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Evaluation of acrylamide formation in potatoes during deep-frying: The effect of operation and configuration

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ABSTRACT

It is nowadays well known that heating, which is carried out to improve the hygienic, sensory and nutritional properties of foods, can be also responsible for the development of acrylamide. Acrylamide levels between a few ppb and in excess of 1000 ppb have been found in many heated foods. As acrylamide is classified as a probable human carcinogen, the knowledge of critical processing variables leading to its formation is needed to ensure safety requirements.

In this work, acrylamide formation during deep-frying of potato samples is analyzed in space and time through a joint HPLC-MS/MS measurement and a computational fluid dynamics simulation. Such an approach allowed to describe the thermal and physico-chemical history of processed potatoes to bring forth their complete and validated multidimensional distributions of acrylamide concentrations during deep-frying. The effect of a number of operational parameters have been scrutinized to make the simulation results closer to the industrial settings.

1. Introduction

In April 2002 unexpected high levels of the suspected carcinogen acrylamide (AA) were found in many heated foods, mainly represented by cereal and potato derivatives. As known acrylamide can form during intense heat treatments as a consequence of the reaction between asparagine and a carbonyl source via Maillard-type reactions (Zyzak et al., 2003; Yayalan and Stadler, 2005). Efforts by the scientific community have contributed to identify potential routes to reduce AA levels in foods and thus consumer exposure. These are relevant to agronomical interventions (i.e. selection of raw materials with low sugar and asparagine contents), and technological strategies, including pre-treatments (blanching, fermentation, use of asparaginase), as well as process (thermal input and moisture control) and recipe (use of organic acids, polyvalent cations or amino-acids) changes.

Reviews of AA and ways for reducing its level in foods have been published by Friedman (2003), Stadler and Scholz (2004), Taeymans et al. (2004), Friedman and Levin (2008) and Anese et al. (2009). Also, the most relevant mitigation strategies are summarized in the Toolbox presented by the Confederation of the European Food and Drink Industries (CIAA, 2009). Recent contributions to chemical modeling can be found in Knol et al. (2009) and De Vleeschouwer et al. (2009).

Much interest has been already attracted by multiple and interdependent transport phenomena during food frying, as in Farid (2001) and Farid and Kizikel (2009), but the related results have been limited to one-dimensional modeling and dependence upon empirical transfer coefficients. Similarly, some food engineering research has been recently presented on AA-forming processes, but with a focus on average parameters only (Palazoğlu and Gökmen, 2008; Gökmen and Palazoğlu, 2008). In this framework, process modeling has a fundamental importance, and can help to establish sounder knowledge when it emphasizes on both local and transient food features (Carrieri et al., 2007, 2009). In this regard, computational fluid dynamics (CFD) models help gaining knowledge of critical processing variables, to improve the product safety and quality for generalized and particular process configurations alike.

With multiple transfer phenomena at stake, a proper modeling can be enforced by recalling the various governing equations (along with their boundary and initial conditions) and impose them on the whole product-bath system (conjugate approach). With this option, no loss of continuity is made for each transport mechanism (e.g. no need of empirical correlation for heat and mass at the product-bath interface). In addition, each transport mechanism may be strongly influenced by other ones: AA formation during food deep-frying is then seen as driven by a series of conjugate phenomena, as the transfer of species and heat to be solved simultaneously in both solid and fluid phases are strongly coupled through evaporation.

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Nomenclature

AA acrylamide

c	concentration (mg/g)
c_p	specific heat (J/kg K)
D	mass diffusivity (m^2/s)
E_a	activation energy (J/mol)
g	gravitational acceleration (m/s^2)
h	convective heat transfer coefficient (W/m^2 K)
H	height (m)
Δh_{vap}	latent heat of evaporation (J/kg)
k	thermal conductivity (W/m K)
K	reaction rate constant (1/s)
L	radial length (m)
m	mass (kg)
M	molecular weight (g/mol)
n	index versor
n	normal versor
p	pressure (Pa)
R	universal gas constant (J/mol K)
t	time (s)
Δt	duration (s)
t	tangential versor
T	temperature (K)
u	velocity vector (m/s)
x	lateral coordinate (m)
z	vertical coordinate (m)

Greek

β	thermal expansion coefficient (1/K)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

0	initial
AA	acrylamide
eli	elimination
f	fluid phase
for	formation
o	operating
R	reactant
ref	reference
s	solid phase
v	vapor
w	water
∞	surrounding environment

In this work, multidimensional distributions of AA concentration during deep-frying of small potato cubes, with variation of operating time/temperature, is analyzed by both a full CFD model, integrated with the opportune chemistry, diffusion and evaporation notations, and an associated validating HPLC-MS/MS investigation. Realistic transfer exchanges are inherently considered and the adoption of empirical (averaged) heat transfer coefficient is limited. The employed approach is similar to what presented in Carrieri et al. (2007, 2009), but this time an electrically operated frying process, with much larger oil/sample ratio, has been exploited. A sensitivity analysis was brought forth to verify the influence of some important operating parameters, including geometry, on the average concentration of AA in the processed food, to show directions for industrial processes optimization.

2. Material and methods

2.1. Sample preparation

Potato tubers (*Solanum tuberosum* cv. "Primura"), bought on a local market, were peeled, cut into little cubes (10 mm side) using a hand-operated potato cutter. About 5 g of material were then deep-fried in 3 L of vegetable oil by using an electrical fryer (Moulinex AF1003, Milano, I), equipped with a static basket and a thermostat. Deep-frying was carried out at two thermal operating conditions: 155 °C ± 3 °C (for $\Delta t = 120$ or 240 s), and 180 °C ± 3 °C (for $\Delta t = 60$ or 90 s). After deep-frying, the potato cubes were drained and wiped to remove the oil excess.

2.2. Determination of temperature and thermal effect

Temperature changes during the deep-frying were measured by two T-type copper-constantan thermocouple probes (Hanna Instruments, Milano, I), placed at the sample centre and at 1 mm under the surface of potato samples. A third probe was also placed in the bath at mid-height, far enough from the heating wall, in order to measure the retort temperature. Time and temperature data were acquired by means of a data logger connected to a PC.

2.3. Analysis of AA

Acrylamide determination was carried out by aqueous extraction at 60 °C for 30 min, purification by solid phase extraction (Isolute Env+, 1 g) and quantitation by LC-ESI-MS-MS in positive ion mode with d3-acrylamide as internal standard, following the method of Anese et al. (2009).

2.4. Analysis of sugars

The analysis of sugars was performed by HPLC. About 5 g of homogenized samples were extracted using 10 mL of deionised water for 10 min at ambient temperature under continuous stirring. The mixture was centrifuged (Beckman, Avanti Centrifyge J-25, Palo Alto, CA, USA) at 12,000 g for 10 min at 4 °C. The supernatant was sequentially filtered through a 0.45 μm and a 0.25 μm Millipore filters prior HPLC analysis. HPLC analysis was performed using a Jasco (880 PU I, Japan) liquid chromatograph, equipped with a manual 20 μL loop injector and a refractive index detector (RID-10A, Shimadzu USA Manufacturing Inc., USA). Chromatographic separation was performed by using a 250 × 4.6 mm 5 μm Alltech ALLTIMA NH2 (Alltech Italia, Milano, Italy) column at isocratic condition. The mobile phase consisted of 70% acetonitrile and 30% water, with a flow of 0.8 mL/min. Standards of glucose, fructose and sucrose were used for quantification.

2.5. Determination of total solid content

Total solid content was determined by gravimetric method by drying the samples in a vacuum oven (1.32 kPa) at 75 °C until a constant weight was achieved.

2.6. Data analysis

The experiments were carried out at least on three replicated runs. Coefficients of variation, expressed as the percentage between the standard deviations and the mean values, were lower than 15 for AA, 10 for sugars, eight for total solid content. One-way