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A Tool for Modelling and Simulation of Irregular Shape and Shrinking Salami During Drying

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This paper describes the extension of a previously developed mathematical model of sausage drying in order to account for irregular geometry and volume shrinking during drying. By using the COMSOL Multiphysics®4.3 software, a code was implemented with features of adaptability, reliability and speed of calculation. To catch the moving boundary at the air-salami interface during shrinking, the moving mesh physics was used and a correlation was applied between the actual actual of sausage and that of water removed. The prediction capability of the model was tested with the results collected from the batch production of “Salsiccia dolce”, a typical meat product of Calabria region, at SSICA (Parma). The results are presented in terms of salami weight loss and time-mapping of moisture and temperature in sausage.

1. Introduction

Within the fermented meat products, dry sausages are of major importance (Zeuthen, 2008). Early salami-type sausages were first produced in Italy at the time of the Roman empire (Zeuthen, 2008). Generally, ripening and drying of fermented sausages largely depend on the recipe and are therefore closely related to intrinsic factors, such as fat, sodium chloride and sugar contents, degree of comminution and kind of starter cultures added. The extrinsic variables are temperature, humidity and velocity of curing air (Baldini et al., 2001). Water activity reduction by drying and salt addition imparts stability to all kinds of meats (De Rosa et al., 2005), whereas fermentation mostly determines the characteristic texture and flavor (Zeuthen, 2008). Moisture removal takes place through water evaporation from the outer surface. As a consequence, a gradient concentration of water between the inner part of the solid and its external surface establishes. Owing to salami granular structure, water actually moves in a complex way and three main transfer mechanisms are usually considered i) capillary flow of free water; ii) bound water movement; iii) diffusion in liquid phase. 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 Jemai, 2013).
Nowadays, ripening of salami under natural conditions has been replaced by batch production in ventilated industrial chambers. So the same product quality can be obtained regardless of local, environmental (Kottke et al., 1996) and climatic conditions (Katz and Stinsky, 1987). Ascending-flow ripening-chambers are prevalently used for industrial applications. A main upward air flow that is cyclically moved along the cell floor, ensures the required average drying homogeneity. In these chambers, the inlet air flow is rationed by a rotary distribution valve between two main distribution ducts, which feed two inlet nozzle banks located at the outermost sides of the cell ceiling (Grassi and Montanari, 2005). The air jets are directed downward along the cell walls, and the flows merge over the cell floor, in a position that depends on their respective kinetic energy.
Nevertheless, carefully designed conditions are necessary to achieve the weight loss and several microbiological, physic-chemical and biochemical changes to guarantee the sensory quality of dry fermented sausages, as well as their chemical and microbial stabilization (Costa et al., 2010). To provide automatic control and optimal cost-effective operation of the ripening chamber through scheduling of ventilation, air temperature and relative humidity, as well as to achieve the targeted quality of the dry fermented sausages, a reliable mathematical model and a handy computer code of sausage drying/maturation are required.

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It is commonly assumed that salami has a perfect cylindrical shape, its weight loss is due to water evaporation only and biochemical changes due to fermentation have no influence (Imre and Kornyey, 1990). Salami have been usually modeled as a homogeneous and isotropic material and water concentration is intended to be a distributed parameter. Imre and Kornyey (1990) subdivided salami structure into two parts, the inner part (core) and the casing, having different chemical-physical and transport properties, and wrote different mass balance equations, respectively. In an earlier work, by considering 1D, axi-symmetric, homogeneous and time-fixed cylindrical geometry, Diaferia et al. (2011) developed and validated a mathematical model predicting drying and temperature history of a single sausage, under both natural and forced air circulation. Actually, sausages exhibit irregular shape and shrinking size. Therefore, the aim of this paper was that of improving such mathematical model to account for sausage irregular geometry and volume shrinking during drying.

2. Modeling and code implementation

The COMSOL Multiphysics® 4.3b software was chosen as the modeling, simulation and graphical environment to overcome the aforementioned limitations arising from the assumption of axis-symmetric, cylindrical geometry. The previous treatment of internal mass transport phenomena as a concentration-dependent Fickian diffusion (Diaferia et al., 2011) and the assumption of an effective diffusion coefficient D_e depending on the local water content (Imre and Korney, 1990) were maintained. Both the "mass transfer in diluted systems" and "heat transfer in solids" physics have been invoked in COMSOL Multiphysics®. The underlying modeling equations, i.e., Partial Differential Equations (PDEs) with their boundary and initial condition, were solved by COMSOL by means of the Finite Element Methods (FEM). The mathematical model has been implemented in two different files in order to separately account for mass and heat 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. Different representations of the sausage geometry have been attempted. They are schematically reported in Figure 1 with increasing complexity: a) cylindrical 2D axi-symmetric geometry; b) irregular 2D axi-symmetric geometry; c) irregular 3D geometry; d) cylindrical 2D axi-symmetric geometry with volume shrinking.

An improvement of the cylindrical geometry (Figure 1a) is provided by the adoption of an irregular domain with two approaches. The first one is still axi-symmetric and generates a solid domain by overlapping three ellipsoids (Figure 1b). In practice, this corresponds to the actual shape of a typical "soppressata". Boolean operations of union and subtraction of sets (ellipsis) are needed for the realization of the domain. A further adjustment is the use of a "non-mapped mesh" in COMSOL due to the irregularity of the domain.

A second approach is that of developing an irregular domain without the symmetry axis and with a non-symmetric solid shape. In practice, this corresponds to the actual shape of a curved sausage. In this case, modeling in 2D is no more possible, and a 3D domain is required (Figure 1c). The 3D formulation has hampered the model by increasing the degrees of freedom and imposing constraints on the mesh. In particular, a mesh of unstructured tetrahedra and a characteristic mesh size larger than that used in the previous cases were required to reduce the calculation load and to achieve convergence in a reasonable time.

In order to account for the effects of sausage shrinkage (due to water removal) during ripening, a further physics has been invoked in COMSOL i.e., the "moving mesh". The two-dimensional and axi-symmetric model in cylindrical geometry (Figure 1d) was chosen as the domain for implementation of the "moving mesh" physics. This choice partly compensates the increased load in calculation resources and time needed to approach convergence. For the sake of simplicity, the cylindrical domain was assumed to undergo radial deformation only, i.e., the edge could move backward in the radial direction only. The "moving mesh" physics requires a constitutive equation describing the rate of edge receding as a function of the residual water content. No quantitative relationship concerning salami was found in literature. Therefore, the following correlation proposed by Feyissa et al. (2009) in the case of meat roasting has been adopted.

$$R(t) = R_0 \left(1 - \frac{\beta\, V_{w,l}(t)}{V_0}\right)^{1/3} \tag{1}$$

where R is the external radius, V_o the initial salami volume, $V_{w,l}$ the volume of lost water and β a shrinkage coefficient, which is taken β=0.1. The time derivative of the Eq(1) provides the surface receding rate.

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, that is temperature, relative humidity and velocity.

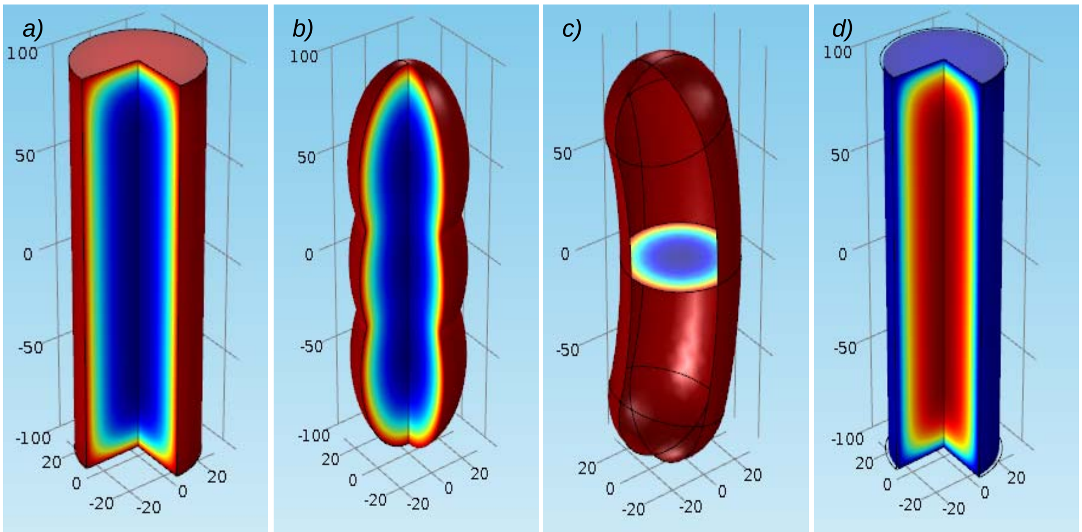

Figure 1. 3D representations of the sausage geometry: a) cylindrical 2D axi-symmetric geometry; b) irregular 2D axi-symmetric geometry; c) irregular 3D geometry; d) cylindrical 2D axi-symmetric geometry with shrinking

3. Results and discussion

3.1 Validation with literature data

The present COMSOL code has been validated against previous literature data concerning the Turista sausage, which was manufactured by the Raspini company as a typical small-size sausage of the Piedmont region and was ripened during an experimental program in a pilot-scale, ascending-flow chamber located in Parma (DRIP, 2000). The Figure 2 shows a commercial view of a product that is fully representative of the Turista dry sausage.

The code predictions of the Turista weight loss under forced air circulation are reported in Figure 2 as a function of the ripening time, together with the experimental data. The outcome is satisfactory. For the cylindrical 2D axi-symmetric geometry (Figure 3a) there is a very good prediction of the final weight loss, i.e., at the end of the maturation, whereas a larger discrepancy in comparison to the experimental data appears in the initial part of the simulation.

For the irregular 2D axi-symmetric geometry (Figure 3b) there is a slight increase in the final value of weight loss, whereas the deviation between predicted and experimental values remains in the initial part of the simulation. Predictions based on the irregular 3D geometry (Figure 3c) show negligible difference and just the same trend of the previous case. For the cylindrical 2D axi-symmetric geometry with volume shrinking (Figure 3d) there is a better overall performance in the prediction of weight loss. In particular, the agreement of the experimental data and the simulation is better in the first week, but the final predicted weight loss is higher than both the experimental datum and the values calculated with the previous model geometries.

3.2 Comparison with new experimental results

The code validation has been further pursued thanks to the recent availability of new experimental data from a test carried out under rigorously monitored and controlled conditions in the pilot-scale, ascending-flow chamber (SSICA, Parma). The tested product was a typical “Salsiccia dolce” from the Calabria region; it was manufactured as a straight, near-cylindrical sausage by the Dodaro company in the framework of the activities planned in an ongoing R&D cooperative project (PON

Figure 2. Commercial view of a ready-to-eat Turista dry sausage

“SafeMeat”). The cylindrical 2D axi-symmetric geometry and forced air circulation conditions have been adopted as the base case for all code runs.

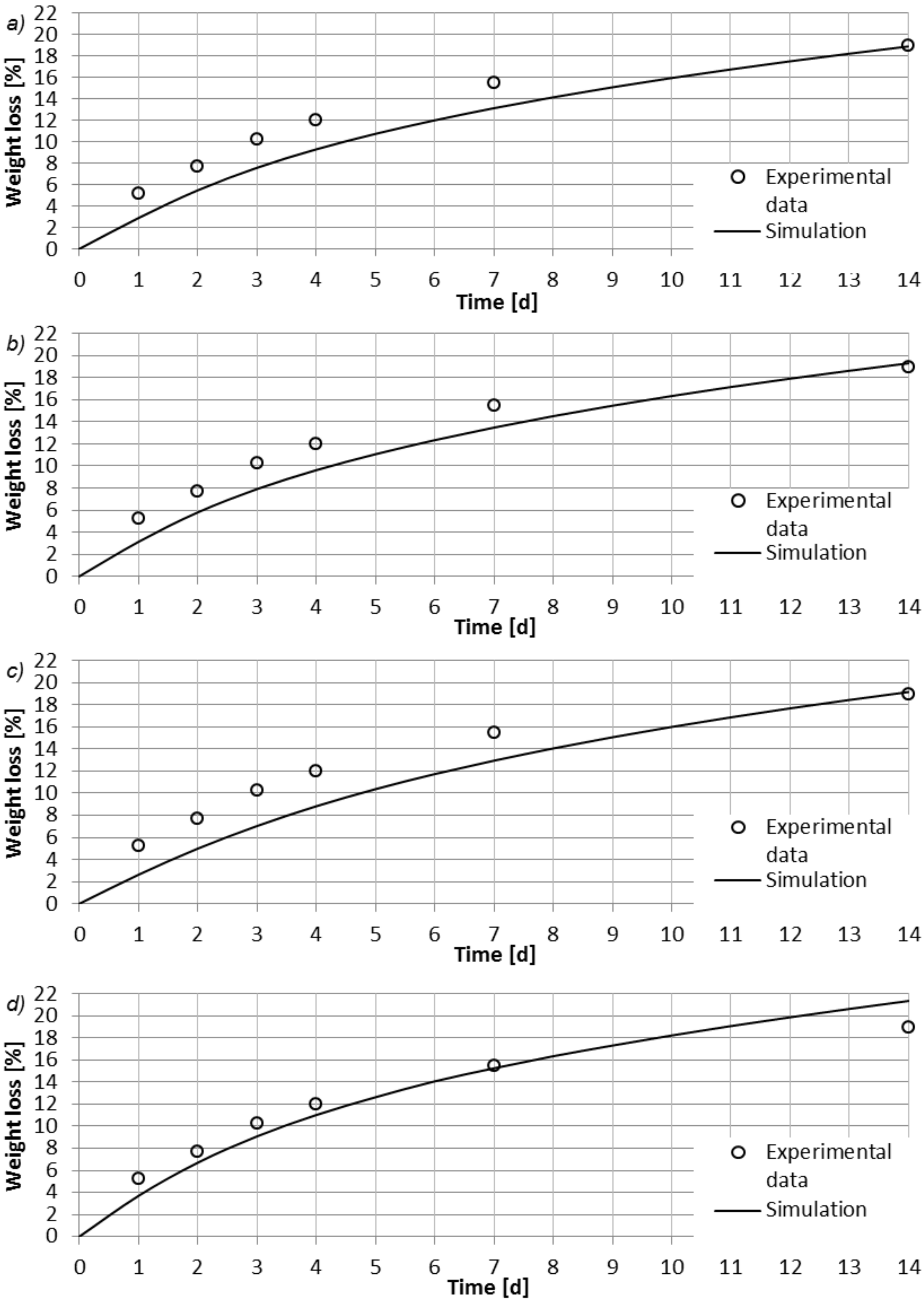

Figure 3. Experimental and simulated weight loss for a) cylindrical 2D axi-symmetric geometry; b) irregular 2D axi-symmetric geometry; c) irregular 3D geometry; d) cylindrical 2D axi-symmetric geometry with shrinking

The first simulation attempt considered drying in a unique phase, under air conditions corresponding to values of temperature, relative humidity and velocity as averaged over the whole duration of the ripening test, i.e., 20

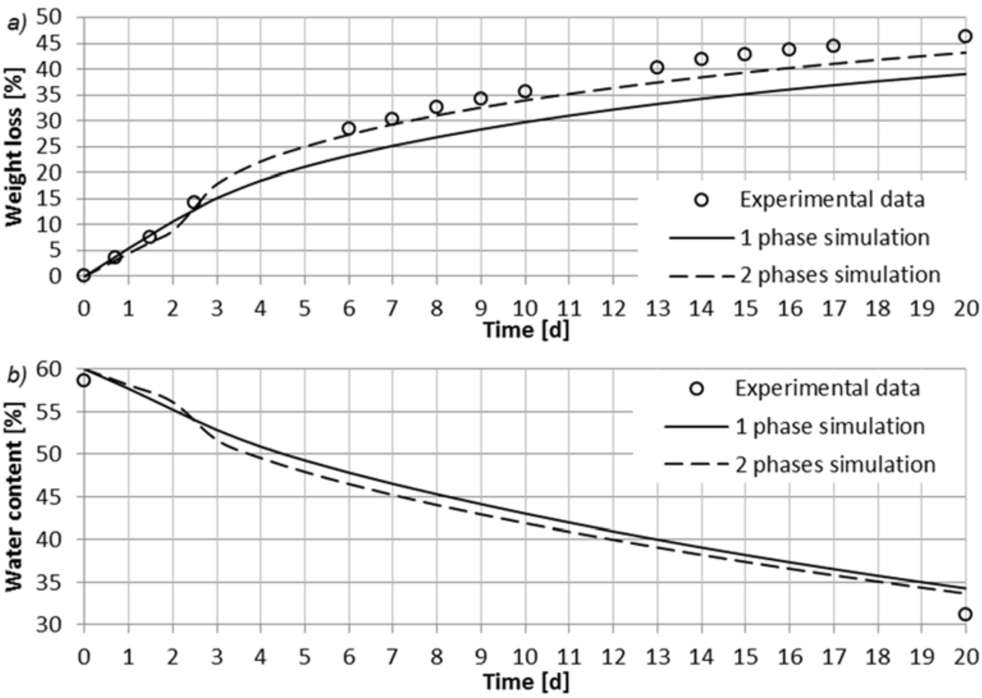

Figure 4. a) experimental data and simulation weight loss curves; b) experimental data and simulation water content curves (considering 1 and 2 phases model)

days. The results are reported as a continuous line in Figure 4 in terms of both single sausage weight loss and water content (% by mass) as a function of the ripening time, together with the experimental data.
The agreement is fair for the weight loss, but the discrepancy between predicted and experimental values is increasing with the ripening time, leading to a 7 % deviation in the final product weight loss. This can be attributed to the approximation induced by averaging the air conditions in the chamber over the entire ripening time: actually, the curing air conditions were suitably changed by the process operator, by acting on the set points of the supervision system according to a schedule provided by SSICA. The Figure 4b allows a qualitative comparison only because the % water content was actually measured at the time zero and the end time; the predicted time profile, however, appears quite reasonable.
The second simulation attempt considered drying in two phases, under two sets of air conditions roughly corresponding to heating/drying (2 days) and ripening (the remaining 18 days). The values of temperature, relative humidity and velocity were averaged over the duration of each phase, respectively. The results are reported as a dashed line in the same Figure 4. In this case cascade simulations are required because the input data of the second phase are the data supplied from the output of the first one. The outcome is much better as the predicted weight loss turns closer to the experimental data throughout time, leading to a 3 % underestimation only at the end of the test. This is true also for the final water content (Figure 4b), which is

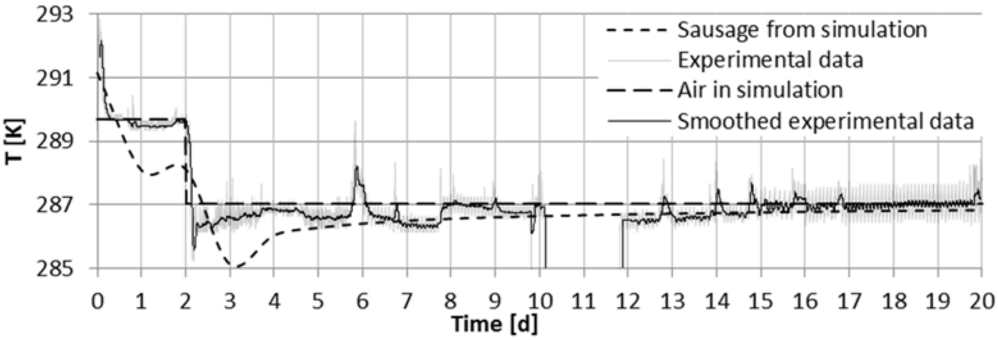

Figure 5. Experimental data and simulated temperature curve (considering 2-phase model)

lower than in the previous case and closer to the measured value.
Among the various outputs of second simulation, the time profile of the volume-averaged calculated sausage temperature turned out interesting. First, it is worth noting that the temperature difference in radial direction is less than 1°C as revealed by the simulation. Figure 5 reports the calculated temperature profile (dashed line) together with the two temperatures set in the simulation for curing air (dashed step down) and the series of experimental measurements (gray continuous line) carried out by inserting a thermocouple in the center of a test sausage. These latter present a shortfall of measurements around the eleventh day due to an unexpected blackout. The measured temperatures appeared subject to noise; therefore, they were filtered with a moving average span of 100 samples and reported as a continuous black line in Figure°5 for a better readability. There is a quite satisfactory agreement between the measured temperatures and the profile predicted by the two phases simulation. The dynamic response time appears in the simulation one order of magnitude longer than in the experiment, but the maximum distance between calculated and measured values during transients is in the order of 1°C.

4. Conclusions

A state-of-the-art, flexible, reliable and fast modeling and simulation tool has been successfully developed with COMSOL Multiphysics®4.3. Further work is in progress by virtue of the powerful COMSOL predictive potentials for analysis, exploitation and representation of calculated results.
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 a given time period provides satisfactory prediction results. The accuracy of predictions is expected to further improve if the code will be equipped with the possibility of handling a higher number of ripening phases, each distinguished for different curing air conditions.

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