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Momentum, heat and mass transfer enhancement during deep-fat frying process of potato strips: Influence of convective oil temperature

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ABSTRACT

A 3-D mathematical model involving coupled momentum, heat and mass transfer within a whole domestic fryer was developed. Simulations were run at different frying temperatures of 150, 170 and 190 °C for 360 s. The results showed good agreement between predicted and experimental potato temperature and moisture content. The estimated average oil velocities were 0.00176, 0.00182 and 0.00171 m s^{-1} at 150, 170 and 190 °C, respectively. The batch potatoes placed at the bottom of the fryer confined oil flow, minimizing the oil velocity. Regardless of oil temperature, the experimental and simulated results revealed that the center temperature of samples reached approximately 97 °C after 100 s and remained constant until end of frying. In contrast, the final surface temperature varied considerably between 100 and 130 °C by changing the oil temperature and the potato strips' location. The results also showed that the oil temperature had a positive influence on the final oil content of potato strips, which decreased by approximately 35% with increasing temperature from 150 to 190 °C. Moreover, simulation results showed how crust formation and vapor flow limited oil penetration during initial frying periods (almost 90 s) to about 2 mm from the potato surface. This study also revealed that fryer's element, vapor bubbles and thermocouple placement are influential factors to obtain good agreement between experimental and simulation data. Additionally, the results of the sensitivity analysis showed that increased surface area to volume ratio (2.16 to 7.16) mainly affected the moisture and oil content, whereas final center and surface temperatures were more dependent on the smallest dimension and the two smallest dimensions, respectively.

1. Introduction

Deep-fat frying is considered as an efficient cooking method in the food processing industries such as factories, catering operations and home food preparation [1]. In this process, food is cooked by immersion in an edible oil such as sunflower or canola, at temperatures between 150 and 200 °C [2]. During the frying, the simultaneous momentum, heat and mass transfer induces a variety of consumer-desired sensory properties including fried food flavor, golden brown color and a crisp texture [3]. These coupled transport phenomena are important subjects in many engineering fields [4]. The quality of the fried product depends on the frying conditions such as temperature and time, product size, type of oil and the food itself [5]. Understanding the coupled momentum, heat and mass transfer, as well as the dependence on the temperature differential as a driving force, are important in improving both process efficiency and product quality [4]. Moreover, the oil temperature during frying, and the thermal and physical characteristics of the product and the oil, are critical factors in the development of the desired sensorial properties found in fried foods, and are mainly attributable to high heat transfer rates [6,7]. High heat transfer rates are in turn attributable to the temperature gradient between the hot oil and food product surfaces, which are intensified by the quick escape of vapor from the food product [6,8].

Overall, an understanding of oil flow, temperature, and moisture and oil distribution throughout the process is very important to control efficiency, and enhance product quality and healthy characteristics [9]. However, laboratory monitoring of these characteristics during frying operation is difficult because multiple sensors and thermocouples must be placed in various positions in the fryer and the product [10]. On the other hand, it has been clearly shown that the temperature distribution cannot be ignored even in the smallest material [11]. For these reasons, computer simulation has proven to be an invaluable tool for development and advancement of this sort of experimental works in the last years.

A wide range of simulation studies have been performed on the potato frying process [4,9,12–16]. Most of these studies focused on multiple and interdependent transport phenomena as well as heat and mass transfer coefficients, but the results were limited to 1D or 2D

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Nomenclature

c	concentration (mol m^{-3})
c_p	specific heat capacity (J kg^{-1} K^{-1})
D	diffusion coefficient (m^2 s^{-1})
D_{exp}	experimental value
D_m	mass diffusivity (m^2 s)
D_{sim}	simulated value
d.b.	dry basis (kg kg^{-1})
E_a	activation energy (J mol^{-1})
g	gravitational acceleration (m s^{-2})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
h_m	convective mass transfer coefficient (m s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
K_0	evaporation rate constant (s^{-1})
K_w	rate of evaporation (s^{-1})
L	characteristic length (m)
M	moisture content (kg kg^{-1})
M_m	molar mass (kg mol^{-1})
n	unit normal vector to the boundary
n_d	data points number
Nu	Nusselt number
P	pressure (Pa)
P%	mean relative percent deviation
Pr	Prandtl number
R	universal gas constant (J kmol^{-1} K^{-1})
Ra	Rayleigh number
T	Temperature (K)
t	time (s)
u	velocity (m s^{-1})

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
λ	evaporation latent heat (J kg^{-1})
μ	dynamic viscosity (Pa s)
υ	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

a	air
co	core
cr	crust
eq	equilibrium
g	gas
i	initial
o	oil
p	potato
s	Solid
surf	surface
v	vapor
w	water
∞	surrounding air of fryer

modeling. Deep-fat frying may be considered as a moving boundary problem similar to that found in freezing. In the moving boundary approach, the simulation domain is separated into core and crust regions, and each region is assessed by different properties and/or equations [17].

Carrieri et al. [4,13] modeled the 2D local and transient changes of a single potato strip during frying, using a small mesh volume and, hence, less computational cost. However, the oil distribution was not included in their simulation. Wu et al. [9] developed a 2D model to analyze the effects of different frying conditions on the moisture, oil and temperature profiles of potato slices during frying in an industrial fryer, but did not consider the momentum equation and moving boundary.

Studies that actually quantified the corresponding 3D simulation of frying are very scarce while 3D simulation of the whole frying system can help to improve our knowledge of this process [18]. Therefore, to improve the frying process and reduce energy consumption, development of a model which includes all transport phenomena is essential to provide insight into the characteristics of deep-fat frying of potato strips. In the present study, the aim was to assess the effect of three oil temperatures on dependent variables, and to establish a three-dimensional transient model capable of predicting velocity, the temperature in the oil, and the temperature, moisture and oil distribution in the potato strips during frying process at any location and time. Finally, a sensitivity analysis was carried out to examine the effects of the potato size on the temperature, oil and moisture content of fried samples.

2. Materials and methods

2.1. Raw material

Sunflower oil as frying medium and fresh potato tubers (variety *Agria*) were purchased from a local market (Tabriz, Iran) and used in the frying experiments. The tubers were stored in a cold store at 7–8 °C with 85–95% relative humidity prior to each set of the experiments. The tubers were washed in cold water, peeled, and cut into strips of

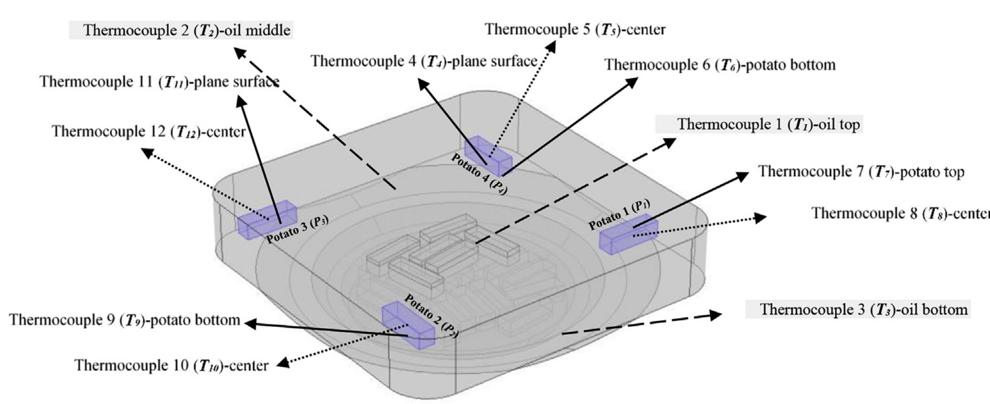

Fig. 1. Placement of the thermocouples and potato strips in the fryer.

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