Food Cooking Process.
Numerical Simulation of the Transport Phenomena.

B. Bisceglia*, A. Brasiello, R. Pappacena, R. Vietri
Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano (SA), Italy
*Corresponding author

Abstract: This work presents a theoretical model describing the transport phenomena involved in food cooking.
Aim of the study is to determine the influence of some of the most important operating variables, especially humidity and temperature, of drying air on the performance of cooking process of pork meat.
Thermal processes are increasingly important in determining the safety and quality of retail products. The design and operation of these processes also influence the total cooking yield, which is an important economic factor for the industry.
Mathematically, cooking can be considered as simultaneous heat and mass transfers between food product and oven ambient. Modeling of cooking includes heat convection, food surface water evaporation, internal heat conduction.
This work evaluates the dependence of temperature and water content on process time, during cooking of meat pieces of two different regular shapes.
The process is simulated using finite elements software COMSOL Multiphysics.
The proposed model considers two geometries: cylindrical and parallelepiped, with fixed physical properties and convective boundary conditions.

Keywords: Meat cooking, Finite elements and Simulation, Coupled heat and mass transfer; Evaporation; Multiphysics.

1. Introduction

To increase consumer convenience, many of today's food products are precooked so that you can quickly re-heat the product, for example in a microwave oven. One industrial precooking method is air-convection cooking. This example builds a time-dependent model of the convection cooking process for a pork meat samples, and it shows the temperature rise over time in the samples.
This simulation also models the moisture concentration in the pieces of meat. From the viewpoint of product quality, it is of interest to minimize the loss of moisture during cooking. In this regard, cooking yield is a quantity that measures how much moisture, in percent, remains in the meat after the cooking process.
Meat cooking in a convection oven is a common operation not only in the industrial production of ready-to-serve meals but also in the catering industry. Mass and heat transfers play an important role in the cooking process. It is essential that their interaction and mechanisms are well understood to allow for better control and optimization of the cooking process.
From a quality point of view, the cooking process must provide a final product with some specific characteristics (sensory properties, microbiological safety). Most of the published work on the modeling of mass and heat transfer during meat cooking does not at all consider shrinkage, and thus the governing model equations were typically solved using a fixed boundary, where the evaporation interface and the material boundary remain the same for the entire roasting period [1]-[3],[6].
The most important cooking requirement is to achieve a final temperature of 75ºC in the thermal center to ensure microbiological safety [2]. Food water content also plays an important role in the final characteristics of the cooked piece of pork meat. Therefore, a complete mathematical model must take into account the mass transfer between the food and the environment.

2. Agro Food Engineering

Food engineering is a broad field that is concerned with the application of engineering principles and concepts to the handling, manufacturing, processing and distribution of foods[4]. This relatively new branch of engineering encompasses the knowledge required to design processes and systems for an efficient food chain extending from the producer to the consumer.

Several current research projects are aimed at generating new knowledge vital to the food industry. Fundamental studies are underway on examining heat and mass transfer in foods during processing. Computer-aided simulations are being used to investigate processes including drying, freezing, frying, extrusion, and thermal processing to destroy harmful bacteria.

A number of projects are focused on obtaining new information on basic food properties. Developments of robotics, vision systems and controls are actively being pursued for applications in food processing. Predicting the quality of foods during processing and storage is one of the most important goals in food engineering.

Computational simulation has proved to be a valuable tool to predict both nutritional, sensory and safety of foods, as well as, to optimize food processes and storage conditions, minimizing the trial and error experimental procedures. Computational design is already recognized as a standard prototyping tool outside the food industry (e.g. automotive and aviation industry), where it has proved to have an advantage in terms of costs and development time. Most of the costs in foods development are concentrated in the design, prototyping and testing phases. Although food companies make a huge investment to improve quality during product development, many of the quality and safety limiting steps occur during storage and distribution, such as temperature abuses for frozen foods. Computational simulation can aid not only product development, but also help to optimize food quality and safety throughout the distribution chain. Experimental methods are limited by the number of parameters that can be studied. This lack of information makes difficult to evaluate the correct procedures to optimize food quality.

Research in food engineering includes improving our understanding on a quantitative basis of changes occurring in foods as a result of the various conversion processes. The large number of food items available in today's supermarket is possible partly because of the application of basic concepts of physics, chemistry, microbiology and engineering to foods.

The numerical simulation methods offer a powerful design and analysis tool to agricultural and food engineering [3]. In this area many problems involve fluid flow, heat and mass transfer and mechanics. Typical examples include cooking, mixing, drying, sterilization and chilling in food industry.

Numerical modeling technology offers an efficient and powerful tool for simulating the heating/cooling and other processes of the food industry. The use of numerical methods such as finite difference, finite element and finite volume analysis to describe processes in the food industry has produced a large number of models. However, the accuracy of numerical models can further be improved by more information about the surface heat and mass transfer coefficients, food properties, volume change during processes and sensitivity analysis for justifying the acceptability of assumptions in modeling.

3. The Model

The aim of this research is to develop a mathematical model that simulates simultaneous heat and mass transfer in three-dimensional pieces of pork meat considering two different geometries: cylindrical [5] and parallelepiped that have the same volume and mass (50g).

Pork meat contains about 72% water, 19.55% protein, 7.14% fat and 1.02% ash [2]. The initial water concentration is 41800 mol/m^3.

The model equations (system of partial differential equations) describing coupled heat and mass transfer in convection cooking of meat were solved using the finite element software, COMSOL Multiphyics®version4.3.

The model takes the following phenomena into account:

1) evaporation of liquid moisture,
2) internal heat conduction,
3) convective heat transport by the liquid moisture flow.

To keep the numerical model tractable, simplifying assumptions are made.

They are as follows:

1) shrinkage of meat has a negligible effect on heat and moisture flow,
2) evaporation occurs only at the surface of the meat,
3) the expelled moisture consists of pure water.

The input parameter values and the algebraic expressions in the model are given in Table 1.

3.1 Governing equations

During convection cooking, heat is transferred mainly by convection from air to the product surface and by conduction from the surface toward the product center. Meanwhile, water diffuses outward toward the product surface, and is vaporized.
Based on the previous assumptions, the general heat and mass transfer equations, boundary conditions and initial conditions for the 3-D problems are as follow:

Heat transfer equation:

$$\rho\, c_p \frac{\partial T}{\partial t} = k_T \nabla^2 T$$

Boundary condition for the heat transfer at the surfaces:

$$k_T \nabla T = h_T\,(T_{air} - T) + D_m\, \lambda\, \nabla C$$

where $D_m\, \lambda\, \nabla C$ is the heat flux out due to moisture vaporization.

Mass transfer equation:

$$\frac{\partial C}{\partial t} = D\, \nabla^2 C$$

Boundary condition for the mass transfer at the surfaces:

$$D\, \nabla C = k_c\,(C_b - C)$$

Initial conditions:

$$T\,|_{t=0} = T_0$$

$$C\,|_{t=0} = C_0$$

where the symbols are defined in Table 1.

4. Cooking yield

Cooking yield describes changes in food weight due to moisture loss (e.g. evaporation or moisture drip), water absorption (e.g. boiling) or fat gains/losses during food preparation and cooking.
Yield is an important economic factor for the industry and it is computed from the change in mass average moisture content.

$$\text{Cooking Yield (\%)} = (C / C_0)*100$$

Where:
C_0: initial moisture concentration
C: moisture concentration at time t.

Cooking yield is a quantity that measures how much moisture, in percent, remains in the meat after the cooking process.

5. Results and Discussion

In the pork meat cooking process, temperature and water content distributions are important factors which determine the quality of the product. The water content distribution is influenced by the temperature distribution.
From the simulation, the time of 600 s was required to heat the meat center to 75°C and so at this time the figure 1 shows simulated spatial moisture distribution, respectively, for 3D parallelepiped meat sample and 3D cylindrical meat sample, under a target air temperature of 175°C [7].
Fig.1 shows that the external surface was more dried than the core, this applies to both geometries, while the figure 2 illustrates the water content distribution in a section of meat samples at time 600s.
The water content distribution within the meat product changes during the cooking process in both parallelepiped and cylindrical geometries.
The increase in temperature causes the meat to reduce its water holding capacity.
The reduction of the water holding capacity of the meat protein network cause the meat to exudate water to the surface, which is lost by evaporation.
As a result, the water content gradient is developed within the meat. A large water concentration gradient is observed near the surface and the gradient gradually shifts towards the interior of the product (Fig.2).
The water transport depends upon the material properties (permeability and elastic modulus), the diffusivity coefficient and the pressure gradient.

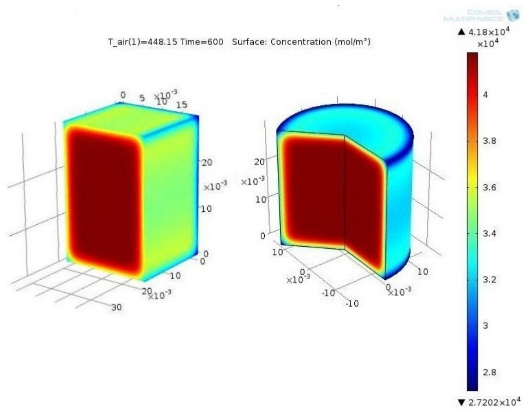

Fig.1: Water content profile at t=600 s and T_{air}=175°C

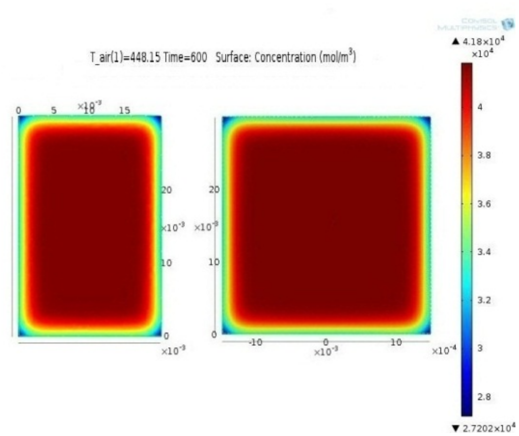

Fig.2:Water content profile in parallelepiped and cylinder at t = 600s and T_{air}= 175 °C

Fig. 3 illustrates the temperature distribution during meat cooking in a convection oven at 600s. The surface of the meat is at a much higher temperature than the inside part of the meat sample, and a large temperature gradient is developed in the region close to the surface.

When the cooking process proceeds, this large temperature gradient shifts gradually from near the surface to inside of the product. Moreover, its magnitude decreases as a function of time, as the heat energy is slowly penetrating into the centre of the product, thereby raising its temperature.

From the simulation, in the parallelepiped geometry the center temperature of 75 ° C is reached after 500 s at difference of cylindrical geometry in which the temperature at the center of 75 ° C is reached at about 600 s.

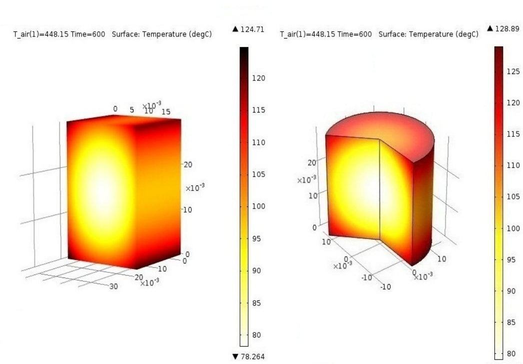

Fig. 3:Temperature profile in the two geometries at t = 600s and T_{air}=175°C

The cooking yield decreases with increasing time in both geometries (Fig.4-5).

At the same temperature of the air (175°C) and cooking time (600s) the cooking yield is 94.5% in the parallelepiped geometry, while it is 96.6% in cylindrical geometry.

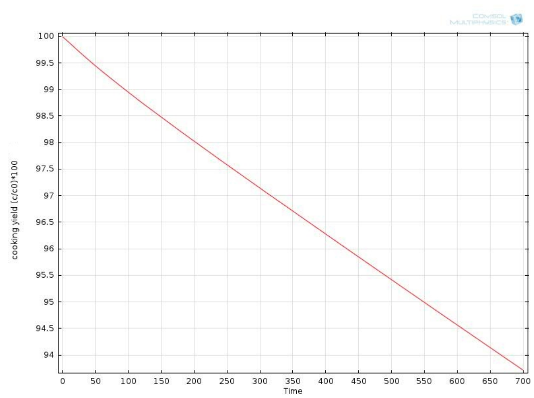

Fig. 4: Cooking yield in parallelepiped geometry

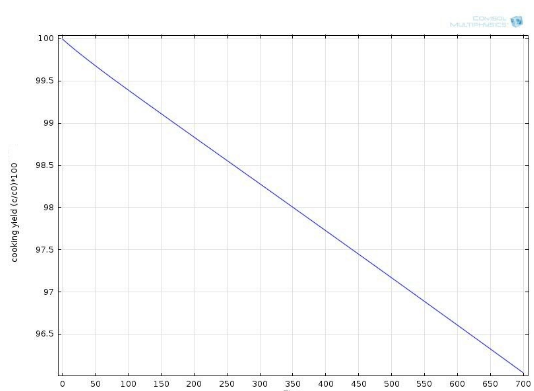

Fig. 5:Cooking yield in cylindrical geometry

For the parallelepiped geometry the cooking yield is lower because the amount of water removed after cooking is higher than that removed from the cylinder as shown in Fig.4 and Fig.5.
The results on cooking yield obtained from the simulation with the software COMSOL Multiphysics can be considered reliable because they are obtained also from real experiments on pork meat cooked in a convection oven [12].

6. Conclusions

A first principles based model of heat and mass transfer is developed for a convection meat cooking process.
Temperature and water content distributions as function of position and time were predicted. Such model can be helpful in understanding the physics of meat cooking and can be used to improve prediction of temperature and moisture loss. A finite element model, which considered coupled simultaneous heat and mass transfer, was established to describe convection cooking of pork meat. The model was used to predict transient temperature and moisture distributions inside the product, as well as transient cooking yield of meat samples during cooking.
With future incorporation of physicochemical models and bacterial lethality models, such a model could be further used to optimize cooking conditions, procedures and facilities for the control of food quality and safety.
Still it is necessary to keep on working in the development of a more complete model that represents more accurately the experimental results.
It is expected in the future to create a model for cooking pork meat in a microwave oven and to compare it with the results obtained for the classical convection oven.
About this, the preliminary tests were made in a reverberation room to a power of 100W and 200W on pork meat cylindrical samples.
In these samples has been reached a center temperature of 75 ° C in a time of 2 minutes with a power of 100 W and 1.09 min with a power of 200 W.

7. References

[1] FDA. (1997). Food Code, Chapter 3, 3-401.11. http://vm.cfsan.fda.gov//dms/fc-3.html

[2] ASHRAE, (1989). Chapter 30: Thermal properties of foods. In ASHRAE Handbook - Fundamentals, SI Edition. American Society of Heating, Refrigerating and Air Conditioning Engineers, GA: Atlanta.

[3] Chen, H., Marks, B.P. and Murphy, R.Y., Modeling coupled heat and mass transfer for convection cooking of chicken patties, J. Food Eng., 42: 139-146, 1999.

[4] Singh R.P., Medina A.G., Food Properties and Computer-Aided Engineering of Food Processing Systems. 1989,Boston, MA: Kluwer Academic Publisher

[5] Ikediala, J.N., Correia, L.R., Fenton, G.A., Ben-Abdallah, N. (1996). Finite Element Modeling of Heat Transfer in Meat Patties during Single-sided Pan-frying. *J. Food Sci., 61*, 796.

[6] Van der Sman, R.G.M., Moisture transport during cooking of meat: An analysis based on Flory–Rehner theory, Meat Sci., 76: 730-738, 2007.

[7] A.H. Feyissa, J. Adler-Nissen, K.V. Gernaey-Model of Heat and Mass Transfer with Moving Boundary during Roasting of Meat in Convection-Oven-Excerpt from the Proceedings of the COMSOL Conference 2009 Milan.

[8] Pham, Q.T., Trujilo, F.J., and Wiangkaew, C., Drying modeling and water diffusivity in beef meat, J. Food Eng., 78: 74-85,2007.

[9] Scheerlinck, N., Nicolai, B. M., Verboven, P., & De Baerdemaeker, J.(1996). Finite element analysis of coupled heat and mass transfer problems with random ®eld material properties. ASAE Paper No. 96-3028, American Society of Agricultural Engineers. MI: St.Joseph.

[10] Huang, E., & Mittal, G. S. (1995). Meatball cooking - modeling and simulation. Journal of Food Engineering, 24, 87-100.

[11] ASAE, (1995). Psychrometric data ASAE D271.2 DEC. 93. (pp. 22-29). ASAE Standards, (42nd ed.). American Society of Agricultural Engineers, MI: St. Joseph

[12] Bethany A. Showell, Juhi R. Williams, Marybeth Duvall, Juliette C. Howe, Kristine Y. Patterson, Janet M. Roseland, and Joanne M. Holden- USDA Table of Cooking Yields for Meat and Poultry- December 2012-U.S. Department of Agriculture.

8. Appendix

Table 1: Parameters values, thermophysical properties and other expression used for finite element simulation

	Value or expression	***Reference***
T_{air}	175 [°C] Oven air temperature	**[7]**
T_0	20 [°C] Initial meat temperature	
ρ	1045 [kg/m^3] Density of patty	**[2]**
h_T	25 [W/m^2*K] Heat transfer coefficient	
C_0	$0.72*\rho/ M_{H2O}$ [mol/m^3] Initial moisture concentration	**[2]**
C_b	1161.1 [mol/m^3] Air moisture concentration	**[11]**
C_m	0.003 Specific moisture capacity	**[9]**
k_m	1.29e-9 [kg/(m*s)] Moisture conductivity	**[2]**
h_m	1.67e-6 [$kg/(m^2*s)$] Mass transfer coefficient in mass units	**[9]**
k_c	$h_m/(\rho*C_m)$ Mass transfer coefficient	
D_m	5e-10 [m^2/s] Surface moisture diffusivity	
λ	41400 [J/mol] Molar latent heat of vaporization	**[9]**
M_{H20}	18 [g/mol] Water molecular weight	
c_p	2930.69 [J/(kg*K)] Specific heat	**[2]**
k_T	0.4533 [W/(m*K)] Thermal conductivity	**[2]**
D	2.23e-5* *exp(-3382.212/T) [m^2/s] Diffusion coefficient	**[8]**