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Heat and Mass Transfer in Roast Beef Cooking. Temperature and Weight Loss Prediction

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The development of food processes, ingredients and formulations is a daily topic for the food industries. Model-based product, process and equipment design are getting increasing industrial attention, due to the high potential in matter of time and money saving. Bringing these advantages to the consumers’ table by the application of this approach is one of the ultimate challenges of food and bioprocess engineering. This work aims to consider roast beef cooking as a practical, widespread, case study. A computational model, which correlates temperature, time and weight loss for a standard piece of meat cooked in oven, is developed and validated with experiments. The thermal properties are derived with a general approach, applicable to other food. The heat and mass transport equations are based both on conservation laws and on the cooking conditions.

1. Introduction

Meat is a very common foodstuff in every part of the world. Indeed, meat is a nutritious food, rich in protein (typically ranging from 16 to 22 % w/w) and essential nutrients including iron, zinc and vitamin B12 (McAfee et al., 2010) which make it scarcely replaceable (Speedy, 2003). Every day, tons of several meat kinds are globally consumed. Meat spoilage due to improper processing or conservation can then be a problem. Dealing with this topic, meat cooking is one of the processes that can extend the storage life and prevent damages to the consumer by the destruction of a considerable number of microorganisms, according to the time and temperature of the process (i.e. it is well renowned that bacteria are gradually destroyed at temperatures above 70 °C. See for instance the paper from van Asselt and Zwietering (2006)). Together with this, meat cooking involve some other transformations (Boles, 2010):

- Water decreases, especially in the surface, leading to a low water activity with a consequent extended shelf life,
- Texture results to be modified inducing a tenderness variation,
- Meat proteins coagulate, altering their solubility,
- Flavor gets intensified increasing the palatability,
- Endogenous proteolytic enzymes are inactivated, preventing proteolysis to occur and the off-flavors to be produced,
- Color changes due to chemical reactions in the colored compounds (e.g. myoglobin).

The study of the cooking process could then comprehend some of these transformations, which are dependent on the processing conditions (e.g. temperature, equipment, heat sources, time, etc.), as well as on the raw material (meat kind, pre-processing, conservation, eventual preservatives, etc.).

Within this context, food modeling could be helpful to suppliers and equipment producers by giving them the possibility to assess the qualitative and quantitative description of specific markers for process control and optimization purposes (Papasidero et al., 2014), to enable model-based design of products with specific

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advantageous characteristics, to investigate the possible physical and chemical mechanisms that lay behind a process (Bessadok-Jemai, 2013) and to pursue the engineering of highly-automated, high-performance processing devices (Ryckaert et al., 1999).

Dealing with this concept, a series of computational and experimental studies related to conventional and combined oven cooking are into development by the authors (e.g. Papasidero et al. (2015)). Since roast beef cooking is a very common dish, it has been considered as a good base case for meat cooking.

Since almost all transformation are dependent on the temperature and on the water content of the roast beef, every model should be based on heat and mass transfer models. As a first assumption, one can think to simplify the problem by discarding the influence of the chemical reactions on the energy and mass balances (e.g. avoiding reaction terms, taking constant properties or temperature dependent properties instead of composition dependent properties). Then, all the further transformations can be described as hierarchically dependent on the heat and mass transfer problem. This approach, for instance, has been successfully applied to the bread baking process with interesting results (Hadiyanto et al., 2007). Heat and mass (water) transfer are then considered in the current work to develop a basic model to be further advanced in the future.

In the matter of basic models with heat and mass transfer, some literature have to be cited. First of all, the model by van der Sman (2007) applies a linearization of the Flory-Rehner theory for the free energy of elastic polymer gels to consider the moisture transport due to swelling pressure (following a Darcy law). In that paper, shrinking and deformations are not considered, evaporation is assumed to occur only at the meat surface, the permeability of meat is constant but anisotropic (fibers constitute a preferential direction for the moisture transport). This model has been complicated in a further work (van der Sman, 2013) with the application of the model to industrial tunnel ovens. A very comprehensive model for meat cooking is provided in a work of Datta’s group from Cornell University (Dhall et al., 2012): they describe beef patties as a multicomponent and multiphase system subject to evaporation and to moisture and fat unsaturated flow in a hygroscopic porous medium. One of the first work in modeling meat cooking, with particular reference to roast beef, is that of Obuz et al. (2002), where the authors consider water evaporation to be driven by the moisture difference between the meat surface and the air. They include latent heat of evaporation in the boundary condition for the energy balance by adding a term in which is multiplied by the surface mass flow, coupling the mass and energy balances. Goni and Salvadori (2010) pay more attention on the difference between dripping loss and evaporative loss. The latter is dependent on equilibrium formulation, while the first is assumed to be dependent on the difference between the initial liquid water content and the so-called Water Holding Capacity, function of the meat temperature, representing the response of the protein matrix (i.e. contraction) to heat. One of the most interesting aspects of their work is the experimental measure of these different losses, which involves the collection of the liquid loss in a roasting pan filled by water. Finally, Kondjoyan et al. (2013) further examines these phenomena, extending the investigation to different processes and meat pieces.

The model presented in this paper is certainly less complicated than some of the mentioned ones. It will constitute a basis for further developments, and it is intended to be simple enough for possible control applications. Indeed, very complex models can require a considerable computational time. The compromise between accuracy and time consumption can be faced by choosing the appropriate assumptions.

2. Theory

First of all, the target process is the roast beef cooking process in a convection oven. This implies to find appropriate thermal properties for the meat, as well as diffusion, heat and mass coefficients depending on the transport mechanisms assumed for the model. In this sense, the following assumptions have been selected:

- Beef meat is assumed to be a continuum medium, where the micro-structure is neglected (i.e. homogenization (Quang et al., 2011) is considered).
- Thermal properties are calculated from a mixture approach coming from the macro-composition in terms of water, protein, carbohydrates, fibers, fats (Choi and Okos, 1986). Each fraction has temperature dependent properties to be mixed according to appropriate mixing rules.
- The meat is considered to have an isotropic behavior with respect to heat and mass transfer.
- Forced convection is described through the use of a global heat transfer coefficient
- Fat transport is not considered, due to the choice of low-fat meat. Diffusion of water is assumed to be described by a Fick diffusion law, with a global diffusion coefficient that should consider all the above mentioned transport phenomena.
- Shrinking due to fibers contraction and the water loss related to that are not considered. Meat volume is assumed to be constant.
- Weight loss is assumed to be attributed to water loss only (and the liquid is assumed to be pure water).

The phenomena taken into account in the model are schematically reported in Figure 1

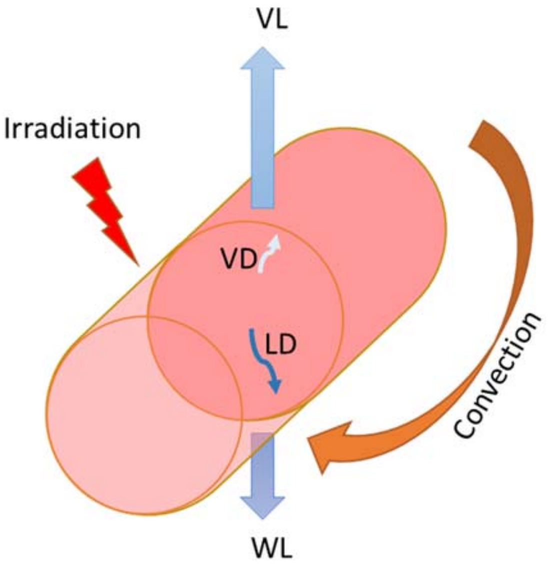

Figure 1: Schematic representation of the Phenomena described by the model: VD=vapor diffusion, LD=liquid diffusion, WL=liquid water loss, VL= vapor loss

According to these assumptions, the energy balance for the roast beef is written as.

$$\rho_{mix} C_{p,mix} \frac{\partial T}{\partial t} = \lambda_{mix} \nabla^2 T - I_{ev} \Delta H_{ev} \tag{1}$$

In this equation, the density ρ_{mix} , the thermal conductivity λ_{mix} and the specific heat $C_{p,mix}$ are referred to the mixture of components in the liquid and solid phases. I_{ev} is water evaporation term, that take into account liquid water evaporation at temperatures higher than 100 °C. In that case, all the energy going to the finite element goes to the evaporation term and the thermal balance is stopped until evaporation takes place. ΔH_{ev} is water latent heat of evaporation.

Coupled with this, a balance on liquid water can be written:

$$\frac{\partial C_w^l}{\partial t} = D_w^l \nabla^2 C_w^l - I_{ev} \tag{2}$$

where D_w^l represents the liquid water diffusivity in the meat matrix, while C_w^l is the liquid water concentration in kg per square meter.

In the meantime, a water vapor balance takes the form:

$$\frac{\partial C_w^v}{\partial t} = D_w^v \nabla^2 C_w^v + I_{ev} \tag{3}$$

where D_w^v represents the water vapor diffusivity in the meat matrix, while C_w^v is the liquid water concentration in kg per square meter. Since only the meat close to the surface undergo evaporation, this model could be simplified by applying the evaporation only on the surface. By the way, the chosen formulation seem to be more comprehensive. The boundary conditions for the presented model are:

$$D_w^v \nabla^2 C_w^v = K_{mat}^v \cdot (C_w^v) \tag{4}$$

$$D_w^l \nabla^2 C_w^l = K_{mat}^{vap} \cdot (C_w^l) \, , \tag{5}$$

that represent the mass transfer of vapor and liquid water from the food matrix to the environment.

$$\lambda_{mix}\nabla^2 T = h\cdot(T_{ext}-T)+\varphi\sigma(T_{wall}^4-T^4) \qquad (6)$$

The latter equation describes the boundary condition for the heat transfer by convection and radiation. The model parameters were either taken from literature, or estimated by regression on the experimental data. The heat exchange coefficient was estimated to be about 10 W/m^2/K, the water transport coefficient equal to 10^{-8} m/s, while that for water vapor was estimated to be 10^{-2} m/s. Liquid water diffusivity is considered to be 10^{-3} m^2/s while that of water vapor being 10^{-4} m^2/s. The surface emissivity of meat was assumed to be equal to 0.91.

3. Experiment

The experiments for the development and validation of the model have been carried out in a commercial domestic oven. A piece of bovine muscle whose dimensions were about that of a cylinder with 18 cm height and 10 cm diameter and that weighted about 1.4 kg was selected for the roasting process.
The procedure consisted of the following phases:

- The meat piece was extracted from the fridge and placed on a grid.
- It was then equipped with 3 thermocouples (T-type) to monitor the center of the roast, a point at 5 mm under the surface and a point in-between them (see Figure 2).
- The oven was then turned on with a set point temperature of 180 °C. The initial oven temperature was 22 °C.
- All the temperatures were continuously measured with thermocouples in the oven and recorded with a data logger.
- The cooking process was stopped when the core temperature reached 65 °C.

The procedure has been replicated for three times to validate the experiment.

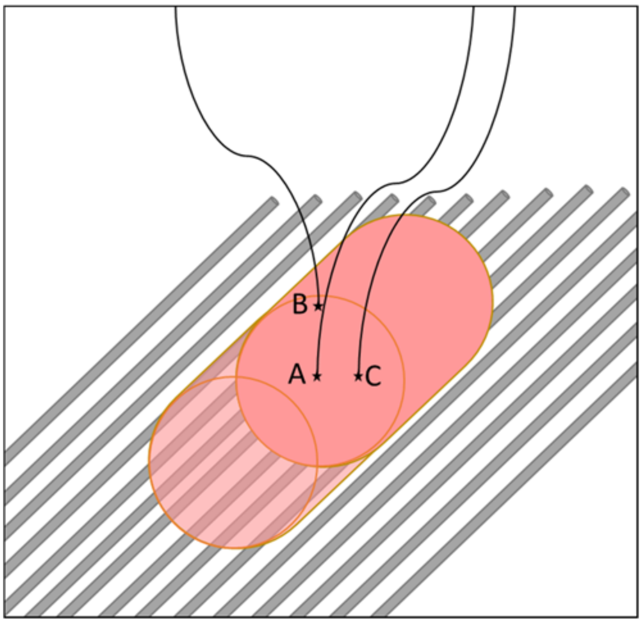

Figure 2: Schematic representation of the experimental layout. Grid and thermocouples in the three points for the central section: A) Core, B) Below Surface, C) Intermediate position

4. Results and discussion

The model has been implemented in a commercial software for the solution of partial derivative equation systems (PDE systems) with finite elements discretization (COMSOL-AB, 2012). A cylinder that approximates the real dimensions represented the meat piece. Axial symmetry was then considered to simplify the model solution. The environment temperature was modeled with a piecewise function to approximate the average conditions in the oven.

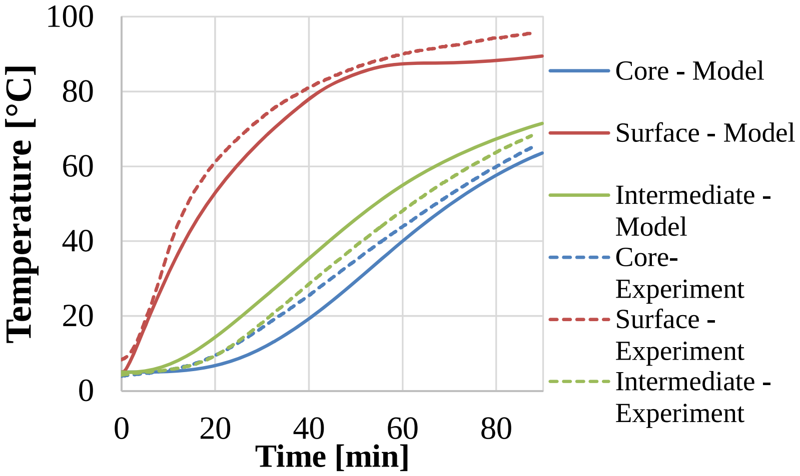

Figure 3: Roast meet temperature. Model and experiment comparison

The results related to heat transfer (see Figure 3) show a good trend for the description of the surface and core temperatures. Actually, the experimental difference between the intermediate point temperature and the core one seems not to be that relevant. By the way, the model is very sensitive to minimum variations, and it is possible that a variation of only 5 mm could be responsible of a temperature difference of 5-10°C. Except from that, the model seem to reasonably reproduce the experimental trend.

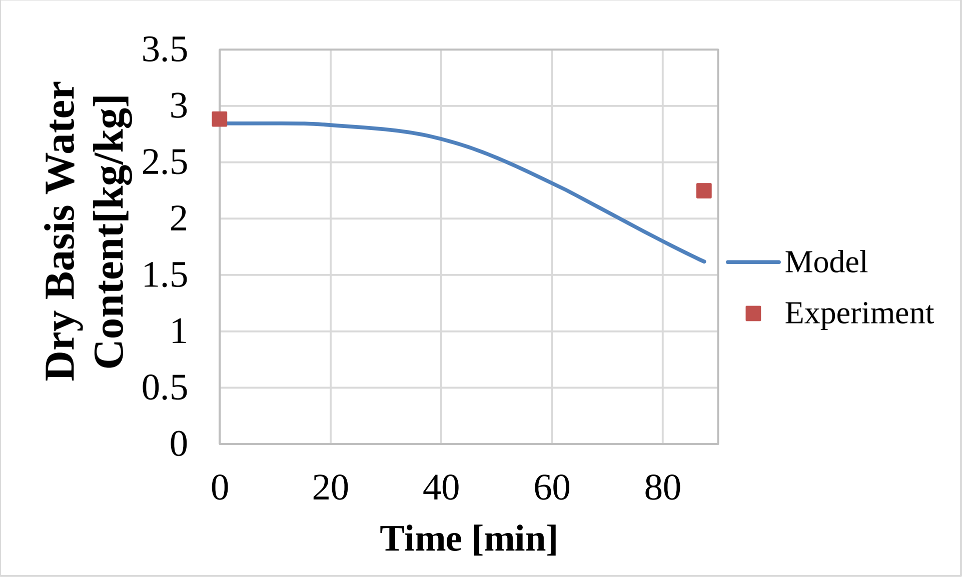

Figure 4 Meat water content. Model and experiment comparison

A reasonable prediction has also been reached dealing with water loss (see Figure 4). The model overestimates the weight loss by 25 % compared to the experiment result. This can be attributed either to the mixture properties calculation or to the estimation of the mass transfer parameters. Additional attention should be paid on parameters estimation. Furthermore, a more accurate description of the experimental results can be obtained through the addition of moisture transport with pressure gradients.

5. Conclusion and future developments

The model seems to reasonably agree with experiments, despite more attention on the thermal properties and diffusion coefficients estimation should be done. A good comparison with the existing literature models and experiments can give a great contribution to the development of the model, in order to better represent several process conditions and meat kinds, with particular reference to the collagen denaturation, the diffusion of fat and the combined oven processing. For instance, fat melting and diffusion can influence system by modifying the diffusion of the liquid phase, then constituted by a fat-water emulsion. Further developments could involve the color and flavor description through the use of kinetic models. These would require adequate experiments and techniques for the validation process.

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