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A pore inactivation model for describing oil uptake of French fries during pre-frying

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ABSTRACT

The reduction of oil uptake during deep-frying is a subject with societal relevance, given the trend towards lower-fat foods. Since research into oil absorption during frying is limited, we here report on developing better mechanistic understanding of this process. The oil uptake for different frying temperatures and fry dimensions was measured as a function of the water evaporation rate and water loss. A pore inactivation model was developed based on the hypothesis that the crust is a porous layer through which the exuding moisture vapour flow inhibits oil migration. Decreases in water evaporation rates will cause pores to inactivate, allowing oil to penetrate into the crust. The model provides good predictions to the experimental data. Since the model has two parameters, a purely statistical comparison with a simple linear fit having one parameter, does not show a significant benefit; however, the model better describes the overall trend of oil uptake.

1. Introduction

In the last decades, deep-fat frying has become one of the most popular methods to prepare food, not only because of the method's ease but also because of the distinctive palatability and mouth feel of oil fried products. Globally, potatoes are easily the most established fried product and, as French fries and potato chips, are an integral part of many western cultures. One of the most important quality parameters of fried foods is the oil content. While the oil gives fried products their specific flavour, consumers tend to move towards lower-fat food products, creating the need to also reduce the fat content in industrial-scale food processing. To minimise the oil content without losing the popular characteristics of fried products, it is essential to understand the mechanisms by which the oil penetrates the product during frying.

The oil uptake into French fries can be divided into 3 parts: (1) the internal oil, which is the oil that is absorbed by the fries during the frying itself; (2) the absorbed surface oil, which is the oil absorbed by the fries directly after their removal from the oil; and (3) the surface oil, which is the oil that adheres to the surface of the fry after cooling (Bouchon et al., 2003). Previous research showed that the final oil content is determined to large extent by the adsorbed surface oil, while during frying itself, oil penetration into the product is partly hindered by water evaporation and expulsion from the fry (Moreira et al., 1997; Pedreschi et al., 2008; Ufheil and Escher, 1996). After the fries are removed from the oil, cooling leads to condensation of the water vapour in the pores, which causes an under-pressure and thus a suction of oil from the surface into the pores of the fries (Vitrac et al., 2000).

Measures have been developed to prevent uptake after frying, mostly revolving around fast removal of the surface oil to minimise the oil uptake due to condensation of the water vapour in the fries. The oil uptake during frying, however, is a phenomenon that has been less well studied and is more difficult to prevent. Previous investigations only empirically described the oil uptake during frying using a first order equation or simply by proposing that the amount of oil absorbed is proportional to the amount of evaporated water (Gamble et al., 1987; Krokida et al., 2000; Moyano and Pedreschi, 2006). Although this gives adequate results for higher frying times, it does not match the experimental data for smaller time intervals, which are the relevant times for industrial pre-frying processes. To better understand this countercurrent migration of oil and water vapour, a more mechanical description is proposed in this study.

We here report on a mechanistic description of the oil uptake during frying, by drawing an analogy to the way that pore inactivation is modelled during cross-flow membrane emulsification. This is a new process that is proposed to produce emulsions with

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narrow droplet size distributions, by pressing a to-be-dispersed fluid through the pores of a membrane that is wetted by the continuous phase. The continuous phase flows over to the receiving side of the membrane. In many studies, it was found that only a small fraction of all pores in the membranes were active, i.e., had dispersed phase flowing through, while most of them were inactive (Vladisavljevic and Schubert, 2002; Yasuno et al., 2002). During emulsification with microsieves (micro-engineered precision membranes) it was observed that lower transmembrane pressures lead to inactivation of a large fraction of the pores, even when all pores are exactly the same (Abrahamse et al., 2002). The reason for this is that droplets at the surface of a pore need a minimum pressure to be released, i.e. the critical Laplace pressure, which is higher than the pressure that is needed to sustain the oil flow and continuous detachment of droplets, as soon as the oil flow has started. If the supplied pressure across the membrane is lower than the critical Laplace pressure, not all pores can be sustained, and inactivation of pores occurs. Similar phenomena have been seen with the formation of foams with membranes (Kukizaki and Goto, 2006).

We here draw the analogy to frying of French fries. Here, water vapour is forced through the pores in the crust of the fry into the oil phase. During frying the pressure across the pores in the crust decreases due to the decreasing heat transfer and water evaporation rate, since the crust slowly become thicker. This will cause some of the pores to become inactivated, and will allow oil to be taken up due to capillary pressure.

We first report on the measurement of water evaporation and oil uptake as function of frying time for different frying oil temperature and dimension of the French fries. Then, the mechanistic approach is presented and used to describe the oil absorption during frying based on the principle of pore inactivation. This approach is then evaluated and compared to the empirical approach assuming linear relation between absorbed oil and amount of water evaporated.

2. Materials and methods

2.1. Preparation of raw potato samples

Alexia potatoes purchased at a local supermarket were used in this study. Potatoes were cut into uniform cylinders with a cork borer and a stainless steel knife into three different diameters: 8.5, 10.5, and 14 mm. The cylinders were cut to a length of 50 mm with a calliper. Samples were then soaked for 10 min in tap water to equilibrate the moisture content of the batch, and tissue paper was used to remove excess surface water.

2.2. Frying experiments

Potato samples were fried in a professional fryer (Caterchef EF 4L) containing 3 L of 100% sunflower oil as frying medium. Three different temperatures were used to fry the samples: 140, 160, and 180 °C. The sample frying times were 20, 40, 60, 120, and 180 s. One fry was fried at a time, and three duplicates were performed for each sample.

2.3. Surface oil determination

Directly after frying, the potato cylinders were dipped for 1 s in a reaction tube containing petroleum ether in order to remove all the adhering surface oil. Afterwards, the petroleum ether was left to evaporate in a fume hood and the weight gain of the reaction tube was used to determine the amount of surface oil that had adhered to the sample (Moreira et al., 1997).

2.4. Moisture content

Prior to the frying step, the raw potato cylinders were weighed to determine their initial mass. After the adhered surface oil had been removed, the potato cylinders were weighed once more and oven dried at 105 °C to constant weight (approximately 24 h). To determine the amount of moisture evaporated from the cylinders during frying, the mass balance was solved assuming oil, water, and dry matter as the only components.

2.5. Oil uptake during frying

After removing the adhered surface oil, the only remaining oil in the potato cylinders was the oil that had been absorbed during frying. This oil was determined using a Büchi Extraction system B-811 with 200 mL of petroleum ether as the extraction medium (boiling range 40–60 °C). The samples were ground and subjected to the extraction (3 h) in pairs to obtain a more significant amount of oil, and thus decrease the relative errors.

2.6. Water evaporation rate

Different methods to determine the water evaporation rate have been documented. Costa et al. (1997) proposed a method to obtain the evaporation rate by recording the frying process in a glass container on video. Since larger amounts of vapour bubbles resulted in lighter patches in the grayscale images, they could well correlate the average lightness with the amount of evaporating water. However, a more reliable method is gravimetric analysis. This has been done during frying by putting the entire frying system on a scale and directly monitoring the weight loss during frying (Farkas and Hubbard, 2000). However, since the weight of the frying setup is much larger than the weight of evaporating water per time unit, this method is not very accurate.

We here use an offline gravimetric analysis to obtain the water evaporation rate. This was done by measuring the water loss at different times and subsequently fitting a line through the obtained data points. The water content obtained at different frying times was fitted using a compartmental model proposed by Costa and Oliveira (1999):

$$\frac{M_0 - M}{M_0} = 1 - \alpha[e^{-K_c t}(1 + K_c t)] - (1 - \alpha)[e^{-K_e t}(1 + K_e t)] \quad (1)$$

in which M_0 is the initial amount of water in the fry (g), t the frying time (s), M the amount of water in the fry (g) at time t and α, K_c (s^{-1}) and K_e (s^{-1}) are fitting constants. By taking the derivative of the compartmental model we obtain an expression for the evaporation rate:

$$\frac{M}{t} = -\alpha K_c^2 t[e^{-K_c t}] - (1 - \alpha)K_e^2 t[e^{-K_e t}] \quad (2)$$

Since these relations are empirical in nature it should be noted that the fitting constants cannot be directly correlated with the process parameters (i.e. temperature and fry diameter) and the data sets need to be fitted separately. For the same reason, extrapolation should be avoided, since the fit is not validated outside the data range.

2.7. Modelling oil uptake

Since existing models for oil absorption during frying all rely on purely empirical relations, a new mechanistic interpretation is useful. For this, we approach the crust as a series of parallel linear pores which connect the moist core of the French fry with the frying medium. As the internal pressure decreases, due to decreasing evaporation rate, pore inactivation occurs (Fig. 1).