CHAPTER 5

Understanding Oil Absorption During Deep-Fat Frying

Pedro Bouchon

Contents

Abstract

One of the most important quality parameters of fried food is the amount of fat absorbed during the process, which undermines recent consumer trends toward healthier food and low-fat products. In order to obtain a product with a low fat content, it is essential to understand the mechanisms involved during the frying process, so that oil migration into the structure can be minimized. To get such an understanding, this chapter briefly describes the frying process from technological and scientific perspectives. First, it gives a general overview of the frying process and describes the most important quality attributes of fried food. Thereafter, it centers on key nutritional aspects, particularly on the effect of excessive oil consumption on human health, oil degradation,

Department of Chemical and Bioprocess Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile

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and toxic compounds generation in fried food. Finally, this chapter discusses the most important factors affecting oil absorption, oil absorption kinetics, and different strategies that may be adopted to decrease oil content.

I. FOOD DEEP-FAT FRYING: A GENERAL OVERVIEW

Deep-fat frying, also known as immersion frying, is one of the oldest and most common unit operations used in the preparation of food. The process was first developed around the Mediterranean area due to the influence of olive oil there, but today numerous processed foods are deep-fat fried because of the unique flavor–texture combination imparted to the food (Varela, 1988). Certainly, fried products are of great importance to the food industry because of their popularity among consumers and the huge quantities of fried food and oils that are used at industrial and commercial levels. A critical aspect of deep-fat fried food is the high amount of oil that is absorbed during the process, reaching in some cases 40% of the total food product weight. Numerous studies have revealed that excess consumption of fat is a key dietary contributor to coronary heart disease and perhaps cancer of the breast, colon, and prostate (Browner *et al.*, 1991), imposing an alert to human consumption. Despite this, consumption of oils and fats is still high. For instance, in the United States, consumers eat four or more snacks a day and consume more than 6.5 billion pounds of snack food annually. As such, salty snacks account for slightly over half of the total snack sales and are consequently a large part of the American diet (Mintel International Group Ltd, 2006). A wide variety of food materials can be used to produce fried products, including vegetables, meat, dairy, and grains. Key growth categories are those that offer the most product variations adhering to convenience, flavor, and health trends. In terms of health, interests in salty snack products that are organic or all natural, low-calorie, low-fat, low-carbohydrate, low-sodium, or offer health-promoting benefits such as elimination of *trans* fat are in greater demand by consumers. Although consumers are interested in healthier snack products, they are not willing to sacrifice flavor. Intense and full-flavor snacks remain an important trend in the salty snack market (Mariscal and Bouchon, 2008).

A. The deep-fat frying process

Deep-fat frying can be defined as a process of cooking food by immersing them in edible oil at a temperature above the boiling point of water, and therefore, may be classified as a dehydration process (Farkas, 1994). Frying temperatures usually range between 130 and 190 °C, but most common frying temperatures are in the 170–190 °C range. Deep-fat frying is a complex unit operation involving high temperatures, significant microstructural changes to both the surface and the body of the food, and simultaneous heat and mass transfer resulting in flows in opposite directions of water vapor (bubbles) and oil at the surface of the piece as depicted in Fig. 5.1 (Bouchon *et al.*, 2003). The high temperatures of the frying oil lead to the evaporation of water at the surface of the food. Due to evaporation, water in the external layers of the product moves to the surrounding oil and surface drying occurs, inducing crust formation. Additionally, oil is absorbed by the food, replacing part of the water (Mellema, 2003). One of major aim of deep-fat frying is to seal the food surface while immersing the food into the oil bath so that its flavor and juices can be successfully retained within the food. As a matter of fact, most of the desirable characteristics of fried food are derived from the formation of a composite structure: a dry, porous, crisp, and oily outer layer or crust and a moist cooked interior (Bouchon and Aguilera, 2001).

Frying technology is important to many sectors of the food industry, including the suppliers of oils and ingredients, fast-food shop and restaurant operators, industrial producers of fully fried, par-fried, and snack foods, and manufacturers of frying equipment (Blumenthal, 1991). Deep-fat fryers basically consist of a chamber where heated oil and food are placed and the size depends on their use. Accordingly, the frying equipment is divided into two broad categories: (1) batch frying equipment, normally used in catering restaurants and small plants and (2) continuous fryers, which are used on an industrial scale to process large amounts of

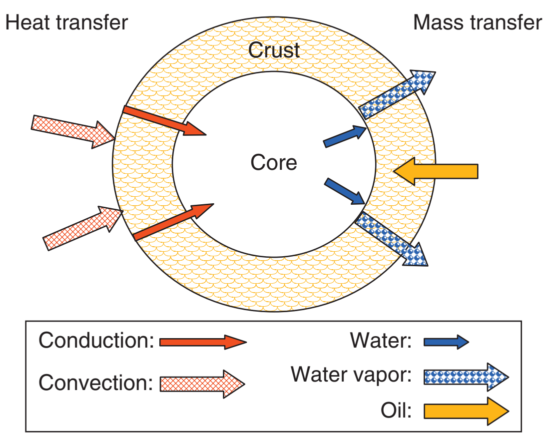

FIGURE 5.1 Schematic diagram of simultaneous heat transfer (left-hand side of the figure) and mass transfer (right-hand side of the figure) during deep-fat frying (with the courtesy of M. C. Moreno).

food. Fryers normally operate under atmospheric conditions; however low- or high-pressure conditions may be used.

1. Fried food

A wide spectrum of fried food is available in the market. They are usually classified into three categories: (1) thin products, such as potato, tortilla, and banana chips, (2) thick products, such as French fries, and (3) battered/breaded food, such as fish fingers. Thin products are nearly fully dehydrated (moisture content lower than 5%), a requirement for shelf-life stability, which is around 2 months. Their fat content is high, achieving up to 40% w.b. (Dobraszczyk *et al.*, 2006). Oil stability is the key factor during storage, rather than fungal spoilage, because of the development of off-flavors. Thick as well as buttered/breaded products have a higher water content (ranging between 30% and 50% w.b.) and lower oil content. Frozen par-fried French fries may have oil content as low as 5% w.b.; however, these products must be either oven-cooked or go through a second frying step before consumption, which necessarily increases the fat intake per portion (there is further dehydration and, if fried, additional oil intake). In fact, when using a second frying stage, the final oil content is generally higher than in fresh fried products. Doughnuts are also an extremely popular fried food category. They have a high oil content that ranges from 15% to 20% w.b., but about 10% of the fat is used in the preparation of the dough. Battered and breaded foods (fish/chicken) contain similar oil contents of around 15–20% w.b. A critical aspect of these products is the contrast between the crispy and oily outer layer and the soft cooked interior (Dobraszczyk *et al.*, 2006).

2. Frying equipment

Modern batch fryers are constructed with high-grade stainless steel to avoid oxidation catalysis. Usually, the operators immerse and remove the baskets manually from the oil, but new equipment may include an automatic basket-lift system. The device may consist of one or more chambers with an oil capacity ranging from 5 to 25 l, and oil may be directly heated through electricity, gas, or fuel (Dobraszczyk *et al.*, 2006). Important factors to consider when selecting a batch fryer are power source, speed of temperature recovery, and safety. The simplest heating system consists of gas flames directly placed underneath the bottom of the vessel. Oil can also be directly heated through an electrical resistance heater that may be installed few inches above the bottom of the fryer, allowing the arrangement for a cool zone at the bottom of the vessel where debris can fall, minimizing oil damage. This is a clear advantage compared to the previous heating system, where the provision of a cold zone under the heaters is not possible (Rossell, 1998). New developed high-efficiency fryers include turbo-jet infrared burners that use up to 40% less energy than the standard gas-fired fryers with the same capacity (Moreira *et al.*, 1999). In order to increase shelf life, avoid smoking, charring, and off-flavor development, oil filtration and removal of food scraps are essential practices that need to be carried out every day. New equipment can also have a built-in pump filtration unit for the removal of sediments (Kochhar, 1998).

Continuous fryers are used to process large amounts of food, having a throughput that varies from 250 to 25,000 kg product per hour (Moreira, 2006). These are automated machines that consist of a frying vessel where oil is maintained at the desired temperature, a conveyor belt that transports the food through the oil (the product is often pushed through the bath by means of a screen and/or paddles), and an extraction system that eliminates the fumes, primarily made up of moisture and a fine mist of fatty acids (Dobraszczyk *et al.*, 2006; Moreira *et al.*, 1999). The oil may be heated directly using a battery of gas burners or an electric heater in the frying vessel, or by means of an external heat exchanger where oil is continuously pumped through. Some continuous fryers are designed with multiple heating zones along the fryer that can be adjusted separately, providing optimal temperature control to improve product quality. Continuous fryers may be also provided with an indirect oil heating system unit. In those systems, oil is heated by pumping a heated thermal fluid into a tube arrangement immersed in the oil bath (Dobraszczyk *et al.*, 2006; Moreira *et al.*, 1999). It is important to mention that in continuous fryers, the oil that is constantly absorbed by the fried product needs to be replaced with fresh oil continuously. The amount of fresh oil added to the vessel is the oil turnover, defined as (*weight of oil in the fryer*)/(*weight of oil added per hour*) (Banks, 1996), and therefore represents the time needed to replace all the oil contained in the equipment. Fast oil turnovers are desired since they preserve the oil quality better. Normally, the oil turnover is kept between 3 and 8 h (Kochhar, 1998).

Deep-fat fryers may also operate at a higher pressure (9–32 psi). These devices have been developed to meet particular needs primarily in certain catering outlets, especially those devoted to chicken frying because of the uniform color and improved texture (higher moisture content) conferred to products. Pressure fryers may reduce the frying time considerably, but they can also increase frying oil deterioration rate since steam retention within the fryer increases free fatty acids content (Moreira *et al.*, 1999).

Another technology that is being increasingly adopted is vacuum frying, which consists of a deep-fat frying process carried out in a closed system under pressure well below the atmospheric levels (preferably lower than 1 psi), making it possible to reduce substantially the frying temperature due to water boiling-point depression. The low temperatures employed and minimal exposure to oxygen account for most of its benefits, which include natural color, flavor, and nutrient preservation

(Mariscal and Bouchon, 2008; Shyu and Hwang, 2001), as well as oil quality protection (Shyu *et al.*, 1998) and reduction of toxic compound generation (Granda *et al.*, 2004). The equipment was first developed by Florigo B.V. during the sixties to produce high-quality chips; however, due to the improvement in blanching technology and in raw material quality, the use of this technology almost disappeared (Moreira *et al.*, 1999). Nowadays, vacuum frying technology is being used to maintain natural colors, flavors, and nutrients in high added-value products, such as vegetables and fruits (Dueik and Bouchon, 2009).

B. Heat and mass transfer during deep-fat frying

From an engineering perspective, deep-fat frying can be defined as a unit operation where heat and mass transport phenomena occur simultaneously. Convective heat is transferred from the frying media to the surface of the product, which is thereafter conducted within the food. Mass transfer is characterized by the loss of water from the food as water vapor and the movement of oil into the food (Singh, 1995).

Water evaporation initiates at the surface of the product after initial heating occurs, and the boiling point of the interstitial liquid is reached, which is slightly higher than the boiling point of water. After the initial surface water is lost, water starts escaping vigorously and heat transferred through natural convection gives path to a forced convection regime due to the high turbulence associated with nucleate boiling. As frying progresses, the evaporation front moves toward the interior of the product and a dehydrated crust layer is formed, whose temperature rises above the boiling point of water. It is important to note that the maximum surface temperature only approaches that of the frying oil, remaining 10–15 °C below it, because of the heat transfer resistance at the boundary oil layer in contact with the surface of the food (Fig. 5.2). On the other hand, the temperature inside the food material (known as core region), where liquid water is still there, is restricted to values around the boiling point of the liquid. As frying proceeds, the water loss rate decreases (falling-rate period) leading to bubble-end point, that is, when water escape stops (Singh, 1995). This is actually the processing condition that must be fulfilled in chip like products (crisps in the U.K.), where a maximum of 5% moisture content is permitted.

Mass transfer during frying is not only characterized by the movement of water in the form of vapor from the food into the oil, but also by the movement of oil into the food. Frying is a dehydration process where water escape leaves empty spaces within the crust structure, which in turn determines the volume available for oil absorption. In fact, the amount of oil uptake has been shown to be directly proportional to

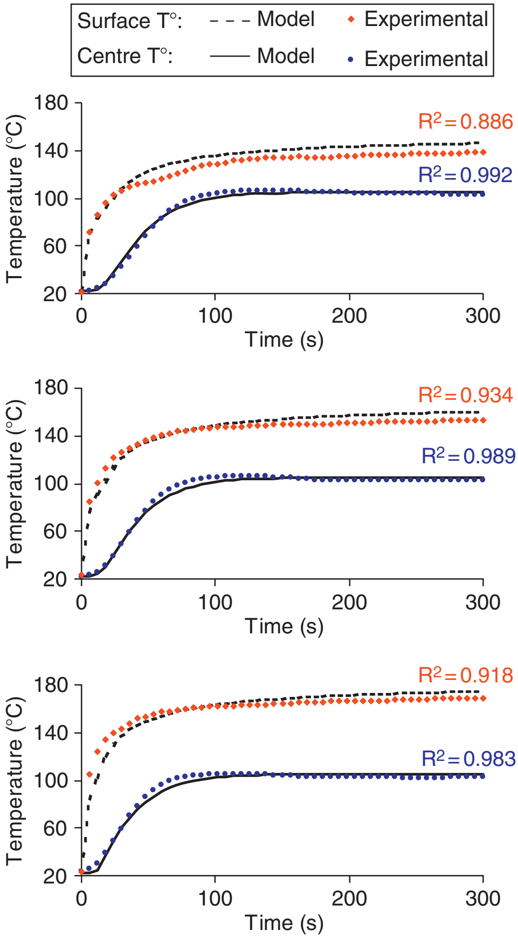

FIGURE 5.2 Predicted and experimentally determined temperatures (mean values) when frying a raw potato cylinder at 155 °C (top), 170 °C (middle), and 185 °C (bottom); from Bouchon and Pyle (2005a).

the amount of moisture lost, as will be discussed in the following sections (Gamble *et al.*, 1987).

One of the key parameters that distinguishes frying from other unit operations is the high heat transfer rates that are achieved, which are far higher than those found during baking and drying. Heat transfer rates to the surface of the food will depend on the thermal properties and chemical composition of the frying medium, and on the turbulence generated by the vigorous vapor escape. Several authors have attempted to measure natural convective heat transfer coefficients mainly using a metal transducer. Evidently, the absence of water vapor surrounding the metal piece yields a natural convective heat transfer coefficient that is different from that when a food is undergoing frying and that is only meaningful during the early stages of frying when few bubbles are present. Using the lumped capacity method with a spherical aluminum transducer, Miller *et al.* (1994) estimated natural convective heat transfer coefficients for canola oil, palm oil, corn oil, and soybean oil at 170, 180, and 190 °C. They obtained values ranging from 250 to 280 W/(m^2 K). Using a similar approach, Moreira *et al.* (1995a) estimated the natural convective heat transfer coefficient for soybean oil, which was 280 W/(m^2 K) when heated at 190 °C. Comparable values were obtained by Bouchon and Pyle (2005a), who determined natural convective heat transfer coefficients of 262, 267, and 282 W/(m^2 K) when heating palm olein at 155, 170, and 185 °C, respectively.

Several studies have attempted to estimate boiling convective heat transfer coefficients for immersion frying. Hubbard and Farkas (1999) obtained maximum average values of 610, 650, and 890 W/(m^2 K), when frying potato cylinders at 120, 150, and 180 °C, respectively, which are far higher than natural convective ones. In addition, they found that the time to reach these maxima decreased as the frying temperature increased and that the convective heat transfer coefficient gradually decreased to 300 W/(m^2 K) over the duration of the process. Costa *et al.* (1999) reported maximum average values of 443 and 650 W/(m^2 K) and average values of 353 and 389 W/(m^2 K), after approximately 5 min when frying French fries at 140 and 180 °C, respectively. Interestingly, they explained that the heat transfer coefficient might be expected to be position dependent due to the difference in turbulence occurring at different locations in the product. In fact, Sahin *et al.* (1999) found differences when determining the boiling convective heat transfer coefficient at the top and bottom surfaces of potato slices during frying (150–190 °C). Contrary to what might be expected, they determined higher coefficients at the bottom surface (450–480 W/(m^2 K)) as compared to the top surface (300–335 W/(m K)) until crust was formed. They attributed this to the fact that a strong insulating effect was produced by the vigorous escape of bubbles at the top surface, while at the bottom surface bubbles remained in a single layer, providing a lower resistance. Bouchon and Pyle (2005a) estimated boiling convective heat transfer coefficients for increasing frying times at different temperatures, which ranged approximately from 260 to 600 W/(m^2 K), similar to those found by Costa *et al.* (1999) and Sahin *et al.* (1999). They adjusted a first-order kinetic model to experimental data to describe the change with frying time, which they used when testing a mathematical model of the process. Overall, all studies have found that convective heat transfer coefficients are up to two or three times greater that those measured in the absence of bubbling. This research has made it possible to get a better understanding of the different heat transfer rates and vapor escaping regimes encountered during the different periods of frying.

C. Structure development during frying

The structure of the crust and core regions of fried food products is the result of several alterations, most of which occur at the cellular and subcellular levels. Aguilera and Gloria (1997), using fast freezing after frying and cryosectioning, demonstrated that three distinct microstructures exist in finished fried commercial French fries: (1) a thin outer layer (approx. 250 μm) formed by the remnants of cell walls of cells damaged by cutting; (2) an intermediate layer of shrunken intact cells, which extends to the evaporation front; (3) the core with fully hydrated intact cells containing gelatinized starch. Microstructural changes in the core region are similar to those occurring during simmering since this inner structure is restricted to temperatures below the boiling point of water. Main changes include starch gelatinization (in starchy products), softening of the middle lamellae (which is greatly responsible for the so-called mealy texture), and protein denaturation.

Microstructural changes at the crust are certainly more aggressive than those occurring in the inner structure due to the exposure to temperatures well above 100 °C (in atmospheric deep-fat frying). Besides the physical damage produced when the product is cut, chemical and physical changes include starch gelatinization and subsequent dehydration, protein denaturation, breakdown of cellular adhesion, water evaporation and rapid dehydration of cells located in the forming crust, and oil uptake itself (Bouchon and Aguilera, 2001).

Desired organoleptic properties, particularly textural ones, are a direct consequence of these microstructural changes. A chip must be firm and snap easily when deformed, emitting a crunchy sound (Krokida *et al.*, 2001a), whereas in thick products the better the contrast between a rich and soft inner structure and a crispy outside, the better the product (Moreira, 2006). Firmness is often related to starch swelling and gelatinization, as well as to the stability of pectic substances of the cell wall and middle lamellae.

The importance of microstructural changes occurring during deep-fat frying has been greatly recognized when studying oil absorption mechanisms. In fact, as commented by Baumann and Escher (1995), the explanation of factors affecting oil uptake needs to be validated by a structure analysis in relation to the location of oil deposition and to the mechanism of oil adhesion to the surface. Numerous studies have shown that oil uptake during deep-fat frying is confined to the surface region of the fried product and in cavities and open pores within the two outer layers that constitute the crust (Bouchon *et al.*, 2001; Farkas *et al.*, 1992; Keller

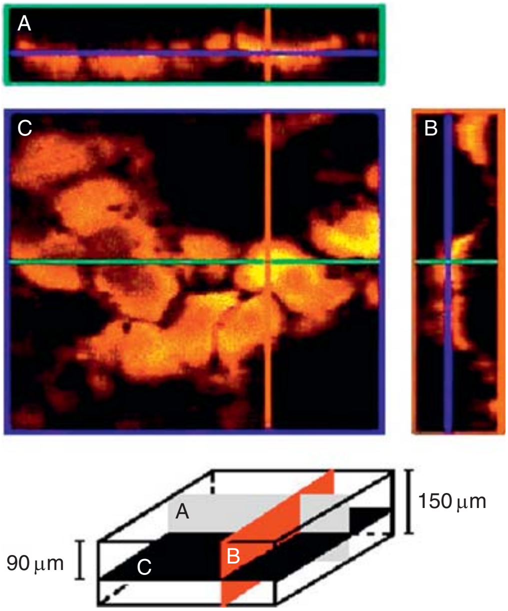

FIGURE 5.3 Orthogonal sections (A, B, and C) of a reconstituted image obtained by CLSM, showing the oil location in the crust of a fried potato; from Bouchon and Aguilera (2001).

et al., 1986; Saguy *et al.*, 1997). Bouchon and Aguilera (2001) and Pedreschi *et al.* (1999) used noninvasive confocal laser scanning microscopy to study oil location directly in fried potatoes, where they observed that oil seemed to flow through the passages that imposed the lowest resistance and was concentrated in concave shells around the cells, with no presence of oil in their interior (Fig. 5.3). Microstructural evidence plus the fact that oil uptake is related to the amount of moisture lost, are key aspects to consider the microstructure of the crust region (mean pore size, connectedness, and permeability) as the single most important product-related determinant for the final oil uptake into the food (Bouchon *et al.*, 2001). Specific aspects related to oil absorption kinetics will be discussed in Section III.

II. NUTRITIONAL ASPECTS OF FOOD DEEP-FAT FRYING

One of the most important quality parameters of fried food is the amount of fat absorbed during the process, which is incompatible with recent consumer trends toward healthier food and low-fat products (Bouchon and Pyle, 2004). In fact, current nutrition recommendations point to a reduction of total dietary fats, including *trans* and saturated fatty acids. In addition, important nutritional compounds degrade during the process, and toxic molecules may generate either in the foodstuff or in the frying oil itself, whose intake should be at least limited.

A. Frying oils and oil degradation

Food can be fried in a wide range of fats and oils, which include vegetable oils, shortenings, animal fats, or a mixture thereof. Most important criteria used to select frying oils are long frying stability, fluidity, bland flavor, low tendency to foam or form smoke, low tendency to gum (polymerize), oxidative stability of the oil in the fried food during storage, and certainly price (Kochhar, 1999). Saturated fatty acids provide a greater stability in frying applications, but they are undesirable from a nutritional standpoint (Sanibal and Mancini-Filho, 2004). Conversely, oils high in polyunsaturated fatty acids show lower thermo-oxidative stability than rich monoenoic unsaturated fatty acids or saturated fatty acids oils (Kita *et al.*, 2005). Antioxidants such as tertiary butyl hydroquinone (TBHQ), butylated hydroxyanisole (BHA), and butylated hydroxytoluene (BHT) may be added to improve oil stability; however, some of them are limited or prohibited under certain regulations. TBHQ is regarded as the best antioxidant for protecting frying oils against oxidation and, like others, it provides carry-through protection to the finished fried product (Dobraszczyk *et al.*, 2006).

Most popular oils used for frying are palm oil and its fractions, sunflower oil (especially high-oleic sunflower oil), rapeseed (canola), and soybean oils. The last two have a high level of linolenic acid (8–10%), making them vulnerable to oxidation and off-flavor development, and therefore, can be slightly hydrogenated for industrial frying. This procedure can also be applied to sunflower oil and may be attractive when requiring a high polyunsaturated-to-saturated ratio for dietary purposes (Rossell, 1998). Olive oil has excellent attributes, which make it suitable for frying, that is, a low level of polyunsaturated fatty acids and a mixture of phenolic antioxidants that make it resistant to oxidation. However, extravirgin and virgin olive oils are far too expensive for industrial use, converting refined solvent-extracted olive oil as a plausible candidate for certain industrial frying operations (Dobraszczyk *et al.*, 2006). Animal fats, despite their high level of saturated fatty acids, may also be used in deep-fat frying due to the characteristic flavor imparted to the food and/or low cost. In turn, fish oils are rarely used as frying medium, since their high level of long-chain polyunsaturated fatty acids makes it prone to oxidation (Rossell, 1998).

Care must be taken when selecting frying oils, since they undergo thermal, oxidative and hydrolytic degradation due to their exposure to elevated temperatures in the presence of air and moisture (Kita *et al.*, 2005). Water, which is released from the foodstuff, attacks ester linkages of triacylglycerols giving rise to di- and monoglycerides, glycerols, and free fatty acids, free molecules that are more susceptible to oxidative and thermal degradation than when esterified to the glycerol molecule (Choe and Min, 2007). Oil thermal oxidation to form peroxides takes place by loss of hydrogen in the presence of trace metals, heat, and light, giving rise to hydroperoxides. Hydroperoxides are compounds that are not stable under deep-fat frying conditions and may undergo fission to produce a wide variety of secondary lipid peroxidation products, including aldehydes, ketones, and other carbonyl-containing compounds (Mahungu *et al.*, 1999). These compounds contribute to the volatile fraction of degraded frying oils, determining the development of off-flavors in the fried product (Melton *et al.*, 1994; Subramanian *et al.*, 2000). In addition, dimers, oligomers, and polymers may be formed, giving rise to excess darkening, increasing oil viscosity, and decreasing smoke point of the frying oil (Choe and Min, 2007; Mahungu *et al.*, 1999).

No-calories fat substitutes, such as sucrose polyesters (Olestra), which are synthesized from sucrose and fatty acid methyl esters, have been widely studied and several snacks fried in this medium are available in the market place. This product has no calories since digestive enzymes are not able to break it down due to structural impairment. A major disadvantage that prevents a wide acceptance of this product is related to the gastrointestinal discomfort that may be caused to some individuals (Dobraszczyk *et al.*, 2006, p. 104).

B. Consumption of fried food and human health

Fat has a strong influence on the palatability of fried foods. The inclusion of cooking fat into the crusty surface, which is developed during the frying process, helps in building up the crunchiness that is highly appreciated by consumers. On the other hand, the linkage between overconsumption of fat and several diseases has been well-documented. Oil consumption, especially saturated fat, is considered to be one of the key dietary contributors to diseases like obesity, coronary heart disease, cancer, diabetes, and hypertension (Saguy and Dana, 2003). In addition, several studies have provided strong evidence that *trans* fatty acids increase plasma concentration of low-density lipoproteins and reduce the concentration of high-density ones (Ascherio and Willett, 1997). *Trans* fatty acids are produced during hydrogenation, a process that is commonly used to increase thermal stability of frying oils, but they can be also generated during high thermal processing, such as deep-fat frying (Choe and Min, 2007). It is estimated that diet-related diseases cost the society over US$250 billion annually in medical expenses and loss of productivity (Anand and Basiotis, 1998). As a consequence, consumer trends are moving toward healthier food and low-fat products, creating the need to reduce the amount of oil in end products. Despite such market forces, the consumption of snack food is increasing in developed and developing countries, and fried products still contain large amounts of fat varying from 5% in frozen French fries to up to 40% in potato chips (Dobraszczyk *et al.*, 2006). Due to the large contribution of fried foods to the total saturated and *trans* fatty acids intake, the use of healthier oil sources offers immense potential to favorably alter population fat intake (Minihane and Harland, 2007).

In relation to cancer, there is some evidence that highly oxidized and heated fats may have carcinogenic characteristics. HNE (4-hydroxy-2-*trans*-nonenal), a secondary lipid peroxidation product derived from linoleic acid oxidation, has assumed particular interest because it has shown cytotoxic and mutagenic properties. Its toxicity, as well other secondary lipid peroxidation products (HHE: 4-hydroxy-2-*trans*-hexenal and HOE: 4-hydroxy-2-*trans*-octenal), is explained through the high reactivity with proteins, nucleic acids, DNA, and RNA. Research links them to different diseases such as atherosclerosis, Alzheimer's, and liver diseases (Seppanen and Csallany, 2006). Research is rapidly progressing, but results are still not conclusive.

In addition to generation of toxic compounds in the frying oil, toxic molecules may be generated in foodstuff. In April 2002, Swedish scientists sounded an alarm when they discovered that certain cooked food, particularly potato chips and French fries, contained high levels of acrylamide, a chemical compound that is listed by the World Health Organization (WHO) as a probable human carcinogen (Mitka, 2002). This substance has been shown to be produced when food is heated above 120 °C due to a reaction between amino acids and reducing sugars (Mottram *et al.*, 2002). WHO has not yet called for any reduction in food containing high levels of acrylamide; however, several studies that aim at reducing its content in fried food are now available (Dueik and Bouchon, 2009). Acrylamide may be converted into glycilamide by living organisms, a compound that is thought to be considerably more toxic than acrylamide; however, little research is yet available in the scientific literature (Besaratinia and Pfeifer, 2004; Koyama *et al.*, 2006). Other heat-induced harmful compounds may be found in certain food. Among them, we can find droxymethylfurfural in carbohydrate-rich foods and heterocyclic amines in protein-rich foods. An in-depth discussion about toxic compound generation may be found in Dueik and Bouchon (2009).

III. OIL ABSORPTION

As explained in previous sections, frying is a complex unit operation involving simultaneous heat and mass transfer, leading to the removal of water from the food and oil absorption at the surface of the piece. It is characterized by the existence of two different regions, the crust and the core, separated by a moving evaporation front, which propagates inward as frying progresses. A key quality factor of fried food is the amount of oil uptake, which should be minimized. In order to obtain food products with a low fat content, it is essential to understand the mechanisms involved during the frying process, especially the kinetics aspects, so that oil migration into the structure can be minimized.

A. Kinetics of oil absorption

Even though it is not fully understood when and how the oil penetrates into the food structure, it has been shown that most of the oil is confined to the surface region of the fried product (Bouchon *et al.*, 2001; Farkas *et al.*, 1992; Keller *et al.*, 1986; Saguy *et al.*, 1997) and there is strong evidence that it is mostly absorbed during the cooling period (Aguilera and Gloria, 1997; Bouchon *et al.*, 2003; Moreira *et al.*, 1997; Ufheil and Escher, 1996). For that reason, it is believed that during frying, after initial heating occurs, the vigorous escape of water vapor would generate a barrier to prevent oil migration into the porous crust and as a consequence oil absorption would be limited during most of the immersion period. As a result, oil uptake would mainly result from the competition between drainage and suction into the porous crust once the food is removed from the oil and cools down, being essentially a surface-related phenomenon. The mechanism of oil absorption was first explained by Gamble *et al.* (1987). They suggested that the largest amount of oil was pulled into the product when it was removed from the fryer because of the vacuum effect due to steam condensation. Accordingly, they suggested that oil absorption depended on the amount of water removed and on the way moisture was lost. In 1996, Ufheil and Escher (Ufheil and Escher, 1996) studied the dynamics of oil uptake during deep-fat frying of potato slices using a fat-soluble and heat-stable dye (Sudan Red B). They determined that most of the oil was absorbed when the product was removed from the oil bath and proposed that oil uptake was primarily a surface phenomenon, involving equilibrium between adhesion and drainage of oil upon removal of the product from the oil. Matz (1993), when focusing on postfrying cooling kinetics, determined that potato chips only absorbed 15% of the total oil when they were rapidly removed from the fryer, while their temperature was still rising. Moreira *et al.* (1997) determined that only 20% of the total oil content of tortilla chips was absorbed while they were immersed in the oil bath and that almost 64% of the total oil content was absorbed during postfrying cooling, the rest remaining on the surface (outer layers of the product). Later, Bouchon *et al.* (2003) combined and adapted the methods developed by Ufheil and Escher (1996) and Moreira *et al.* (1997) and were able to distinguish three different oil fractions when frying potato cylinders (155, 170, and 185 °C), that is, (1) *structural oil (STO)*, which represents the amount of oil absorbed during frying, (2) *penetrated surface oil (PSO)*, which represents the amount of oil suctioned into the food during cooling following its removal from the fryer, and (3) *surface oil (SO)*, that is, the oil that remains on the surface. A schematic diagram showing these oil fractions is presented in Fig. 5.4. Results showed that only a small amount of oil was able to penetrate during frying since most of the oil was picked up at the end of the process, suggesting that oil uptake and water removal were not synchronous phenomena. After cooling, oil was located either on the surface of the product or was suctioned into the porous crust microstructure, with an inverse relationship between them for increasing frying times. According to experimental facts, several approaches have been used to describe and model oil absorption. Moreira and Barrufet (1998) explained the mechanism of oil absorption during cooling in tortilla chips in terms of capillary forces. This hypothesis was supported by experimental results, where they determined that oil uptake occurred during the first 20 s of cooling, that is, when the temperature was still above the condensation temperature (~100 °C). Ni and Datta (1999) developed a multiphase porous media model to predict energy transfer, water loss, and oil absorption during frying. They assumed that vapor and air transport took place through convection and diffusion, whereas liquid phase transport (water and oil) was mediated by convective and capillary flows. In their model, they

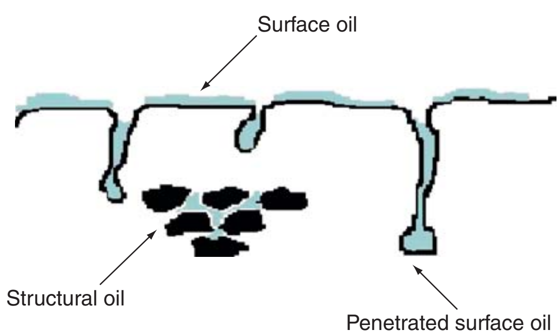

FIGURE 5.4 Diagram showing the three locations of oil in the product microstructure after deep-fat frying; from Bouchon *et al.* (2003).

considered that oil absorption could take place during the immersion period as water moved out from the food, and therefore, they did not take into account oil absorption during postfrying cooling, as determined experimentally by several authors. In recent years, Bouchon *et al.* (2005b) developed a modified form of the Washburn equation, where they expressed the pressure difference needed to initiate oil infiltration during postfrying cooling ($P_{atm} - P_{pore} > 0$), as a function of capillary pressure and vapor pressure, enriching the total driving pressure. A schematic diagram showing the capillary penetration phenomena when having different arrangements is shown in Fig. 5.5.

If a reference datum plane ($h = 0$) is set at the bottom of each of the capillaries shown in the previous Fig. 5.5, the expression for the total driving force, that is the piezometric pressure difference along the penetration length h for a capillary with an upward ($+\rho gh \cos \alpha$) or a downward ($-\rho gh \cos \alpha$) orientation, can be represented by following equation (Bouchon and Pyle, 2005b),

$$\begin{aligned}\Delta P^* &= P_2^* - P_1^* = P_{atm} - P_{pore}\\ &= P_{atm} - \left(P_V - \frac{2\sigma\cos\theta}{r} \pm \rho gh\cos\alpha\right)\end{aligned} \qquad (1)$$

where P_2^* is piezometric pressure at the bottom of the capillary (Pa);P_1^*, piezometric pressure at the liquid side of the meniscus (Pa); P_v, vapor pressure (Pa); P_{atm}, atmospheric pressure (Pa); r, radius of the capillary (m); σ, oil surface tension (N/m); θ, contact angle (rad); ρ, oil density (kg/m^3); g, acceleration due to gravity (m/s^2); h, oil penetration distance (m); and α, angle between normal and vertical axes (rad).

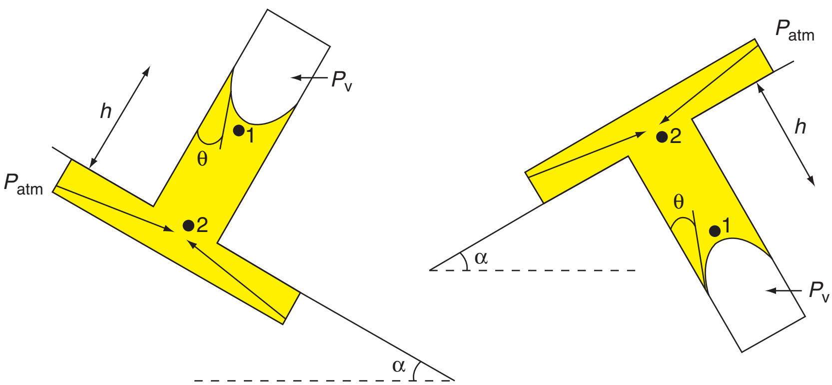

FIGURE 5.5 Schematic diagram showing the capillary penetration phenomena when having different arrangements. *Left*: upward configuration, the action of gravity restricts capillary penetration. *Right*: downward configuration, the action of gravity enhances capillary penetration; from Bouchon and Pyle (2005b).

Since P_{pore} depends heavily on vapor pressure, this is expected to occur after some cooling takes place. As P_{pore} decreases and vapor condenses, the pressure difference is expected to force the oil within the structure. The condensation mechanism should predominate in thick samples and short frying times, since in thinner samples or longer frying times, moisture loss rate may diminish considerably (and therefore P_{pore}), allowing oil absorption to begin early.

Oil drainage upon removal of the food from the oil bath certainly plays an important role, since this defines the surface oil layer to be sucked upon cooling. It has been suggested that surface roughness may importantly increase the surface area, enhancing oil absorption (Saguy *et al.*, 1998). In an effort to quantify the irregular conformation of the surface, Pedreschi *et al.* (2000) and Rubnov and Saguy (1997) have used fractal geometry, confirming the significant role of crust roughness in oil absorption.

Wetting properties are certainly important since they affect the oil capability to drain. Pinthus and Saguy (1994) used a fundamental approach based on surface chemistry to describe the relationship between the initial interfacial tension between a restructured potato product and various frying media, and the medium uptake during deep-fat frying. They found that total oil uptake was higher for lower initial interfacial tensions, showing a power relationship. This result suggests that a lower interfacial tension between the fluid and the solid would increase wetting adhesion and, therefore, increase the total oil content, reflecting the importance of the wetting phenomena. In addition, the authors found a linear relationship between medium uptake and $\sigma.\cos\theta$, suggesting the importance of capillary displacement in the mechanism of medium uptake.

As can be seen, the surface properties of the product and the physical and chemical properties of the frying media are extremely relevant to the oil uptake mechanisms. Blumenthal (1991) noticed the importance of oil surface tension during deep-fat frying, and developed what he called the ''surfactant theory of frying.'' He explained that several classes of surfactants are formed during frying of food as a result of the degradation of the frying oil itself or as a result of the reactions occurring between the food components and the oil. These compounds act as wetting agents, reducing the interfacial tension between the food and the frying oil, causing increased contact between the food and the oil and finally producing excessive oil absorption by the fried product. In fact, Tseng *et al.* (1996) evaluated the effect of oil degradation on the thermal and physical properties of soybean oil, and they determined how the quality attributes of tortilla chips were affected by oil degradation. They found that surface tension decreased and viscosity increased significantly with oil degradation, a fact that may well affect oil tendency to drain. Fracturability, moisture content, and oil uptake of tortilla chips were not significantly affected by the oil degradation time. However, after allowing the chip to cool down, only 19% of the total oil was on the surface of the chips fried in fresh oil, while 49% remained on the surface of those fried in degraded oil. Also as frying oil degrades, polymer formation increases oil viscosity, affecting its tendency to drain. Extended discussions about oil absorption mechanisms are reviewed by Mellema (2003) and Zaiifar *et al.* (2008).

B. Factors affecting oil absorption

There has been much research to examine the different factors affecting oil absorption during frying and many empirical studies have correlated oil absorption measurements with process and/or product characteristics. According to the oil absorption mechanisms explained in the previous section, some factors that may be relevant to the amount of oil absorbed will be now presented.

1. Moisture content

The amount of oil uptake has been shown to be directly proportional to the amount of moisture lost. Several studies claim that higher initial moisture content results in an increased oil uptake; however, oil absorption seems to be better related to the amount of water loss than to the initial moisture content (Gamble *et al.*, 1987). As explained in the previous section, it is well-established that oil absorption will occupy the empty space left by water, which in turn determines the maximum available volume for oil absorption. The effective water vapor transport through the forming crust is, therefore, an important parameter that affects water escape and probably oil uptake, and as explained by Saguy *et al.* (1998), diffusion rate is markedly affected by the mechanical properties of the product and the crust. Because of the aforementioned relationship between moisture loss and oil absorption, many studies aim at reducing initial water content in order to decrease the uptake. The effectiveness of these pretreatments though, which is usually achieved through drying, is not due to a reduction of the moisture content on its own (as commonly believed), but due to the structural changes occurring at the surface of the food, which reduce surface permeability (Moreno and Bouchon, 2008).

2. Crust microstructure

It has been found that a decrease in the initial porosity in the food may reduce oil absorption (Pinthus *et al.*, 1995). However, as explained by the authors, crust formation plays an additional and fundamental role as soon as frying commences. As the moisture turns to steam and exits the product, it leaves behind a sponge-like tunnel network, which constitutes the oil reservoir. In accordance, the microstructure of the crust region, which is formed while the food is cooking in the frying oil, has been pointed out as the single most important product-related determinant for the final oil uptake into the product (Bouchon *et al.*, 2001). In fact, pore development (Thanatuksorn *et al.*, 2007) and pore size distribution (Saguy *et al.*, 1998) have been found to directly influence oil absorption during frying. Some natural ingredients are added to reduce oil uptake because of their film-forming capability and/or because they reduce the porosity of the external layers. In formulated products, the permeability of the outer layer of the product depends on the thickness of the sheeted dough since it determines the structural resistance to vapor escape. A stronger and more elastic network can result in a less permeable outer layer that may act as an effective barrier against oil absorption (Bouchon and Pyle, 2004).

3. Product geometry

The surface area of the food plays an important part in oil uptake. As explained previously, oil absorption is a surface phenomenon involving equilibrium between adhesion and oil drainage as the product is removed from the fryer. Therefore, products with a greater surface-to-volume ratio will absorb more oil as revealed by the linear relationship found between exposed surface area and amount of oil uptake (Gillat, 2001). Also, several studies have shown that oil absorption decreases with increasing product thickness (Baumann and Escher, 1995; Gamble and Rice, 1988; Selman and Hopkins, 1989). Surface roughness is another factor that can result in an increased oil uptake, since it not only impairs oil drainage but also increases overall surface area (Saguy *et al.*, 1998).

4. Frying oil temperature and frying time

These two process parameters are closely related since products must be fried until they reach certain final moisture content, so a lower oil temperature implies a longer frying time. A clear influence of oil temperature on oil absorption has not been found. Gamble *et al.* (1987) found no correlation between oil temperature and oil content when frying potato slices, but concluded that a lower oil temperature resulted in lower oil content in the early stages of frying with a greater difference between 145 and 165 °C than between 165 and 185 °C. Similarly, Moreira *et al.* (1997) determined higher differences in oil absorption between 130 and 160 °C than between 160 and 190 °C. In addition, Moreira *et al.* (1995b) determined that the oil absorption rate was unaffected by the oil temperature when frying tortilla chips and that a frying temperature of 190 °C gave a higher oil content (3–5%) than a frying temperature of 155 °C. Nonaka *et al.* (1977) also found that oil content in French fries increased with increasing frying temperature. Bouchon *et al.* (2003), in deep-fat frying potato cylinders, showed that total oil absorption is a temperature-independent process for short frying times (1 min at 155, 170, and 185 °C). For longer frying times, they found that oil content of potato cylinders fried at 155 °C was significantly lower than those fried at 170 and 185 °C, but no difference was found between the two higher temperatures. Krokida *et al.* (2000), when frying potato strips for increasing time (from 0.3 to 20 min), also concluded that a lower oil temperature resulted in a lower oil content for long frying times (over 3 min), the difference being higher as frying proceeded. They also found that equilibrium moisture content varied as the oil temperature increased from 150 to 190 °C. In accordance, they concluded that the lower oil content could be explained by the lower moisture loss and not necessarily as an effect of the oil temperature itself. They also determined that oil content increased for increasing frying times, especially for thinner products. The effect of frying time in the amount of oil absorbed may be related to the microstructure developed during frying, as previously explained. Pinthus *et al.* (1995) concluded that crust porosity increased linearly with frying time and, as the crust structure has been demonstrated to play a significant role in the oil uptake, a thicker porous crust would lead to higher oil content.

It is important to point out that some conclusions about the effect of oil temperature on oil uptake may be biased by the way results are expressed. Some researchers have reported that oil absorption results as a percentage of the total weight of the product, that is, a wet basis. Conclusions must be analyzed with care in these situations since when frying at a higher temperature for the same frying time, a higher dehydration results. When results are expressed on wet basis (w.b.), there is a systematic reduction in the basis as the water content diminishes. When oil uptake results are measured as a percentage on a dry-weight basis (d.b.) and the solids remain constant throughout the whole process, it may provide a consistent basis for comparison (Moreno and Bouchon, 2008).

5. Oil type and deterioration

The influence of the oil type and quality on oil absorption and residues absorbed by fried foods is widely documented (e.g., Blumenthal, 1991; Blumenthal and Stier, 1991; Krokida *et al.*, 2000; Nonaka *et al.*, 1977; Pokorny, 1980). No relationship has been found between oil type and oil absorption; however, it has been shown that an increase in the initial interfacial tension between oil and restructured potato products decreases oil absorption (Pinthus and Saguy, 1994). Further, as mentioned earlier, oil degradation produces surfactants that act as wetting agents, which also increase the absorption (Blumenthal, 1991).

Food materials leaching into the oil, breakdown of the oil itself, and oxygen absorption at the oil–air interface contribute to change the pure triglyceride oil into a mixture of hundreds of compounds. These materials increase heat transfer and also reduce the surface tension between the food and the oil (Blumenthal, 1991). These surface-active agents may have a pronounced effect on fat absorption. By improving the wetting capabilities of oil and reducing the surface tension, these surfactants may lead to a higher oil uptake (Saguy *et al.*, 1998). Also, oil viscosity increases as a result of dimer and polymer formation in aging oils (Blumenthal, 1991). A higher viscosity would make oil drainage from the product surface difficult, increasing the oil taken up.

C. Oil absorption reduction

Oil reduction in deep-fat-fried products may be obtained through prefrying and/or postfrying treatments. Prefrying treatments are mainly based on the marked effect that the crust microstructure has in oil absorption, and mainly intend to reduce surface permeability. Postfrying treatments aim to remove surface oil before postcooling suction begins.

Drying (microwave, hot-air treatment, baking) prior to frying is shown to be effective in oil uptake reduction in several food products (Gamble and Rice, 1987; Krokida *et al.*, 2001a; Moreno and Bouchon, 2008). It is important to note that the effectiveness of these pretreatments is not due to a reduction of the moisture content on its own (as commonly believed), but due to the structural changes occurring at the surface of the food, which reduce surface permeability. Interestingly, osmotic dehydration had also been extensively reported as an effective pretreatment in oil absorption reduction, whose effectiveness greatly depends on the solution employed (Bunger *et al.*, 2003; Krokida *et al.*, 2001b; Moyano and Berna, 2002). However, as revealed in a recent study, the decrease in oil absorption has been shown to be really due to the increase in solid content occurring during the osmotic dehydration process, rather than a reduction in the amount of oil taken up (Moreno and Bouchon, 2008). Actually, the study demonstrated that osmotic predehydrated samples may absorb as much oil as freeze-dried samples.

In addition, during the last decade, much attention has been given to the use of hydrocolloids with thermal gelling or thickening properties, such as methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), long-fiber cellulose, corn zein, and alginates, among others, to inhibit oil uptake (Albert and Mittal, 2002; García *et al.*, 2002; Mellema, 2003). The hydrocolloid mixture can be added to the product in several ways: (1) added directly in the formula, such as in doughnuts and restructured potato products, (2) included in the batter or breading, (3) sprayed on the product as a solution (Pinthus *et al.*, 1993).

A pioneering work in relation to direct incorporation was carried out by Pinthus *et al.* (1993), where they determined that the addition of HPMC and powdered cellulose to doughnuts and falafel balls reduced oil absorption, being more effective with HPMC as an oil barrier. In a more recent study, Bouchon and Pyle (2004) examined the oil-absorption capacity of three different restructured potato chips during deep-fat frying using low-leach potato flake and native or pregelatinized potato starch. Interestingly, they found that the product containing native potato starch as an ingredient picked up the lowest amount of oil when sheeted into a thick chip, whereas it absorbed the largest amount of oil when sheeted into a thin chip. They explained that thin chips are vulnerable to high levels of stretching, as they result in highly permeable and brittle outer surfaces susceptible to oil infiltration. In contrast, thick restructured potato chips could withstand higher steam pressures due to their stronger solid structure, which was not ruptured. In addition, a flat and smooth outer surface was obtained, which allowed oil to drain easily from the surface and was less vulnerable to oil absorption, as revealed qualitatively by SEM and quantitatively by reflective confocal microscopy. Recently, Gazmuri and Bouchon (2009) studied the oil absorption capacity of a restructured matrix made with different proportions of native wheat starch and vital wheat gluten, which were either directly fried or fried after a predrying step. Results showed that gluten had a predominant role in the structure, making the dough more elastic and less permeable to oil absorption. Interestingly, they found that even though predried products with high gluten content had higher moisture content before frying, they absorbed the lowest amount of oil, suggesting that oil uptake is not clearly related to the amount of moisture lost but rather to the product microstructure.

Even though some results can be found in relation to restructured sheeted products, most research has been focused on coatings and batters. The effectiveness of a coating depends on its mechanical and barrier properties, which in turn depend on its microstructure and composition, along with food substrate characteristics (García *et al.*, 2002). Mallikarjunan *et al.* (1997) explained that when edible films made of cellulose derivatives are used, a protective surface layer is formed due to thermally induced gelation above 60 °C, which inhibits fat absorption. They determined that an edible coating made of MC was more effective than corn zein and HPMC when applied on mashed potato balls. Williams and Mittal (1999) also determined a higher reduction in oil uptake when applying an edible film of MC, compared to HPMC and gellan gum films, on a pastry mix. Similarly, García *et al.* (2002) determined that MC was more effective than HPMC when applied on the surface of potato strips and dough discs. Albert and Mittal (2002) evaluated the effect of several edible coatings applied to the surface of a pastry mix. They determined that soy protein isolate (SPI), whey protein isolate (WPI), and MC were the most effective coatings.

Postfrying treatments, such as hot air (Nonaka *et al.*, 1977) and superheated steam drying (Kochhar, 1999) have been shown to be effective in oil uptake reduction. These processes are aimed to remove surface oil before postcooling suction takes place. The equipment, know as ''low-fat box,'' is mounted at the discharge end of the fryer and it removes the fat excess from the recently fried food normally using superheated steam at 150–160 °C. The oil–vapor mixture that is obtained is then filtered, and the oil is pumped back to the fryer. Units range from batch strippers for pilot plant to continuous production units and they can reduce oil content by up to 25% (Kochhar, 1999). Following the same principle, in common continuous production lines the excess fat is removed by passing the product immediately after emerging from the fryer over a vibrating screen, which allows the fat to drain off (Dobraszczyk *et al.*, 2006). The effect of vacuum frying in terms of oil uptake reduction is still not clear, but it appears to be instrumental in reducing oil absorption (Mariscal and Bouchon, 2008).

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