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Finite element model of salami ripening process and successive storage in package

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ABSTRACT

Salami are typical European dry fermented sausages manufactured mainly with pork meats. Water loss is a crucial aspect of industrial ripening process because it is responsible for the lowering of water activity, which determines limitations to successive conservation.

This paper describes two parametric numerical models developed to study the moisture diffusion physics, during ripening and storage in package. Mass transfer equations inside the sausage volume were numerically solved using a finite element technique. A first model describes diffusion phenomena occurring inside the salami and the exchange phenomena involving the surface of the product and the industrial environment, while a second one describes also the evaporation and condensation phenomena occurring between the salami surface and the atmosphere inside the packaging. The models were experimentally validated showing a good agreement with observed data.

The numerical models allowed to study the water transfer inside of dry fermented sausages with a detail unreachable by any experimental technique. In addition the models could be used to find the best conditions for ripening, packaging and distribution.

1. Introduction

Dry fermented sausages are the result of a fermentation process and a ripening period during which the products reach the desired characteristics. From several centuries, different kinds of dry fermented sausages have been produced in the Mediterranean area (Toldrá et al., 2007; Zeuthen, 1995; Ordóñez et al., 1999). The wide variety of dry fermented sausages is a consequence of variations in formulation, raw material, manufacturing and ripening processes which come from the traditional habits of different countries and regions (Zanardi et al., 2010). Often fermented sausages get different names according to geographic origin (Toldrá, 2006). In particular, salami are typical European dry fermented sausages manufactured mainly with pork, but also with bovine, ovine and equine meats, with the addition of salt, curing agents (nitrate and nitrite), spices, and sometimes herbs and/or other ingredients (Feiner, 2006).

The primary European countries producing salami are Germany, Italy, Spain, France and Hungary, with a production of several hundred-millions kg per year, and ripening and storage periods play an important role on the final characteristics of these fermented sausages (Bertolini et al., 2006). In particular, in the dry fermented sausages industry, ripening is considered one of the most important stages of the integrated supply chain needed to ensure that end products have the final requirements in terms of quality and safety standards (Grassi and Montanari, 2005). In fact, the ripening stage influences over the main physical, chemical and microbiological transformations that take place in salami after manufacturing.

A large number of studies regarding the influence of ripening conditions on the microbiological, physical and chemical properties of dry fermented sausages are available (Baldini et al., 2000; Campbell-Platt and Cook, 1995; Zanardi et al., 2010; Tabanelli et al., 2012; 2013). All these researches show that the final quality and safety standards achieved by the sausage manufacturing process can be considered to be strictly dependent from the conditions under which ripening stage is designed and carried out (Rizzi, 2003).

The most important mass transport phenomenon occurring inside the matrix during ripening is the water transfer. Many theoretically and experimentally studies about transfer of water and

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solutes through meat and meat products matrices are reported in literature (Costa-Corredor et al., 2010; Graiver et al., 2006; Hansen et al., 2008; Sabadini et al., 1998; Unal et al., 2004). Water loss is a crucial aspect of ripening because it is responsible for the lowering of water activity (a_w), which determines limitations to the growth of many spoilage and pathogenic microorganisms. In addition, the water loss has to be as uniform as possible to avoid the formation of moisture gradients in the sausages causing the case hardening which is negative for the textural properties and also for the safety of the final products. Water loss can be modulated during ripening by controlling the temperature of the ripening chambers and their relative humidity (Feiner, 2006).

As reported in many specific reviews, the recent progress in computing efficiency coupled with reduced costs of codes has set out the numerical simulation as a powerful tool to study many food processes with the aim of providing effective and efficient plant design or operating solutions (Scott and Richardson, 1997; Xia and Sun, 2002; Wang and Sun, 2003; Norton and Sun, 2006; Smale et al., 2006; Verboven et al., 2006; Mirade, 2008). In this regard, the numerical simulation was used to study the mass transfer in various foods during drying, baking, freezing and ripening (Mirade, 2008; Sakin et al., 2007; Lemus-Mondaca et al., 2013; Floury et al., 2008).

As concerning the salami ripening, Rizzi (2003) developed a parametric model for the fluid dynamic simulation of ascending flow ripening chambers as a function of operational conditions. The model was experimentally validated comparing measured and simulated air velocity modules.

Grassi and Montanari (2005) developed a parametric model very similar to that of Rizzi (2003), but in addition, the authors built a sausage drying model that computes mass and heat exchange between sausage and the air flows. However, the model has not been experimentally validated.

The aim of this research was to develop two parametric numerical models, concerning the moisture diffusion physics, describing salami ripening and storage. Mass transfer equations inside the sausage volume were numerically solved using a finite element technique. A first model describes diffusion phenomena occurring inside the salami and the exchange phenomena involving the surface of the product and the environment, while a second one describes also the evaporation and condensation phenomena occurring between the salami surface and the atmosphere after the whole sausage packaging. The models was experimentally validated, comparing the numerical outputs of the simulations with experimental data. In addition, the models could be used to find the best conditions at which whole fermented sausages should be packaged for distribution.

2. Materials and methods

2.1. Ripening model

Commercial computational multiphysics codes are available nowadays, allowing an exceedingly flexible simultaneous numerical solution of the energy, mass and moment equation (Scott and Richardson, 1997) and are extensively adopted in the food engineering field (Xia and Sun, 2002; Wang and Sun, 2003; Norton and Sun, 2006; Fabbri et al., 2011).

The equations of mass transfer inside and on the salami surface were solved using Comsol Multiphysics 4.3 (COMSOL Inc., Burlington, MA, USA), a commercial partial differential equations solver, based on finite element technique. During ripening, the moisture diffuses from the inside, towards the salami surface and about half of the initial water content is lost through evaporation. To simulate moisture transfer inside of product, salami material was treated as homogeneous and isotropic, initial moisture was set uniform and salami volume was considered constant.

In order to limit the computation time, a one-dimensional model was built because the salami geometry is axisymmetric and it was considered an indefinite length salami. Subsequently, with a simple geometric operation, a 2D model can be visualized. The geometry dimensions reflect the real ones of the salami considered, in particular a simple radius (r: 25 mm) between the longitudinal axis and the external cylindrical surface was considered.

The moisture transfer is governed by Fick's law:

$$\frac{\partial C}{\partial t} = D_{\mathrm{H_2O}}(\nabla^2 C) \tag{1}$$

where C is calculated moisture concentration (mol m^{-3}) at time t.

Mass diffusivity ($D_{\mathrm{H_2O}}$) through the involved material was found in literature (Simal et al., 2003; Trujillo et al., 2007).

Initial moisture concentration (C_{Rin}) was considered constant in space and defined as following:

$$C_{Rin} = \left(\frac{X_{Rin} \cdot \rho_s}{PM_{\mathrm{H_2O}}}\right) \tag{2}$$

where X_{Rin} is the initial moisture content on dry basis (experimentally determined: 1.2 kg kg^{-1}), ρ_s the dried salami density (experimentally determined: 600 kg m^{-3}), while $PM_{\mathrm{H_2O}}$ the water molecular weight (0.018 kg mol^{-1});

A flux condition was imposed on the interface between salami surface and air:

$$N_R = k_t(C_{bound} - C) \tag{3}$$

being N_R (mol m^{-2} s^{-1}) the water flux, k_t (m s^{-1}) the mass transfer coefficient and C_{bound} the moisture concentration of salami at equilibrium.

Mass transfer coefficient can vary within very broad limits, without problems of physical model fidelity: convergence could be compromised for high values, while for small values an artificial resistance to the moisture passage could be introduced. A value must therefore be determined empirically by choosing a level slightly lower than that which causes convergence problems (in our case k_t: 1E−6 m s^{-1}).

Moisture concentration of salami at equilibrium was defined by following equation:

$$C_{bound} = \left(\frac{X_{bound} \cdot \rho_s}{PM_{\mathrm{H_2O}}}\right) \tag{4}$$

where X_{bound} is the moisture content on dry basis at equilibrium. This value was determined by using the Oswin law:

$$X_{bound} = A\left[\frac{a_w}{(1 - a_w)}\right]^B \tag{5}$$

being a_w value equal to that of relative humidity of the ripening room by definition. A (0.4287) and B (0.2397) parameters were determined by fitting the experimental data of water activity vs moisture content, measured during the ripening, with the Oswin law.

Model was validated by comparing water activity and water concentration, numerically and experimentally determined. For the experimental determination a Milano type dry fermented salami made with pork shoulder (72% w/w) and streaky bacon (28% w/w), NaCl (2.6% w/w), dextrose (0.30% w/w), KNO_3 (0.015% w/w), $NaNO_2$ (0.010% w/w), wine (1% w/w) and spices (white pepper powder and black pepper whole grain, 0.12% w/w) was used (Tabanelli et al., 2013).

Salami had a length of about 200 mm, a diameter of about 50 mm and an initial mean weight of about 430 g. The drying conditions were the following: 48 h at 23 °C and relative humidity