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2D water transfer finite elements model of salami drying, based on real slice image and simplified geometry

Angelo Fabbri, Chiara Cevoli *

Department of Agricultural and Food Sciences, University of Bologna, P.zza Goidanich 60, 47521 Cesena, FC, Italy

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ABSTRACT

In the sausage industry, ripening is considered to be the most important phase of the production process. Numerical models were successfully used to study the mass transport in many food during baking, freezing, ripening and drying process. The aim of this research was to develop two finite element models of water diffusion inside a salami, taking account of the vapour exchange phenomena at the surface. One model was based on the real fat and meat distribution, as acquired by image analysis, while a second one, more simple, considering the salami material as homogeneous and imposing an equivalent value of diffusion coefficient, based on compositional equations (parallel, series, Maxwell and Krisher) or literature data. The vapour exchange phenomenon at the surface was described using a surface mass transfer coefficient (h_m) calculated on the basis of the well-known Chilton–Colburn analogy. The two models were compared and validated with experimental mean moisture concentration. The agreement between mean simulated and experimental values was reported in terms of determination coefficients (R^2). For all models, the R^2 value is higher than 0.95, supporting that the experimental and all calculated data are in good agreement. The less good data were obtained with the simplest model, based on equivalent diffusion coefficient coming from literature (R^2 = 0.955, RMSE = 1665 mol/m^3). Very small difference was observed between results related to structural models. The finite element model based on the real fat and meat distribution underestimated experimental results, giving results not far from structural models, but giving the best result at the end of ripening time. The deviation from experimental results probably is due to geometrical reconstruction uncertainties and particularly on binarisation triggering on a grey scale.

Considering the real fat distribution, a more complex model, but not more precise results than those calculated considering an equivalent homogeneous material, were observed.

1. Introduction

Dry sausages are the result of a fermentation process and a ripening period during which the products reach the desired characteristics (Tabanelli et al., 2013). The wide variety of dry fermented sausages is a consequence of variations in raw material and is therefore closely related to intrinsic factors such as the content of salt, fat, sugar, kind of starter and degree of comminution (Zanardi et al., 2010; Kottke et al., 1996). Salami are typical European dry sausages manufactured with pork, beef, or veal, added with salt, spices, and sometimes herbs and/or other ingredients. The use of preservatives is also allowed in certain cases (Aquilanti et al., 2012).

In the sausage industry, ripening is considered to be the most important phase of the production process. A number of studies indicate that the final quality and safety standards achieved by the sausage manufacturing process can be considered to be strictly dependent from the specific ripening conditions (Grassi and Montanari, 2005). During the ripening, main physical, chemical and microbiological transformations take place inside the products and define the final colour, texture, shelf-life, taste and flavour of dry sausage.

To get feasible data about the drying of fermented sausage with given intrinsic and extrinsic parameters (temperature, air velocity and humidity), the diffusion inside and mass transfer outside the sausage need to be studied. The most important diffusion phenomenon occurring inside the matrix during ripening is the water transfer, frequently described by the Fick Laws (Le-Page et al., 2009; Welti-Chanes et al., 2005).

Finite Element (FE) models were successfully used to study the mass transport in many food during baking, freezing, ripening and drying process (Lemus-Mondaca et al., 2013; Mirade, 2008; Floury et al., 2008; Sakin et al., 2007). As concerning the salami ripening, Cevoli et al. (2014) developed a parametric finite element model of

* Corresponding author.
E-mail address: chiara.cevoli3@unibo.it (C. Cevoli).

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Nomenclature

aw	water activity
C	moisture concentration (mol/m^3)
D	diffusion coefficient (m^2/s)
f	distribution factor
g	gravitational acceleration (m^2/s)
Gr	Grashof number
h_m	mass transfer coefficient (m/s)
L	characteristic length (m)
N	water molar flux (mol/m^2 s)
Nu	Nusselt number
P	pressure (Pa)
PM	molecular weight (kg/mol)
Pr	Prandtl number
Sc	Schmidt number
Sh	Sherwood number
T	temperature (°C, K)
X	water content (kg/kg)

Greek symbol

ρ	density (kg/m^3)
μ	viscosity (Pas)
ε	volume fraction

Subscripts

air	air
airSat	saturation
atm	atmospheric
ba	air close to salami surface
bS	salami surface
f	fat
H_2O	water
i	components number
in	initial
K	Krisher
m	minced meat
M	Maxwell
p	parallel
s	series
S	salami
∞	air far from salami surface

salami ripening process and successive storage in package, while Rizzi (2003) and Grassi and Montanari (2005), developed two parametric models for the fluid dynamic simulation of ascending flow in the ripening chambers as function of environmental parameters (temperature and air velocity).

The material properties definition is one of the most critical phase during the numerical model development. Biological materials are complex and it is not always possible to neglect their heterogeneity and anisotropy. Moreover their physical properties (e.g. density, thermal and electrical conductivity, specific heat, viscosity, permeability, moisture diffusivity, composition) can vary with temperature, humidity and time (Fabbri et al., 2011). The diffusion coefficient is the fundamental material parameter related to mass transfer phenomena and its estimation influences the model result.

The problem of the water diffusion in a heterogeneous media can be studied by using the similarity of this phenomenon with the heat transfer. In this way, compositional equations developed for prediction of the effective thermal conductivity of heterogeneous systems (e.g. Series, Paralleles, Maxwell, Random, Krischer and Higuchi model) could be used also to predict the effective diffusion coefficients (Vagenas and Karathanos, 1991).

On the other hand, the heterogeneous material could be described by the real distribution of the phases, imposing different values of diffusion coefficient as function of the material. To do this, a geometry describing the real distribution of the components is required. In a more simple way, the material properties definition could be made using global diffusion data coming from literature.

An experimental ripening test, in one specific condition, needs about one month, while the solution of a FE model requires just some minutes. As a consequence it is possible, with a well calibrated FE model, to check the effect of many different ripening conditions in terms of initial moisture, environment moisture, daily time–temperature curve, fat distribution and salami dimensions.

The aim of this research was to compare two parametric FE models able to describe water diffusion phenomenon occurring inside the salami and the vapour exchange phenomenon that take place at the interface between the product surface and the environment. The first model was based on a simple 2D geometry considering the salami material as homogeneous and imposing an equivalent value of diffusion coefficient, based on compositional equations (Parallel, Series, Maxwell and Krisher) or literature data. The second model was developed by using a 2D geometry describing the real distribution of fat in a salami slide by using a 2D image of a sausage slice. The material properties were defined considering the diffusion coefficient of the minced meat and fat.

The two models results were experimentally validated, comparing the mean moisture content experimentally determined, on salami ripened for 28 days at 15 °C and about 80% relative humidity.

2. Material and method

2.1. Models development

2.1.1. Geometry definition

It was hypotized that physical parameters does not vary on the salami length. This approximation made possible to reduce the 3D problem to a 2D, with great advantages in term of computational time. According such hypothesis the salami slice was considered as representative of a salami of infinite length.

In the first model, the geometry dimensions reflected the real ones of the salami considered in the experimental validation, in particular a simple circle (radius 22 mm) corresponding to a mean cross section of the cylinder representing the shape of the salami, was considered.

In the second model, the geometry reproduced the real phases distribution (minced meat and fat). A 2D picture (Fig. 1a) of a slice from a salami characterized by the 22% of fat was used. The type of salami was the same used for the model validation. The image was acquired as an 8 bit gray-scale, than binarised as B/W (Fig. 1b) by using Image J 1.47v (Wayne Rasband, USA), referring to a gray threshold level such as the white to black ratio was the same as fat to meat. Subsequently the image was imported into the FE software. A specific Comsol function named *image function* makes it possible to import an image (in BMP, JPEG, PNG or GIF format) and map the image's RGB (red, green, blue) data to a scalar (single