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Combined heat transfer and kinetic models to predict cooking loss during heat treatment of beef meat

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ABSTRACT

A heat transfer model was used to simulate the temperature in 3 dimensions inside the meat. This model was combined with a first-order kinetic models to predict cooking losses. Identification of the parameters of the kinetic models and first validations were performed in a water bath. Afterwards, the performance of the combined model was determined in a fan-assisted oven under different air/steam conditions. Accurate knowledge of the heat transfer coefficient values and consideration of the retraction of the meat pieces are needed for the prediction of meat temperature. This is important since the temperature at the center of the product is often used to determine the cooking time. The combined model was also able to predict cooking losses from meat pieces of different sizes and subjected to different air/steam conditions. It was found that under the studied conditions, most of the water loss comes from the juice expelled by protein denaturation and contraction and not from evaporation.

1. Introduction

During cooking, meat can lose a large quantity of its mass in the form of meat juice. Water loss determines the technological yield of the cooking operation, making it a critical factor in the industry. Cooking time and losses also affect the quality of the cooked meat: color, savor, juiciness, tenderness, micronutrient content, etc. (Modzelewska-Kapitula, Dabrowska, Jankowska, Kwiatkowska, & Cierach, 2012). Water debinding and migration in meat during cooking are related to the denaturation and contraction of protein structures caused by increasing temperature (Laroche, 1978; Lepetit, 2007; Lepetit, Grajales, & Favier, 2000; Palka & Daun, 1999; Tornberg, 2005). Up to 80% of the water can be lost during pan frying of beef burgers (Oroszvari, Bayod, Sjöholm, & Tornberg, 2006). Van der Sman (2007) modeled water transport in meat pieces during cooking by using **Flory–Rehner** theory and Darcy law. This approach was validated using a "rectangular roast" cooked in an air oven at two air temperatures, 175 and 225 °C. More recently, Dhall, Halder, and Datta (2012) have developed a multiphase model to predict the transport of water and fat during meat cooking. However, the effect of collagen contraction on fluid flow is not taken into account in this model, despite the fact that it leads to meat shrinkage and also dictates water transport in non-ground meat (Bouhrara, Clerjon, Damez, Kondjoyan, & Bonny, 2011, 2012). Dhall et al.'s (2012) modeling approach therefore essentially remains dedicated to cooking hamburger patties. Extending the work of Van der Sman (2007), Feyissa, Gernaey, and Adler-Nissen (2013) have inserted swelling pressure and elastic modulus into the Darcy law to model the effect of protein contraction on the water transport inside roast meat. A mathematical relation was proposed to take into account the effect of temperature on the elastic modulus, and the parameters of this relation were fitted on the experimental data of Tornberg (2005). This approach assumes that whole meat is a uniform porous material, which permeability does not vary during heating. Permeability values for whole meat are unknown and Feyissa et al. (2013) use reported data for ground meat and emphasized the need for more quantitative knowledge of the effect of temperature on meat permeability. Moreover, the assumption of juice circulating in a uniform porous material is disputable for whole meat since it has been observed that the juice expelled from the myofibers by heat denaturing and contracting circulates in channels of different dimensions formed by the shrinkage of the complex perimysium, endomysium and myofiber bundle network (Bouhrara et al., 2012). Other combined heat transfer and kinetics approaches are used to model the cooking of whole meat (Goni & Salvadori, 2010). These approaches have recently been used for a multi-objective optimization of beef roasting (Goni & Salvadori, 2012). The rate constant used in the kinetic models was explicitly only dependent on meat temperature and was applied on both meat slices and *semitendinosus* muscles, but an implicit variation of the rate constant was also integrated into the model by dividing this rate

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List of symbols used

A, B:	parameters used in relation (3)
C_p	thermal capacity of the meat (J kg K^{-1})
$[DM]$	percentage of dry matter
d	distance to the nearest meat surface (m)
E_a	activation energy (J mol^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
k and k_0	rate constant of the kinetic models (s^{-1})
M	mass of the sample (kg)
R	molar gas constant = 8.314 J mol^{-1} K^{-1}
T	temperature, (°C) or (K)
t	time, (s) or (min)
V	volume of the sample (m^{-3})
X	water content (kg of water per kg of dry matter)
λ	thermal conductivity of the meat (W m^{-1} K^{-1})
ρ	density of the meat (kg m^{-3})

Subscripts

raw	sample thawed and uncooked
cooked	sample after cooking
DM	dry matter measured on the sample dried for 48 h at 104 °C
0	value of the raw sample
eq	value obtained at equilibrium
CL exp	Experimental cooking loss

Muscle types

IS	Infraspinatus
LT	*Longissimus thoracis*
MA	Masseter
SM	*Semimembranosus*
ST	*Semitendinosus*

constant value by the dry mass of the sample. It is important that the rate constant of the kinetic models does not solely depend on temperature since it has been observed experimentally that there is a different timescale between heat transfer and mass transfer in meat samples, this timescale being connected to the duration needed for the juice to migrate from inside the meat sample to its surface (Oillic, Lemoine, Gros, & Kondjoyan, 2011). Van der Sman's and Goni and Salvadori's validations were performed directly on roast meat of given size and shape derived from one type of muscle and subjected to oven-cooking air conditions. This falls short, since a real determination of model performance requires a wide range of sample sizes and muscle types. Moreover, oven-cooking in dry air is not the best setting for a first test of model performance, since: (i) it is a complex situation where uncertainties on heat transfer “mix” with uncertainties due to the mass transfer model and the phenomena driving crust formation, and (ii) air-cooking makes it difficult to effectively separate water loss by evaporation from water loss by protein denaturation–contraction.

The work reported here is based on a combined heat transfer and kinetics modeling approach to predict weight losses during the cooking of beef meat. The rate constant of the kinetic models is calculated locally both from the meat temperature and from the distance between the calculation point and the nearest meat surface. Introducing this distance in the expression of the rate constant explicitly takes into account the effect of sample thickness on mass transfer. The parameters of the kinetic models were identified using a set of experiments performed on meat cubes of different sizes heated in a water bath. A first validation step was performed on rectangular cuboid (parallelepipeds with perpendicular faces) samples heated in a water bath. These experimental results have already been published in Oillic et al. (2011). In the second step, model validation was performed in a fan-assisted oven. Experiments were performed on meat samples derived from one muscle type (*Semimembranosus* muscle) whose size varied from thin steaks up to big muscle cuts. Different air/steam conditions were applied to analyze the transition from wet air to dry air microenvironment, and a handful of experiments were performed on muscles other than SM. All these results were analyzed to identify how far the combined heat transfer and kinetic models can be practicably used to predict and control the evolution of juice loss and meat quality during cooking.

2. Modeling beef cooking

The first phase of the modeling process was to calculate local 3-dimensional temperature kinetics inside the sample. In-product heat transfer was assumed to be purely conductive (Oillic et al., 2011). Energy exchanges at the boundaries were calculated classically by a Newtonian law in which the difference between water bath or oven temperature and sample surface temperature was multiplied by the convective transfer coefficient. Under these assumptions, the accuracy of the simulated temperatures was essentially dependent on how accurately sample dimensions are known and on the accuracy of the parameter values that were introduced into the model. These parameters were thermal diffusivity of the sample (D_T), and heat transfer coefficient value at the solid/fluid interface (h). Thermal diffusivity was calculated from $\lambda/\rho C_P$ using a density value of 1060 kg m^{-3} and the thermal capacity of the meat, equal to 3200 J kg K^{-1} (Oillic et al., 2011; Tsai, Unklesbay, Unklesbay, & Clarke, 1998). Thermal conductivity was 0.45 W m^{-1} K^{-1} and considered constant during the cooking process (Baghe-Khandan & Okos, 1981; Oillic et al., 2011). During water-bath heating or cooling treatments, heat transfer at the surface of the meat was purely convective. In-oven energy exchanges by radiation were neglected, since the oven walls were made of polished stainless steel that has an emissivity of less than 0.1 (Kondjoyan, 2006). Evaporation during dry-air treatment at 95 °C or sample cooling was taken into account using an apparent transfer coefficient value (Kondjoyan, 2006). Heat transfer coefficients due to free or forced convection were measured experimentally using aluminum objects of different shapes and sizes and the method described by Ghisalberti and Kondjoyan (1999), and the effect of evaporation on heat transfer coefficient during oven treatments in air were determined from the author's previous experimental studies (Kondjoyan, 2006; Kondjoyan et al., 2006a,b).

Cooking losses were calculated from the time-course of water content in the sample. This evolution was described using a first-order kinetic models based on local water concentration X, with $X_{eq}(T)$ being water concentration at equilibrium. Equilibrium was reached when loss was no longer observed whatever the duration of additional treatment. $X_{eq}(T)$ was connected to the maximal protein denaturation–contraction and myofiber water debinding able to occur at a given temperature.

$$\frac{dX}{dt} = -k(T,d)\cdot\left(X - X_{eq}(T)\right) \quad (1)$$

The dependence of the reaction rate on temperature was given by an Arrhenius Eq. (2), with local temperature calculated using the heat transfer model described previously.

$$k(T,d) = k_0(d)\ e^{\left(\frac{-E_a}{R\cdot T}\right)} \quad (2)$$

The rate constant of the kinetic models was also rendered dependent on distance between the calculation point and the meat surface. Preliminary experiments proved that the dependency between k and product thickness was a power law. Thus, a power law was retained to describe