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Crust pore characteristics and their development during frying of French-fries

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ABSTRACT

This work determines pore characteristics of the French-fry crust and their development at two time intervals during frying. dynamic wicking (DW) and scanning electron microscopy (SEM) are used for that reason. DW is used to determine the effective mean pore radius of the crust. SEM is used to observe the microstructural characteristics of the crust interior and surface. The shapes and sizes of openings/pores in the crust and surface and cell sizes in the crust and core are determined by analysis of the SEM images. Except from new to the literature data on pore sizes in French-fry crusts the above observations provide insight on phenomena occurring in the crust during frying. In addition, the behavior of the interconnected crust porous network during capillary penetration is assessed by DW. Finally, an approximate rate of frying oil uptake in the crust region is estimated considering a capillary penetration theory for oil uptake.

1. Introduction

Frying is a complex process involving simultaneous heat and mass transfer between the food being fried and the surrounding oil. The above phenomena result in the formation of an outer thin layer with different characteristics from the rest of the food being fried: the crust. This layer is dehydrated, porous and contains the oil taken up by the fried food. This layer is significant not only because of its sensory attributes, but also because it plays a significant role in heat and mass transfer during frying as well as oil uptake (Aguilera, 2005; Halder et al., 2011; McDonald and Sun, 2001; Moreira et al., 2009).

French-fries are probably the most typical example of fried foods world-wide. They have a crust with a thickness of the order of 0.5 mm (Kalogianni and Smith, 2013; O'Connor et al., 2001) and a water content of 2–4% (Guillaumin, 1988). The formation of this thin layer is the result of the advancement of the dehydration front towards the center of the potato with simultaneous pore formation and shrinkage (Kalogianni and Smith, 2013). Complex physical and chemical phenomena have been reported during the formation of the crust. These include starch gelatinization, change in the shape and size of cells as well as tissue disruption (Aguilera et al., 2001; Pedreschi and Aguilera, 2002; van Marle et al., 1997). Regarding French-fries existing information on crust pore structure include mainly morphological features. To the best of our knowledge, there has not been any systematic approach to measure pore sizes in French-fry crusts. The determination of pore sizes and the effects of frying variables on the porous structure of fried foods can contribute to the comprehension of the complex changes occurring during frying. Furthermore, it can provide valuable information related to comprehension and modeling of heat and mass transfer within the potato and the mechanisms and phenomena relating and controlling oil uptake.

Microscopy and tomography techniques are valuable tools to understand the microstructure of porous foods. They can be used as a means to observe and measure structures down to a few nm. Nevertheless, and mainly with 2D techniques, it is difficult to obtain information about pores length in three-dimensional networks, representative pore size distributions and tortuosity. 3D techniques can provide information also on pore three-dimensional networks. Yet, all above techniques provide local information. Consequently, for a more representative characterization of the porous structure investigation with the above methods should be complemented by another technique providing global information on the pore structure. Most of microscopy and tomography methods are difficult to apply in delicate samples such as potato crusts. This is probably why these techniques have been used in limited cases of fried foods (Adedeji and Ngadi, 2011; Adedeji et al., 2011; Bouchon et al., 2003; Lisińska and Gołubowska, 2005; Llorca et al., 2005; Miranda and Aguilera, 2006). Amongst them only a few works to our knowledge present information on French-fries. Bouchon et al. (2003), Lisińska and Gołubowska

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(2005) and Miranda and Aguilera (2006) present scanning electron microscopy (SEM) and Confocal Laser Scanning Microscopy images of fried potato crusts but neither report values on pore sizes or pore size distributions.

A standard technique providing global information on porous media is Mercury Intrusion Porosimetry (MIP). MIP can be used to determine pores radii (from a few nm to about 100 m), pore size distributions and pore volumes. MIP has been used in the past for the characterization of the porous structure in different fried foods but not French-fries (Kassama and Ngadi, 2005; Lalam et al., 2013). A concern about using MIP in foods is that mercury, which is a high energy liquid, is very susceptible to contamination by impurities embedded in food systems resulting in significant reduction in surface tension and contact angle, a fact that affects drastically the determination of pores characteristics (Li et al., 1994).

Another technique that can be used to determine pore sizes is dynamic wicking (DW). The technique has been used extensively in the past to characterize inorganic and polymeric materials (e.g. Li et al., 1994; van Oss et al., 1992). The DW technique has been adapted for biological material and used to determine pore sizes in pregelatinized starch sheet (Kalogianni et al., 2004). The wicking technique can prove especially valuable in cases where pore interconnectivity is important for the process in question. This is the case of frying where oil enters in an interconnected porous network whereas isolate pores within the matrice cannot serve as oil reservoirs.

DW relies on describing liquid penetration kinetics inside a thin layer of a material by the Lucas–Washburn equation (van Oss et al., 1992). In this technique, liquids that can penetrate spontaneously into the capillaries of the porous solid are used and the effective pore radius of the medium as well as the contact angle between the porous medium and the liquid can be determined. The information provided by DW is global in the sense that the properties determined represent the whole material under test. Nevertheless, recently local information on pore structure heterogeneity has been obtained via image analysis (Fragiadaki et al., 2012).

When the penetration occurs on the horizontal plane then the rate of penetration can be described by the Lucas–Washburn equation (Washburn, 1921):

$$\frac{h^2}{t} = \frac{r\gamma \cos\ \theta}{2\eta} \tag{1}$$

where h is the distance traveled by the liquid, t the corresponding time, r the capillary radius, γ the surface tension of the liquid, θ the liquid–solid contact angle and η the viscosity of the liquid. For porous media, r stands for the effective mean pore radius. The Lucas–Washburn equation is derived by combining the Poiseuille's law for viscous flow and the Young–Laplace equation for capillarity. The basic conditions for Eq. (1) to be valid are that laminar flow conditions must prevail in the pores and that the liquid meniscus must be roughly hemispherical (Fisher and Lark, 1979). Furthermore, an adsorbed film of the penetrating liquid needs to preexist in the porous body otherwise an additional driving force arises for liquid spreading due to the free energy reduction of the solid in the process of the adsorbed film formation (Chibowski and Holysz, 1992; Good, 1973).

When penetration occurs on the vertical plane, it is soon influenced by gravity and the penetration rate gradually drops as the height of the liquid increases. In this case wicking data can be treated following the analysis of Marmur and Cohen (1997) who modified Eq. (1) to account for gravity effects. Eventually, equilibrium between hydrostatic and capillary pressure is reached at a height h_{eq}:

$$h_{eq} = \frac{2\gamma\ \cos\ \theta}{\rho g r} \tag{2}$$

where g is the acceleration of gravity and ρ the liquid density. When $h << h_{eq}$, gravity effects can be ignored and the Lucas–Washburn equation describes adequately the capillary rise.

When porous foods or other biological material are used for the determination of the effective mean pore radius via the wicking technique certain experimental conditions have to be respected. The main of which relate to the water content and hygroscopicity of the samples which may be the cause of increasing the contact angle between the food matirce and the penetration liquid. The experimental conditions that need to be respected in the case of porous foods are analyzed these were discussed in detail elsewhere (Kalogianni et al., 2004).

In the present work the pore structure characteristics of French-fries are examined using two techniques, one providing detailed local information at the microscale (SEM) and the other one providing global average information (DW). DW is used for the determination of the effective mean pore radius of the crust. SEM is used for studying the morphology of the pore structure in cross sections of the potato and surface morphology. Furthermore, analysis of the SEM images provides information on pore sizes, cell sizes and the thickness of the crust. All above analysis is applied in samples coming from two different time-intervals within frying: par-fried and fully fried French-fries are examined.

2. Materials and methods

2.1. Frying experiments

Frying experiments were conducted using pal oil (donated by Elais S.A., Greece) and Agria potatoes. Frying experiments were performed exactly as in Kalogianni and Smith (2013). The potato to oil ratio used was 1/7 $kg_{potatoes}/L_{oil}$. The oil temperature at the time of potato immersion was 180 °C. The oil and potato temperature profiles obtained under the applied conditions are presented in Kalogianni and Smith (2013).

Samples were taken at 180 s and 720 s during frying. Once samples obtained ambient temperature, the porous crust was first removed from the potato stick by cutting it with a razor blade. Then any residual core remaining on the inner side of the crust was removed by scraping it off with the blade. This was a very delicate procedure and care was needed in order not to destroy the fragile crust. In addition samples were also prepared by cutting French-fry cross sections. The crust samples were dried using a freeze dryer. Drying is important in order to keep the liquid/solid contact angle close to zero for DW measurements (Kalogianni et al., 2004) and a necessary step before fat extraction and SEM. The use of a freeze dryer prevents the alteration of the porous crust characteristics. Subsequently oil was extracted by hexane (analytical grade, Merk) using an automatic Soxhlet-type apparatus (SER 148, Velp sScientifica, Italy) for 2 h 30 min at 165 °C.

2.2. Wicking experiments

The effective mean pore radius of the porous crust was determined by using a DW technique (van Oss et al., 1992). The wicking experiments are based on adaptation of the technique for porous foods (Kalogianni et al., 2004). The experimental assembly used for the wicking experiments is shown schematically in Fig. 1. An optical cell (4 cm × 4 cm × 4 cm, Hellma) closed with a rubber lid was used as the measurements cell. Due to the hygroscopic nature of the samples, the glass box contained dry silica gel, which was renewed between measurements. The advancement of the front of the wicking liquid was observed and acquired using a Charge-Coupled Device videocamera (DCR-VX1000E, Sony) connected to a monitor. Polydimethyl siloxanes of different molecular weights