Modeling and Simulation of Fermented Sausages Ripening with a Heterogeneous Porous Media Approach

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This paper presents a mathematical model of fermented sausage drying, which relies on an innovative description of the sausage as a heterogeneous material, i.e., separately made of fat and lean meat, and a porous medium. The fat is considered as an inert matter dispersed in the meat matrix, while the lean meat is a porous medium in which the transport phenomena of water take place to the outside of the matrix during the ripening process.

The implementation of the mathematical model in a Comsol Multiphysics®4.3 software code, the exploitation of the code outcomes and the validation of the code predictions are discussed against the results collected from a closely monitored and controlled batch production of "Salsiccia dolce", a typical meat product of Calabria region, at the Dodaro factory within the recent PON01_01409 "Safemeat" project. The "transport in porous media" physics was invoked in Comsol Multiphysics®4.3 and a semi-empirical correlation was adopted from literature for the capillary diffusivity as a function of the local moisture content and temperature. The simulation outcomes are discussed in terms of weight loss as well as space&time mapping of moisture in sausage, compared to the experimental measurements and to the results previously obtained by following a homogeneous model approach. The present results show an excellent agreement with the experimental data and an improvement with respect to the previous homogeneous model.

1. Introduction

In meat processing salami products are of great interest from historical, nutritional and economic viewpoints. The various types of dry sausages differ in composition (e.g., type of meat, cut size of lean and fat, ingredients and additives, nature of the casing, microbial starters) or in process and technique for drying and curing (e.g., long-maturing vs short-maturing salamis).

The preparation of salamis is based on an apparently simple procedure and usually includes the following steps: 1) sorting and trimming of meat; 2) mincing and mixing; 3) filling a natural or synthetic gut with the above mixture; 4) fermentation and drying; 5) ripening.

The shelf life of fermented sausages belonging to the Italian tradition is determined by lowering free water (i.e., water activity, a_w) below the limit for growth of spoilage microorganisms (Leistener et al., 1987).

The acquisition of scientific knowledge about the mechanisms involved in the maturation of the meats is fairly recent (Letablier et al., 1994; Pirone et al., 2007). Presently, the ability to describe the drying process depends to a greater extent on the knowledge of the phenomena related to water transport inside the product and, to a lesser extent, of evaporation from the outside surface. Obviously, a water concentration gradient establishes between the inner part of the sausage and its external surface. Owing to salami granular structure, water actually moves in a complex way and the main transfer mechanisms are usually considered I) capillary flow of free water; II) bound water movement; III) diffusion in liquid phase; IV) condensation-evaporation (Rossen et al., 1977; Okos et al., 1992). These mechanisms are often competitive (Baldini et al., 2001) and the drying kinetics is the consequence of both their interaction and the external conditions applied (Bessadok et al., 2013).

Nowadays, ripening of salami under natural conditions has been replaced by batch production in ventilated industrial chambers. Hence, the same product quality can be obtained regardless of local, environmental (Kottke et al., 1996) and climatic conditions (Katz et al., 1987). Nevertheless, well planned and carefully monitored process conditions are necessary to achieve the targeted weight loss and quality of dry fermented sausages. Therefore, the availability of reliable mathematical models and manageable software codes for sausage drying, maturation and optimal production are highly welcome. In this paper a mathematical model is presented that is more realistic with respect to the structure of the sausage and overcomes the limit of homogeneity of previous models (Cascone et al., 2015a; Cascone et al., 2015b).

2. Problem formulation

2.1 Mathematical modeling of fermented sausages during ripening

For the mathematical model considered here, geometry is 2D, axis-symmetric and cylindrical (Cascone et al., 2015a); the sausage material is heterogeneous but isotropic, with no distinction between the inner part and the casing. Therefore, the sausage is a two-phase material consisting of a fatty part regularly dispersed in a porous matrix (lean meat) in which the moisture transport phenomena take place. The water present in the whole sausage is assumed present in the lean meat only. The model of the porous system assumes small pores ($\approx 100\ \mu m$), weak evaporation and a capillary pressure formulation (Datta, 2007). Water concentration is a distributed parameter with the assumption of an effective diffusion coefficient D_e depending on the local water content (Saravacos, 2001).

The porous medium approach makes it possible to consider the fat as inert and the lean meat as a porous medium in which the water transport takes place.

The governing equation (Datta, 2007) for moisture transfer in porous media is

$$\frac{\partial c_w}{\partial t} - \nabla \cdot (D_w \nabla c_w) = 0 \tag{1}$$

with the following boundary conditions:

- Water concentration in the fresh lean meat at t=0: $c_0 = 43870\ \frac{mol}{m^3}$;
- Symmetry along the vertical axis;
- Outlet flux on the three external boundaries: $N_{0,c} = k_c \cdot \Delta c$;

    where $k_c = u \cdot j_d \cdot Sc^{-\frac{2}{3}}$, $\quad j_d = 0.037 \cdot Re^{-0.2}$, $\quad \Delta c = \left[\frac{a_{we}(z)|_R \cdot P_{air}^{sat}|_{T_{wall}}}{R \cdot T_{wall}} - \frac{RH_{air} \cdot P_{air}^{sat}|_{T_{air}}}{R \cdot T_{air}} \right]$;

- No flux on the boundaries of the impervious fat grains.

2.2 Description of the sausage ripening test

Dodaro SpA conducted a ripening test on a fresh sausage lot of 300 kg at industrial scale, under carefully monitored and controlled conditions for both process and product, as an activity planned in a R&D cooperative project (PON "SafeMeat").

Table 1: Ripening program (set points of Temperature and Rel. Humidity) of the industrial ripening chamber at the Dodaro SpA factory throughout the test conducted on a lot of 300 kg of a typical "sweet sausage"

Day	Temperature (° C)	Relative Humidity (%)
0	2.5	---
1	21-23	99
2	19-21	65-75
3-5	18-20	66-76
6	14-16	70-80
7	12-14	76-86
8	12-14	70-76
9-24	12-14	70-80

Figure 1: Progressive images of the same sausage sampled at ripening days 0, 2, 6, 13, 17, 24 (The radius of the fresh sausage is about R_0=20 mm)

The tested product followed the recipe of a typical "sweet sausage" ("Salsiccia dolce") of the Calabria region, but it was manufactured as a straight, near-cylindrical sausage, with an average radius $R_0=20$ mm, and the paste was added with a microbial starter developed in the framework of the same PON "SafeMeat" project. The grains forming the sausage paste (both fat and meat) have a typical size of about 5 mm.

The tested product was differentiated in 2 different experimental "theses", depending whether the fresh sausages were subjected or not on their outer surface to a fungal inoculum developed within the same PON "SafeMeat" project.

The test lasted 24 days in an industrial ascending-flow ripening chamber, with the drying air properties described in the program reported in *Table 1*.

During the test the most important process and product parameters were monitored by the staff at the sausage factory Dodaro, including the features of the products related to drying and maturation as well as growth of mold on their gut. In addition, the sausage shrinkage phenomena were monitored by sequentially measuring the circumference of the same sausage sample, thus determining the % reduction in the diameter at each ripening time with respect to the fresh sausage at time 0. For the same purpose, digital photos of samples were taken at various times. The *Figure 1* provides an example of the evolution of the same sample sausage during initial drying and subsequent ripening.

2.3 Laboratory experimental activity

To give greater validity to the porous media approach for the sausage ripening, the structure and water content of a lean meat matrix were experimentally analyzed. A sample of the *longissimus dorsi* was taken as representative of pork lean meat. The water content was experimentally evaluated by cutting the *longissimus dorsi* in cubes of 10 mm side and putting them in a stove at 105 °C for 24 h. The recorded weight loss averaged over a number of 10 samples yielded the water content, i.e., 74 % wt.

Then the porosity of the meat matrix was evaluated, following a pre-treatment which did not induce shrinkage of the matrix during the dehydration. After keeping the meat in the freezer @ –20 °C for 24 h, it was gently cut in order to realize cubic samples of 10 mm side as uniformly as possible (*Figure 2A*). The samples were subjected to a two-stage freeze-drying process (Babić et al., 2009): primary freeze-drying @ 5 °C for 24 h and secondary freeze-drying @ 35 °C for 7 h (*Figure 2B*).

The porosity of the samples was evaluated with Hg penetration technique using the ''PASCAL 140'' and ''PASCAL 240'' Thermo Finnigan instruments and yielded a value of $\varepsilon= 0.78$; this corresponds to the volume of water lost after freeze-drying under the reasonable assumption that all the porosity of the matrix was filled with water.

SEM (scanning electron microscopy) images were taken of freeze-dried samples. These samples were cut in liquid nitrogen along an orthogonal plane to the direction of the muscle fibers. From the SEM images a "shell and tube" structure emerges (*Figure 2C*), which supports the porous media approach to the study of meat matrices.
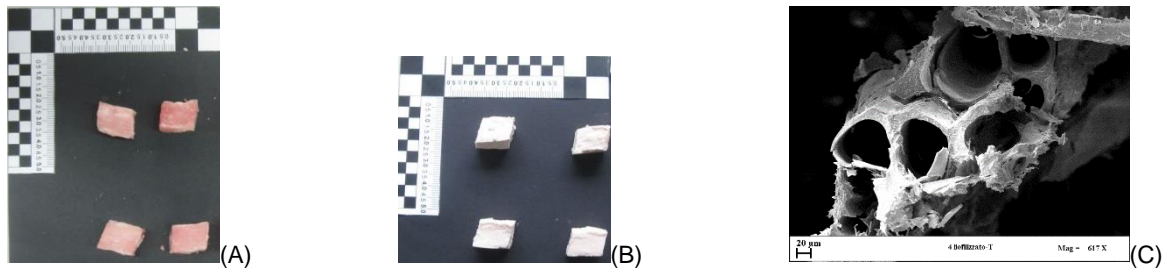

Figure 2: Frozen samples (A), Freeze-dried samples (B) and S.E.M. image (C) of lean pork meat

3. Problem solution

3.1 Implementation of the mathematical model

The COMSOL Multiphysics® 4.3b software was chosen as the modeling, simulation and graphical environment to handle the issue of the porous media approach during drying.

In very wet materials as the fresh sausage the capillary diffusivity D_W is equal to effective diffusivity D because the vapor diffusion is insignificant at the typical ripening temperatures. For this reason, in this work an expression of the effective diffusivity (Saravacos, 2001) will be used:

$$D = \frac{1}{1+X}D_0\, exp\left[-\frac{E_0}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right] + \frac{1}{1+X}D_i\, exp\left[-\frac{E_i}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right] \tag{2}$$

where $X[=]kg/kg_{db}$ is the moisture content of the lean meat.

In literature values of the activation energies E_0, E_i for the sausages are not available, for this reason a rough estimation for them is here taken from the case of a well investigated material, i.e., potato, giving E_0= 76.9 kJ/mol and E_i= 44.7 kJ/mol.

The grains that form the sausage paste (both fat and meat) introduce a discontinuity and represent obstacles to the moisture transport to the outside. This further resistance was dealt with the introduction a tortuosity factor ($\tau \approx 2$) liable to lower the moisture diffusion rate:

$$D_{eff} = \frac{\varepsilon}{\tau} D \qquad (3)$$

The "*Transport in porous media*" physics was adopted to develop a code in COMSOL Multiphysics®. The governing equations, i.e., the water mass balance, expressed in terms of Partial Differential Equations (PDEs) with their boundary and initial condition, were solved by COMSOL by means of the Finite Element Methods (FEM).

The implementation was finalized in two different code versions in order to separately account for mass transfer in either forced or natural convection. In particular, this was required because, depending on the type of convection, some parameters (e.g., the dimensionless numbers) must be calculated with different formulas.

To limit the load in calculation resources and the time required for the model resolution, a two-dimensional and axis-symmetric model in cylindrical geometry was chosen as the domain for implementation. For the same above reasons the energy balance was neglected considering the salami as isothermal material; actually, the previous work from the Authors (Cascone et al., 2015b) had showed that the thermal transient develops in a negligible time compared to the whole duration of ripening.

The volume to be attributed to the fat phase was calculated from the original recipe of the manufacturer and suitably assigned to the cylindrical domain. In particular, the fat was evenly divided in toroids with a diameter of 5 mm (i.e., the same size of the fat grain) placed inside the cylindrical matrix. The fat phase was not assigned in the form of spheres because this would have required a 3D modeling geometry with a heavier computational burden.

The development of the codes and the simulation runs have been carried out with a MS Windows workstation based on the Intel® Core™ i7-4820K processor with 3.70 GHz clock rate and 64 GB RAM. Running the code requires as input data the initial properties of the fresh sausage and the curing air conditions, i.e., temperature, relative humidity and velocity.

3.2 Simulation results

The simulation work has been started by taking as a reference the previously mentioned ripening test carried out at Dodaro SpA. Drying in a unique phase was considered under forced air circulation, that is conditions corresponding to values of air temperature, relative humidity and velocity as averaged over the whole duration of the ripening test, i.e., 24 days.

The developed COMSOL code allows obtaining time and space profiles of the dependent variables in an easy and fast way, with a clear and meaningful graphical representation.
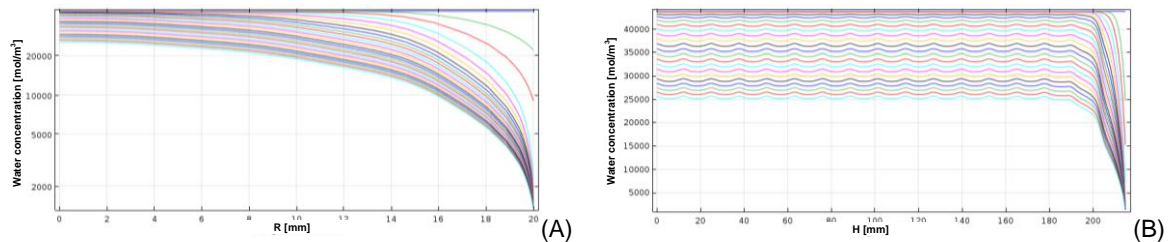

Figure 3: Water concentration (mol/m^3) profile as a function of the radial position R (A) and the axial position H (B) parametrically in the ripening day

The *Figures 3* are examples of the ways in which the profile of water concentration can be graphically reported as a function of time from the center to the surface of the sausage. First of all, *Figure 3A* confirms that the water concentration has to be intended as a "distributed parameter" variable in the investigated mechanism. In particular, *Figure 3* shows how the water concentration profile is gradually lowered day by day both along radial (*Figure 3A*) and axial (*Figure 3B*) position. The *Figure 3B* shows how the presence of inert fat elements placed in the calculation domain influences the moisture concentration profiles, by causing a characteristic series of small oscillations along the vertical axis H.

Figure 4 shows the 3D color plot of the water concentration (mol/m^3) in the sausage, precisely at both extremes of the ripening test, that is the end of day 1 (*Figure 4A*) and that of day 24 (*Figure 4B*). In the 3D representation the effect of the inert fat phase is well shown on the moisture concentration profile.

(A)

(B)

Figure 4: 3D plot of the water concentration (mol/m^3) in the sausage at day 1(A) and at the day 24(B). The color scale is at the right side

3.3 Comparison between predicted and experimental results

The code validation has been pursued thanks to the results of the previously mentioned ripening test at Dodaro SpA.

Figure 5A reports the comparison between experimental and predicted single sausage weight loss; this latter has been obtained according to a simulation of homogeneous and heterogeneous material (porous medium), respectively. The experimental data are provided in 2 different sets for Inoculated (I) and Non Inoculated sausages (NI), each averaged over several samples. The measurements were very close to each other at each ripening day.
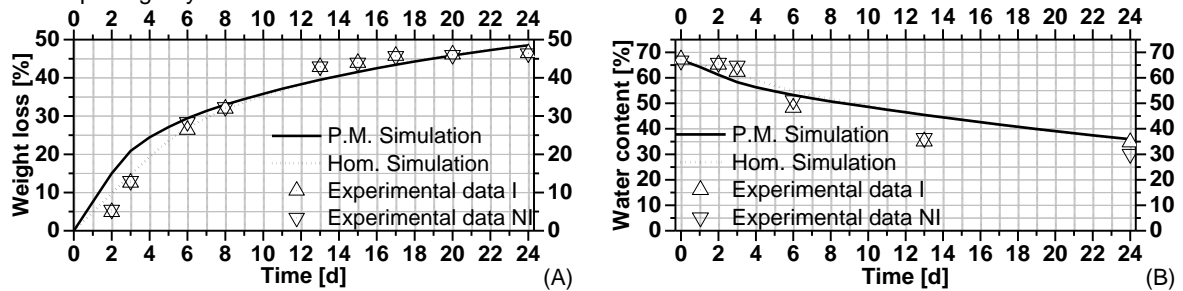

(A)

(B)

Figure 5: Comparison between experimental and (A) predicted sausage weight loss in heterogeneous (porous medium) and homogeneous model, (B) predicted values of the average sausage water content in heterogeneous (porous medium) and homogeneous model
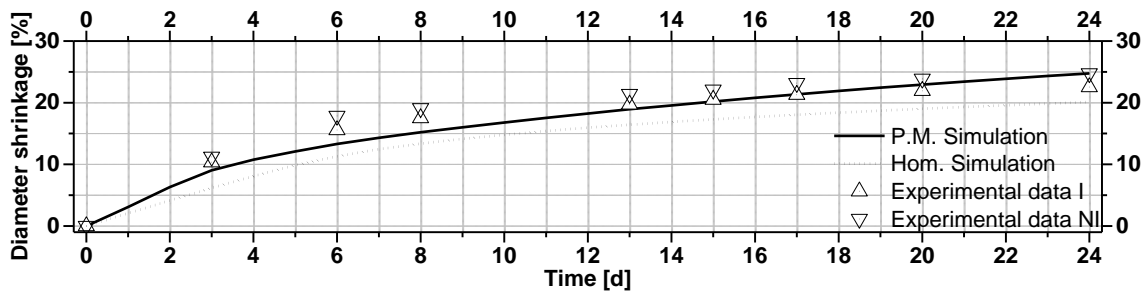

Figure 6: Comparison between experimental and predicted diameter shrinkage curves: simulation with the homogeneous model with shrinking and calculation of a diameter reduction with the data of the porous medium

All in all, the prediction of the sausage weight loss turns out satisfactory. The simulated curves appear close enough to the experimental data despite the underlying assumption of a unique value (averaged conditions) of air temperature, relative humidity and velocity throughout the whole duration of the test. One noticeable difference is seen in the early days of ripening in the simulation based on the porous media approach compared to experimental data. This is probably due to the approximation induced by expression of the effective diffusivity (as a function of the water concentration) that uses some literature parameters not specific for the sausage. In the following days both models give a good prediction of weight loss compared to the experimental data.

Figure 5B shows the trend of the volume-averaged water content for the different simulations compared to the experimental data. Also here there was a discrepancy in the first days of ripening with a good prediction in the following days for the reasons mentioned above.

The use of "*moving mesh*" (Cascone et al., 2015a) for a simulation with the porous media approach should have been too heavy; therefore, the diameter reduction was evaluated using the Feyissa (2009) equation with the results of the heterogeneous material simulation. *Figure 6* shows an excellent agreement of the new heterogeneous model with the experimental data and an improvement with respect to the previous homogeneous model.

4. Conclusions

A flexible, reliable and fast modeling and simulation tool has been successfully developed with COMSOL Multiphysics®4.3 to cope with the issue of heterogeneity of the sausage during the ripening process. The present COMSOL code retains the satisfactory prediction performance for the time evolution of the single sausage weight loss and volume-averaged water content.

The simplification introduced by considering the ripening process to be totally in forced convection (although the chamber has an alternation of natural and forced convection) with average values of curing air conditions over the whole ripening time provides satisfactory prediction results.

The heterogeneous model allows a definition of the sausage structure much closer to the real salami structure with good predictive results. The model with porous media approach can be improved by identifying a semi-empirical relationship for the effective diffusivity in the porous medium, going beyond the approximation induced by the absence of literature data.

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