Journal of Food Engineering 119 (2013) 125–134

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Quality and safety driven optimal operation of deep-fat frying of potato chips

Ana Arias-Mendez [a], Alexander Warning [b], Ashim K. Datta [b], Eva Balsa-Canto [a,*]

[a] Bioprocess Engineering Group, IIM-CSIC, C/Eduardo Cabello 6, 36208 Vigo, Spain
[b] Department of Biological and Environmental Engineering, Cornell University, 208 Riley-Robb, Ithaca, NY 14853-5701, United States

ARTICLE INFO

Article history:
Received 20 December 2012
Received in revised form 20 March 2013
Accepted 5 May 2013
Available online 21 May 2013

Keywords:
Deep-fat frying
Acrylamide
Model identification
Dynamic optimization

ABSTRACT

Increasing oil temperature and heating duration in deep-fat frying of potato chips can improve textural quality but worsen the chemical safety of acrylamide formation. Optimal design of this complex process is formulated as a non-linear constrained optimization problem where the objective is to compute the oil temperature profile that guarantees the desired final moisture content while minimizing final acrylamide content subject to operating constraints and the process dynamics. The process dynamics uses a multi-component and multiphase transport model in the potato as a porous medium taken from literature. Results show that five different heating zones offer a good compromise between process duration (shorter the better) and safety in terms of lower acrylamide formation. A short, high temperature zone at the beginning with a progressive decrease in zone temperatures was found to be the optimal design. The multi-zone optimal operating conditions show significant advantages over nominal constant temperature processes, opening new avenues for optimization.

1. Introduction

Frying generates tasty products that have crispy crusts, tempting aromas and visual appeal. These unique properties make fried foods a major part of the prepared foods market and therefore deep-fat frying is still one of the most important unit operations in the food processing industry.

Type of oil, oil temperature, and duration of cooking greatly affect the final quality attributes of fried foods. Often in literature, the quality is related to the oil uptake and oil deterioration. Oil uptake occurs during frying due to replacement evaporated water by oil and during post frying when it is absorbed due to the vacuum from cooling. Hydrolysis and oxidation contribute to the development of rancid flavors deteriorating oil quality (Saguy and Dana, 2003).

Recent works showed that fried foods are a significant source of dietary acrylamide (Tareke et al., 2002; Zhang et al., 2005), an emerging factor that has been associated with cancer risk and neurotoxic effects. Although the details of acrylamide synthesis are not fully understood, the Maillard-driven generation of flavor and color in the frying process can be linked to the formation of acrylamide (Medeiros-Vinci et al., 2011).

The increased awareness of the consumers to the relationship between food, nutrition and health has emphasized the need to design (pre-)process conditions, product specifications and type of oil so as to improve product quality and to minimize oil uptake and acrylamide formation. In this regard some recommendations may be found in, for example, Alvarez et al. (2000), Mestdagh et al. (2008), and Brigatto-Fontes et al. (2011).

However, these recommendations are often obtained by means of response surface models thus having a number of important drawbacks due to the empirical, local and stationary nature of the simple algebraic models used.

A fundamental understanding of the deep-fat frying process and the application of adequate optimization techniques could lead to new equipment and operation designs that may improve safety and quality of the final product.

To understand the mechanisms involved in the process, mathematical models were developed, from the first attempts that included heat, moisture and fat transfer in the frying of foods (Ateba and Mittal, 1994; Moreira et al., 1995; Farkas et al., 1996) to the most recent porous media based models which also account for texture and acrylamide evolution (Halder et al., 2007; Thussu and Datta, 2012; Warning et al., 2012).

Bassama et al. (2012) considered, via simulation, two types of transient oil temperature profiles in order to asses the impact on the final acrylamide content. The first oil temperature profile started at a high temperature, followed by a lower one and the second frying oil temperature profile was vice versa. Their work

* Corresponding author. Tel.: +34 986 23 19 30x403.
E-mail addresses: anaarias@iim.csic.es (A. Arias-Mendez), adw88@cornell.edu (A. Warning), akd1@cornell.edu (A.K. Datta), ebalsa@iim.csic.es (E. Balsa-Canto).

0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.05.001

concludes that the first type of profile results in significant reductions on the final acrylamide content.

However at the time of designing processing profiles, not only should have acrylamide content been taken into account, but quality attributes and processing time. Of course solving such a problem via simulation is rather complicated, if not impossible, due to the numerous degrees of freedom and constraints. This work proposes the use of advanced model based optimization techniques (Banga et al., 2003; Banga et al., 2008) to design optimized frying processes to ensure appropriate safety through minimized final acrylamide content and quality by guaranteeing the desired specifications in terms of color and texture.

2. Theory

2.1. Formulation of the optimization problem

In industry, the traditional operation conditions for frying potato chips consist of immersing the chips in continuous fryers where the frying oil is held at high temperatures. The process duration is long enough (typically between 1 and 3 min) to guarantee a desired final color, texture, and a final moisture level less than 2% of the initial moisture content (Brennan, 2006).

The objective of the present work is to formulate and solve a general dynamic optimization problem to find the operating conditions (oil temperature and process duration) that produces the desired quality attributes while minimizing the final acrylamide content. Mathematically stated as:

Find $T_{oil}(t)$ and t_f to minimize $c_{AA}(t_f)$ such that:

$$T_{oil_{min}} \leqslant T_{oil} \leqslant T_{oil_{max}} \tag{1}$$

$$t_f \leqslant t_{f,max} \tag{2}$$

$$QC(t_f) <= 0 \tag{3}$$

$$\Phi(S_w, S_o, S_g, T, M, P, w, c_{AA}, T_{oil}, \boldsymbol{\kappa}, \xi, t) = 0 \tag{4}$$

where T_{oil}, t_f, and c_{AA} are the oil temperature, process duration, and acrylamide content respectively. QC stands for the quality constraint defined in Eq. (5).

Eq. (3) defines the constraints for quality as defined by color, texture, and moisture content. Pedreschi et al. (2005),Pedreschi et al. (2006) showed that the color in the product during the frying process follows a first order kinetics. The higher the red component of the color, the darker the potato and the worse the commercial acceptance of the final product. In addition, these authors show how acrylamide content is linearly correlated with the color at 1.8% of the initial moisture content whereas Pedreschi et al. (2005) show a clear correlation between the increase of acrylamide content and the increase of redness. In this optimization work, it is assumed that the minimization of acrylamide content also minimizes redness of the product. Regarding texture, Thussu and Datta (2012) presented a mechanistic model to predict Young's module development during frying. Their results suggest that there is not critical difference in considering the texture or the moisture content to control the process duration. Therefore, the constraint imposed in the optimization will be related to the moisture content at the end of the process. In this way, the solution of the equations to predict texture evolution is not really necessary. The quality related inequality constraint now becomes:

$$M(t_f) - 2 \leqslant 0. \tag{5}$$

where M is the percentage of the final moisture content, which is intended to be 2% or lower at the end of the process.

There is an additional set of constraints (Eq. (4)) which corresponds to the system dynamics from the mathematical model of the process which describes the evolution of the saturation of water, oil and vapor (S_w,S_o, S_g), product temperature (T), moisture content (M), pressure (P), water vapor mass fraction (ω_v) and acrylamide content c_{AA}; the corresponding spatial and temporal derivatives, as functions of the spatial coordinates (ξ); time (t) and oil temperature (T_{oil}). The vector $\boldsymbol{\kappa}$ keeps all model thermo-physical and kinetic parameters.

2.2. Mathematical model of the process

In the deep-fat frying process, water containing foodstuff is immersed into oil or fat at high temperatures (typically between 160 and 180 °C, Pedreschi et al. (2005)). The high temperature induces water evaporation and the formation of a thin crust. Due to the evaporation, the water is gradually transported to the boundary layer whereas the oil is absorbed by the food replacing some of the lost water. As soon as the transfer of water ends, the temperature inside the food starts to rise and the typical deep-frying sensory characteristics begin to develop.

A multiphase porous media based model describing heat, mass and momentum transfer and acrylamide kinetics within a potato chip will be used. The potato chip is assumed to be a porous media where the pores are filled with three transportable phases: liquid water, oil, or gas (mixture of water vapor and air). The model considers a 2D geometry as illustrated in Fig. 1, the potato chip is assumed to be cylindrical and heated from outside therefore axi-symmetry can be assumed. The physical mechanisms and corresponding equations derivation are described in detail in Warning et al. (2012) and Halder et al. (2007). The final system of equations is presented in Appendix A.

It should be noted that most of the thermo-physical and kinetic parameters present in the model may be found in the literature (see Table A.1 in the Appendix) but the heat transfer (h) and the surface oil saturation $S_{o,surf}$. Previous works provided different parameter values for different oil temperature values. However for the purpose of dynamic optimization either a unique value for the parameters or a functional dependency with the oil temperature is required. In either case, unknown model parameters have to be identified from experimental data.

2.2.1. Model parametric identification

The objective of parametric identification (model calibration or parameter estimation) is to compute a unique value for the vector of unknown parameters ($\boldsymbol{\theta}$), which either coincides or is included in the vector $\boldsymbol{\kappa}$, so as to minimize the distance among experimental data and model predictions. In this work, this distance is quantified by the sum of the weighted squared differences among experimental and simulated data (weighted least squares).

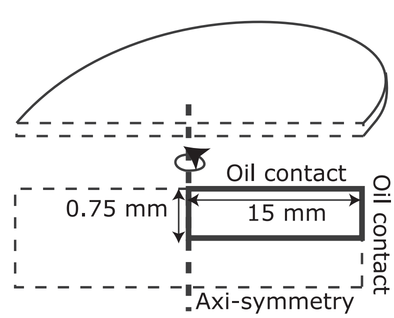

Fig. 1. 2-Dimensional computational domain and geometry of the potato chip.