc)	5.60±1.71 (ab)	5.37±1.71 (b)
8	5.43±1.71 (b)	6.55±1.37 (a)	5.95±1.42 (abc)	5.44±1.83 (bc)	5.18±1.86 (b)
GF1	4.68±1.78 (cd)	5.71±1.64 (bc)	5.81±1.43 (bcd)	4.80±1.87 (cde)	4.01±1.83 (c)
GF3	4.54±1.69 (de)	5.53±1.67 (c)	5.72±1.39 (bcd)	4.65±1.83 (def)	3.68±1.90 (c)
GF5	4.27±1.63 (de)	5.22±1.44 (c)	5.60±1.24 (bcd)	4.37±1.63 (ef)	3.64±1.73 (c)
GF7	4.33±1.57 (de)	5.48±1.59 (c)	5.54±1.36 (bcd)	4.38±1.71 (ef)	3.55±1.79 (c)
G2	4.44±1.65 (de)	5.64±1.38 (c)	5.61±1.32 (bcd)	4.57±1.80 (ef)	3.86±1.77 (c)
G3	4.22±1.58 (de)	5.64±1.61 (c)	5.56±1.47 (bcd)	4.22±1.69 (ef)	3.65±1.71 (c)
G7	3.81±1.59 (e)	5.26±1.72 (c)	5.18±1.55 (d)	3.95±1.57 (f)	3.28±1.53 (c)
G8	3.98±1.61 (de)	5.60±1.50 (c)	5.47±1.49 (cd)	4.11±1.82 (ef)	3.45±1.71 (c)
CW	6.38±1.48 (a)	6.94±1.08 (a)	6.47±1.45 (a)	6.31±1.58 (a)	6.41±1.60 (a)

Note: Trial number indicates the heating treatment or formulation for the corresponding number in Table 4.2 (1, 2, 4, 8), Table 5.2 (GF1, GF3, GF5, GF7), and Table 6.2 (G2, G3, G7, G8). CW is the fully-fried wheat control donut. Data are given as mean ± standard deviation. Letters in each column that are different indicate significant differences among data in that column.