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A two-dimensional frying model for the investigation and optimisation of continuous industrial frying systems

H. Wu, T.G. Karayiannis*, S.A. Tassou

School of Engineering and Design, Brunel University London, Uxbridge, Middlesex UB8 3PH, United Kingdom

HIGHLIGHTS

► A new two-dimensional model for continuous frying systems was developed.
► Simulation results compared well with industrial plant data.
► The effects of operational factors on final moisture and oil content were systematically analysed.

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ABSTRACT

In this study, a coupled two-dimensional transient model was developed to predict the temperature, moisture content and oil uptake as encountered in industrial continuous deep fryers. The set of transient governing equations developed were solved numerically with the variable time-step finite volume method. The mathematical model can be used to analyse the effects of different frying conditions on the moisture, oil and temperature profiles during the frying processes. Numerical results are presented to show the applicability of the developed model and can help researchers and designers to ascertain optimum operational conditions of frying processes. The physical and mathematical construction of the model not only allows extension of the formulae so that the frame of the model can be used in other similar food processes systems, but also utilizes the dynamic characteristics of the fryer for development and evaluation of advanced control strategies.

1. Introduction

Frying is a widely used and industrially important food process. In addition to the actual production of the desired foodstuff, the designer of the process should consider improving quality, reducing or controlling oil absorption and producing healthier products. Therefore, it is a field of major interest to engineering and scientific researchers, as well as designers, developers and manufacturers [1,2]. Frying is classified as one of the most complex food-processing operations due to the numerous interactions that take place within the food. A generic schematic is depicted in Fig. 1, showing that simultaneous heat and mass transfer occurs during frying. The important parameters in such a process include temperature of oil, frying time, initial moisture content and thickness of slice. Many attempts have been made to combine heat and mass transfer principles to describe the temperature, moisture content and oil content profiles in a product in deep-fat frying processes. In the literature, numerous research works relating the deep-fat frying modelling are described, which focused on potato chips and French fries [3–11].

A more detailed model of temperature and moisture transport in deep-fat frying of an infinite potato slab was provided by Farkas et al. [12,13]. The separate equations for the two regions, crust and the core, with a moving boundary were considered. However, their model did not include the oil phase. A one-dimensional transport model that includes oil phase to simulate the effects of different frying conditions on the oil, moisture, and temperature profiles during the frying process of tortilla chips was developed by Chen and Moreira [14]. In 1999, a multiphase porous media model was developed and used to predict the moisture migration, oil uptake and energy transport in food material such as a semi-dry potato during deep-fat frying, and were validated with available experimental data by Ni and Datta [15]. Later, a two-dimensional model based on the approach of Ref. [15] was developed for frying and cooling of tortilla chips and a set of coupled heat and mass transfer equations were solved using a 2-D finite element method [16,17].

* Corresponding author. Tel.: +44 (0) 1895 267132; fax: +44 (0) 1895 256392.
E-mail address: tassos.karayiannis@brunel.ac.uk (T.G. Karayiannis).

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Nomenclature

a	coefficient [−]
A_{eff}	effective heat transfer area between frying oil and air [m^2]
A_p	specific area [m^2/m^3]
b	source term [−]
c_p	specific heat [kJ/kg K]
D	oil diffusivity [m^2/s]
E_a	activation energy [kJ/mol]
h_a	natural convective heat transfer coefficient of air [W/m^2 K]
h_{fa}	heat transfer coefficient between frying oil and air [W/m^2 K]
h_{fg}	latent heat of vaporization [J/kg]
h_{fs}	heat transfer coefficient between frying oil and potato slice surface [W/m^2 K]
H_{fo}	oil height inside the fryer [m]
k	thermal conductivity [W/m K]
L	fryer length up to takeout conveyor [m]
L_{ff}	length of free frying section [m]
$\dot{m}$	mass flow rate [kg/s]
R_g	universal gas constant [J/mol K]
S_{VFw}	water vapour source term [1/s]
t	time [s]
T	temperature [K]
v	velocity [m/s]
VF	volume fraction [−]
x	axial coordinate [m]
y	vertical coordinate [m]

Greek letters

δ	potato slice thickness [m]
ρ	density [kg/m^3]
ϕ	generalized variable

Subscripts

a	air
amb	ambient
c	characteristic
eff	effective
E	East
fo	frying oil
FG	foul gas
in	inlet
N	North
ps	potato slice
pss	potato slice surface
P	control volume
rps	raw potato slice
ss	steady state
surf	surface
sw	surface water of raw potato slice
S	South
v	vapour
w	water
W	West
0	initial
1	fuel
2	combustion air
3	foul gas
4	re-circulated exhaust gas
5	combustion products
6	Exhaust gas
7	oil inlet
8	oil outlet
9	air flow
10	raw potato slices
11	surface water of raw potato slices
12	oil return
13	fines removal
14	potato crisp

Bouchon and Pyle [18,19] presented a good review of oil absorption modelling in 2005 and they developed a predictive mechanistic model that can be used to understand the principles behind post-frying cooling oil absorption kinetics, which is helpful to identify the parameters such as pressure that affect the final oil intake by the fried product. Halder et al. [20,21], afterwards, developed a multiphase porous media model of deep-fat frying that can be applied to both frying and post-frying cooling to predict important industrial food quality parameters such as oil pick up and acrylamide content. The model was validated with the experimental results of Ref. [12] and a better agreement was obtained compared with the previously developed model of Ni [15].

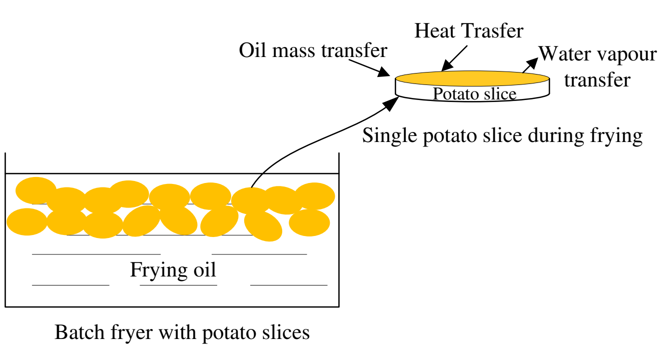

Fig. 1. A generic schematic of frying process (batch and single potato slice).

Datta [22] presented the relationship between various models used to study simultaneous heat and mass transfer in food processes, starting from the most elaborate multiphase porous medium model that includes evaporation and going down in complexity to the simplest equation of isothermal diffusion. A more general multiphase porous media model with distributed evaporation was shown to effectively describe a number of heat and mass transfer processes in foods in Ref. [23]. Most recently, Farid [24] presented a unified approach to food dehydration, which was based on a moving boundary [25] and previous studies [26,27] which used a single equation to describe the dehydration processes of food with different geometries. It was concluded that the developed method can account for moisture diffusion and could be used to predict heat and mass transfer in all drying and frying processes. The single parameter defined in Ref. [24] is a physical parameter, which reflects the extent of mass diffusion relative to thermal diffusion. It was dealt by using an empirical parameter due to the lack of information of physical properties of food such as moisture permeability and crust thermal conductivity.

Examination of above researches indicates that the vast majority of the published works has mainly concentrated on the investigation and modelling of the heat and mass transfer processes for a single or a batch product in the laboratory. However, batch frying is not common at the industrial scale since it is more costly than