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Effect of hydrocolloid type on transfer phenomena during deep-fat frying of coated potato strips: Numerical modeling and experimental analysis

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ABSTRACT

Numerical simulation is a valuable tool to predict the behavior of systems as well as to optimize and control various food processes. The main aim of this work was to develop a 3-D model to numerically simulate momentum, heat, and mass transfer during deep-fat frying of coated potato strips with a particular focus on the influence of hydrocolloid type. The samples were pre-treated with different hydrocolloids (sodium alginate, Arabic gum, and carrageenan) separately and then fried at different positions of fryer. In order to validate the model, experimental measurements of moisture content (*MC*), oil uptake (*OU*), core (T_{co}) and surface (T_{surf}) temperatures of potatoes, and oil temperature (T_o) were carried out. Oil velocity ($\vec{u}_o$) was also simulated. The results indicated that profiles of dependent variables were not significantly ($p > 0.05$) affected by four positions of the samples in the fryer. The *MC* and *OU* were significantly lower in coated potatoes ($p < 0.05$) compared to non-coated samples. Sodium alginate was more effective than two other gums in decreasing *OU*. In addition, the rates of T_{co} and T_{surf} increased in the samples and T_o and $\vec{u}_o$ distributions were influenced by pre-treatment. The maximum values of computed $\vec{u}_o$ were 5.41×10^{-3}–5.57×10^{-3} m/s during frying of different potato strips. A comparison of model predictions and experimental data showed their overall good agreement (except for *OC* with mean relative error > 20%). Generally, the findings of this work may be used to provide further insights into the influence of hydrocolloid type on transfer phenomena during frying. It may also be valuable to better understand the process and improve quality of fried coated food.

1. Introduction

Deep-fat fried food is one of the most popular thermally processed products in the food industry. However, the major drawback associated with a fried product is its high oil content (*OC*), resulting in high blood pressure, diabetes, and coronary heart disease (Bansal et al., 2015). Deep-fat frying (DFF) has attracted significant research and development efforts over the past decade due to the growing demand of health-conscious consumers to lower the *OC* of fried products. It has been well argued in the literature that oil uptake (*OU*) is influenced by various factors such as frying time-temperature combinations, initial composition, and shape/size of food material (Mellema, 2003), among others. Several strategies have been proposed to reduce *OU*, especially for potato products. One of the most promising methods is the use of pre-treatment(s) such as surface coating with edible hydrocolloids (Khazaei et al., 2016; Naghavi et al., 2018), pre-drying by either hot-air or microwave (Dehghannya et al., 2016; Karacabey et al., 2017), and osmotic dehydration (Dehghannya and Abedpour, 2017).

Surface coating is a simple pre-treatment with low complexity to improve the nutritional quality of fried foodstuffs by decreasing their *OC* (Naghavi et al., 2018). During frying, hydrocolloids are able to decrease the permeability of product surface by creating a strong surface with low empty pores. These materials possess thermo-gelling, film-forming, and/or crosslinking properties during frying (Mellema, 2003; Varela and Fiszman, 2011). Thus, they form a barrier to the inner water diffusion during the process, and decreasing the rate of *OU*. This is mainly due to the strong and positive correlation between water loss (*WL*) and *OU* during frying (Dehghannya et al., 2016; Karimi and Esmaeilzadeh-Kenari, 2016; Khazaei et al., 2016).

According to the literature, different hydrocolloids might have different effects on mass transfer properties of fried product (Daraei-Garmakhany et al., 2014; Karimi and Esmaeilzadeh-Kenari, 2016). Therefore, it is necessary to investigate the effects of hydrocolloid type on *WL* and *OU* of fried food both experimentally and numerically. Generally, hydrocolloid type is important from different aspects such as easy to work (in higher concentrations), viscosity of gum solution (interaction with the food product surface), and the effect on heat and mass transfer (HMT) during DFF. In the past two decades, some

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researchers have experimentally explored the effect of pre-treatment of a food with different hydrocolloids on mass transfer properties during frying (Kim et al., 2012; Daraei-Garmakhany et al., 2014; Karimi and Esmaeilzadeh-Kenari, 2016). For example, Daraei-Garmakhany et al. (2014) reported that at a given gum concentration, xanthan was more effective in decreasing the *WL* and *OU* compared to other hydrocolloids (pectin, guar, and carboxymethyl cellulose). In addition to mass transfer, it is expected that the oil flow in fryer, as well as heat transfer rate in fried product and frying oil, are influenced by coating pre-treatment (Naghavi et al., 2018). The reason is that during frying, simultaneous momentum, heat and mass transfer (SMHMT) occur. However, only very few experimental studies have been undertaken on this subject. Two studies by Kim et al. (2011) and Kim et al. (2012) showed that coating pre-treatment with different hydrocolloids (guar, gellan, and xanthan gum) affected the experimental temperature profile at the center of fried potatoes. The researchers reported that heat transfer coefficient (h) was also influenced by concentration of the hydrocolloids used. The reduction in h and core temperature (T_{co}) of the sample was attributed to the higher total volume of vapor bubbles escaped from the pre-treated food surfaces into oil bulk during frying (Kim et al., 2011; Kim et al., 2012). In fact, the bubbles formed on the surface of food acted like a thermal insulation, and consequently limited the rate of heat transfer from the frying medium to the product. Moreover, during DFF, the value of h for guar gum-coated potatoes was significantly lower than that for samples pre-treated with gellan (Kim et al., 2011). The higher viscosity of guar gum solution compared to gellan gum was considered to be the main reason for this observation, which enhanced resistance to heat transfer (Kim et al., 2011; Kim et al., 2012). More recently, Naghavi et al (2018) studied the effect of different concentrations of sodium alginate on SMHMT during DFF of coated potato strips. The results showed that *WL* and *OU* in pre-treated potatoes were significantly lower than the control samples. In addition, the rates of T_{co} and surface temperature (T_{surf}) increased in the samples and oil temperature (T_o) and oil velocity ($\vec{u}_o$) fields were affected by pre-treatment. These results show that type and concentration of gum are two critical factors influencing the quality of fried coated food. Therefore, further studies (both based on experimental data and numerical simulation) are required to evaluate the influences of the type of gum on SMHMT during frying of coated food samples.

On the other hand, in order to design a frying process, the knowledge about the moisture content (*MC*), *OU*, and temperature (T_{co} and T_{surf}) profiles in fried product, and T_o and $\vec{u}_o$ distributions in the fryer is required (Naghavi et al., 2018). This is necessary both for the optimization of unit operation, and for food producers to approve the process. Computational simulation can be a valuable tool in meeting these requirements to produce a high-quality fried food. It provides a good alternative to expensive and time consuming experiments in the laboratory (for example, measurement of T_{co}, T_{surf}, and *OC*). Furthermore, during the DFF, $\vec{u}_o$ is very difficult to be directly measured, if not practically impossible (Naghavi et al., 2018). For these reasons, numerical modeling has attracted much attention in the last 20 years (Halder et al., 2007a,b; Wu et al., 2013; Bansal et al., 2015; van Koerten et al., 2017; Naghavi et al., 2018). In general, DFF is a highly complex thermal processing operation in the food industry. The vapor bubbling phenomenon which takes place during frying results in rapid agitation (intense turbulence) of the fluid phase. This makes the numerical modeling of the process significantly more difficult. Generally, to develop a comprehensive fundamental model and to analyze DFF from an engineering point of view, SMHMT should be taken into account (Naghavi et al., 2018). There are some empirical and fundamental models (1-D or 2-D) in the literature on HMT during frying of different food products. Nevertheless, all of the previous research on food frying have focused on modeling of heat and/or mass transfer during frying of non-coated food products. For example, an unsteady-state model to numerically simulate the *MC* of chicken drum during frying was developed by Ngadi et al. (1997). The model did not include the *OU* and heat transfer. Later, a porous media based model for predicting HMT during DFF of foods was developed by Yamsaengsung and Moreira (2002a,b) and validated for tortilla chips. Baik and Mittal (2005) also proposed a numerical model to predict HMT during frying of tofu. In another work, mathematical modeling of HMT (based on porous media) during DFF of a restructured potato slab was successfully performed and validated (Halder et al., 2007a,b). However, in these three studies, the model was applicable only for non-coated foods and did not include T_o and $\vec{u}_o$ in the fluid. Moreover, in the study of Halder et al. (2007a,b), the model did not include the formation of crust during DFF and its influence on the model predictions. Food frying model can be described by a moving boundary (a sharp interface phase change) problem with SMHMT. In this model, two different regions can be defined in the food sample: core and crust. According to the literature, thermo-physical properties of crust region are different from that of core region (Farid and Kizilel, 2009; van Koerten et al., 2017; Naghavi et al., 2018). Additionally, Farinu and Baik (2008) modeled a frying process to predict the temperature rise (T_{co} and T_{surf}) and *MC* change in sweet potato. Nevertheless, modeling of *OU*, the prediction of T_o and $\vec{u}_o$ in the fluid, and the formation of crust during the process were not studied by these authors. Later, Carrieri et al. (2009) and Carrieri et al. (2010) proposed a 2-D numerical model for predicting the temperature distribution in the sample and velocity field in oil during frying of a single potato cube. The model did not include the *OU* and the simulated results of *MC* were not reported. Some years later, a CFD model was developed by Wu et al. (2013) and Bansal et al. (2015) to numerically simulate the mass transfer kinetics during frying of non-coated potato slice and rice crackers, respectively. An important effect – not included in the model – was the formation of crust during the process. In addition, one of the main limitations of the model presented by Wu et al. (2013) was the assumption of constant oil concentration as a boundary condition at the food/oil interface, which is not true. In practice, oil concentration on food surface changes with frying time, which needs to be taken into account in the model.

To the authors' knowledge, although a number of studies have been made on the use of surface coating with various gums before frying of foodstuffs, none of these papers investigated numerical modeling of SMHMT during frying of coated food. In our previous work, we have shown that SMHMT during DFF of potato strips were affected by different concentrations of a given gum (Naghavi et al., 2018). The novelty of the present research consists in investigating the effect of hydrocolloid type on transfer phenomena during DFF of coated potato strips. With this background, the objectives of this work were to: (1) develop a numerical model for the prediction of the SMHMT during frying of potato strips using a finite-element commercial solver (COMSOL Multiphysics) with a particular focus on the influence of hydrocolloid type; (2) investigate experimentally and numerically how three different hydrocolloids (sodium alginate, Arabic gum, and carrageenan) affect T_o and $\vec{u}_o$ profiles in the fryer, temperature distribution (T_{co} and T_{surf}), and *MC*, and *OU* profiles in potatoes during frying of the control and coated samples; (3) validate the model using measured data.

2. Materials and methods

2.1. Materials

Potato tubers of the *Agria* variety and sunflower oil (Bahar, Behshahr Industrial Company, Tehran, Iran) were purchased from a local market in Tabriz, Iran. The samples from the same batch were selected. Food grade gums (sodium alginate, Arabic gum, and carrageenan) used in this work were supplied from Lotte Chemical Titan (Malaysia).