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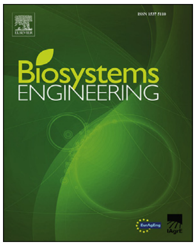

Research Paper

Finite element model to study the thawing of packed frozen vegetables as influenced by working environment temperature

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Freezing is the most common process for long-time preservation of food. In order to avoid changes of texture, colour or flavour, the frozen products should not be subjected to temperature fluctuations; however, in between the packaging and cold storage steps, the products are frequently subjected to routine controls at an environment temperature of about 10 °C, which risk inducing a heating of the frozen foods. To study the effect of environment temperature on heat transfer inside frozen foods a parametric finite element model capable of describing the conduction and convection phenomena, inside and on the surface of the packages, was developed and validated for three products (peas, spinach cubes and grilled aubergines). The initial and final thawing temperatures were measured by using a differential scanning calorimeter. Acceptable agreement was obtained between numerical and experimental results with a maximum error of 1.8 °C. The relation between calculated product temperatures, environment temperature and time was investigated and a good fit was obtained ($R^2 > 0.97$). Furthermore, specific relations between time required to reach the initial thawing temperature and the ambient temperature, were determined. The model could be used for other different vegetable products by changing material properties.

1. Introduction

Among all food preservation methods, freezing is one of the most important operations for long-term preservation of food quality (Campanone, Salvadori, & Mascheroni, 2005). Properly frozen products are considered to be closest to fresh foods since their valuable nutritional components, colour and flavour are retained for a long time, due to the inhibition of chemical, enzyme reaction and growth of microorganisms (Wiktor, Schulz, Voigt, Witrowa-Rajchert, & Knorr, 2015). This situation is likely to continue in the foreseeable future; in fact, the demand for the frozen food continues to grow at a rate of 20% annually (Ahmad, Jeenanunta, Chanvarasuth, & Komolavanij, 2014).

During freezing, packaging and cold storage operations, significant physical, chemical and biochemical changes could take

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Nomenclature

d	thickness (m)
f	Krischer parameter
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
n	normal vector of the boundary
q	heat flux (W m^{-2})
t	time (s)
C	specific heat (J kg^{-1} K^{-1})
D	thermal diffusivity (m^2 s^{-1})
L	characteristic length (m)
R	contact resistance (m^2 K W^{-1})
T	temperature (K)
Gr	Grash of number
Nu	Nusselt number
Pr	Prandtl number
β	air thermal expansion (K^{-1})
ε	volume fraction
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
ϑ	area fraction

Subscripts

a	air
app	apparent
c	convective
env	environmental
p	food product
pm	package material
C	contact
1	initial thawing
2	final thawing

place, especially if the process conditions are far from the optimal ones (Sun, 2011). The time-temperature tolerance of frozen products is the most important factor responsible for the final quality of products (Taoukis, Giannakourou, & Tsironi, 2011). Temperature increase could induce undesirable changes in texture, colour or flavour, followed by safety problems related to the microbial development at the food surface (Sun, 2011).

After the freezing process, the product should not be subjected to the temperature fluctuations; however, between the packaging and cold storage (at −18 °C) steps, the frozen products are generally subjected to the routine controls, which are performed in an environment with the temperature between 5 °C and 10 °C. During this time, the packaged products are subjected to heating. In order to set an optimal working environment temperature, which considers also the wellness of the worker, it is essential to study the evolution of the temperature field in the food as a function of the temperature of the environment. This variation with time and food type can be determined experimentally; however, experimental tests are often time consuming and arduous to set up (Karthikeyan, Desai, Salvi, Bruins, & Karwe, 2015). Furthermore, the thermal sensors are able to estimate the temperature only in specific points of the product.

Analytical and numerical heat transfer models are considered to be an alternative valuable tool to estimate food temperature changes under thermal environment fluctuations (Norton & Sun, 2006; Scott & Richardson, 1997; Wang & Sun, 2003). Goral, Kluza, Spiess, and Kozlowicz (2016) developed different models (analytical, empirical and graphical) to determine thawing times of frozen foods. Delgado and Sun (2001) presented a literature review on freezing time prediction models. The main advantages of the numerical models compared to analytical ones, are related to the higher complexity of geometry, materials and boundary condition that are possible to consider. For example, in order to take into account the dependence of food properties on temperature, numerical models are required (Ousegui, Le Bail, & Havet, 2006). Moreover, these models allow the prediction of the temperature distribution inside the whole package and not only the mean product temperature.

To carefully predict the temperature variation using numerical solutions, the physical changes observed in the product during phase change have to be well understood. The most suitable numerical method that could be used to obtain a converged solution is the finite element method (Kumar & Panigrahi, 2009).

In the phase transition temperature range that separates the completely thawed and the completely frozen food, the solid ice is generally dispersed in liquid water (mushy zone) (Bhattacharya, Basak, & Ayappa, 2002). Consequently, the latent heat is released or absorbed, over a temperature range, due to the change in ice and water concentration (Franke, 2000; Karthikeyan et al., 2015). The thermo-physical properties (density, thermal conductivity and specific heat capacity) significantly vary with temperature in the mushy zone, while they remain almost constant in completely thawed and frozen regions (Voller, 1997). Density and thermal conductivity can be simply reported as functions of the temperature, based on the phase distribution of the food system. The inclusion of the latent heat during the phase change represents a modelling problem. Several approaches have been proposed, but the most popular and reliable technique is the use of the *apparent specific heat* useful to describe both the specific heat of the product and the released latent heat (Franke, 2000; Karthikeyan et al., 2015; Kumar & Panigrahi, 2009; Leung, Ching, Leung, & Lam, 2005).

The aim of this work was to develop and validate a parametric finite element model for the evaluation of the effect of environment temperature on heat transfer inside packed frozen vegetable (peas, spinach cubes and grilled aubergines). The initial and final thawing temperature, the latent heat and the thermo-physical properties of the products needed for the model implementation were measured experimentally. This modelling approach has the is proposed as a general engineering tool useful for the prediction of frozen vegetable behaviour under realistic conditions.

2. Materials and methods

2.1. Materials

The products used for the experimental determinations (DSC measurement and thermophysical properties) and the model validation were peas, spinach cubes and grilled aubergines.