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Modelling of heat and mass transfer during cooking in steam-assisted hybrid oven

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ABSTRACT

Semitendinosus muscle in a cylindrical shape was cooked in a domestic steam-assisted hybrid oven, and the simultaneous heat and mass transfer during the cooking process was modelled using commercial software COMSOL Multiphysics (version 3.5a). The temperature and moisture profiles of the product were predicted as functions of both position and time, and the predicted results were compared with the experimental ones. The surface convective heat transfer coefficient was determined experimentally using the lumped capacity method, and the surface convective mass transfer coefficient was calculated by simulation of the developed model at different temperatures. Also, the thermal conductivity of muscles was determined as a function of the temperature and moisture content by the line heat source method. The convective heat transfer coefficients were found to be in the range of 17.31–18.35 W/m^2K, and the calculated surface convective mass transfer coefficients were in the range of 1.7×10^{-7}-2.2×10^{-7} m/s at 180, 210 and 240 °C cooking temperatures. The predicted results for the steam-assisted hybrid cooking process agreed well with the experimental temperature and moisture profiles, and the developed model is considered to be suitable for predicting cooking times in a steam-assisted hybrid oven.

1. Introduction

Electric ovens are commonly used household appliances that rely on thermal exchange to produce the desired cooking effect in a foodstuff and cooking in convection ovens is a common way of cooking whole meat in households and professional kitchens. The forced convection process in oven cooking, which causes the drying of meat surface and the important formation of crust, can be coupled with steam injection (steam-assisted cooking) in the oven chamber to reduce cooking time and prevent surface dehydration (Murphy et al., 2001; Isleroglu et al., 2015). The consumer commonly associates crust formation with a nice roasted/grilled smell and taste, but it can also lead to the formation of carcinogens such as heterocyclic amines. When considered from this point of view, steam-assisted hybrid ovens combine the advantages of convection ovens and steam in a single piece of equipment, which enables healthy products and fast cooking and also retains desirable product quality characteristics (Isleroglu et al., 2015, 2016). However, the introduction of steam into the oven chamber during cooking makes heat and mass transfer more complex because of the increase of the heat transfer rate and modification of the surface water evaporation process (Rinaldi et al., 2010).

During the cooking process, the meat surface is mainly subjected to convection, radiation, evaporation and conduction if it occurs at the bottom part of the meat. Therefore, the knowledge of heat and mass transfer properties (thermal conductivity or diffusivity, convective heat transfer coefficient, mass diffusion coefficient) is essential to estimate final temperature and cooking time which are the two main parameters of product microbiological safety and quality (Tocci and Mascheroni, 1995). Although there is much literature devoted to the heat transfer phenomena that occur during industrial treatments, domestic heating has been more rarely studied. Domestic oven manufacturers are increasingly concerned about how their products are prepared at a domestic scale, because domestic cooking is the final step for consumers, and they affect both the nutritional and sensory characteristics of food products. The variability associated with domestic cooking operations causes inadequate data about the heat transfer properties in the oven (Cernela et al., 2014). Also, there is a great limit to cooking modelling because the thermal properties of a product largely

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depend on the cooking process, sample temperature, meat composition and several other events that simultaneously occur on both the meat surface and interior, and it is very difficult to split the effect of each one. As sensible heat absorption causes temperature increase, the latent heat of vaporisation due to moisture evaporation slows down the surface temperature increase at the meat surface. Furthermore, as the temperature increases inside of the meat, water diffusion, dimensional changes because of muscle fibre shrinkage and compositional changes caused by water and fat losses simultaneously occur, and the interaction of all these events makes the boundary layers of the sample surface very complex. For that reason, the prediction of the cooking time by considering all these factors is very complicated and time-consuming (Marcotte et al., 2008; Rinaldi et al., 2010). When considered from this point of view, mathematical modelling contributes to the better understanding of heat and mass transport during cooking if it is simply formulated, and it is a very useful tool in the improvement of the design and control of the cooking process. Modelling studies of the oven cooking process have been investigated by researchers for some decades (Bengtsson et al., 1976; Skjöldebrand and Hallström, 1980; Singh et al., 1984; Chang et al., 1998) and different hypotheses have been formulated to model mass transfer during cooking with regard to types of moisture transfer mechanisms (Chen et al., 1999; Huang and Mittal, 1995; Ngadi et al., 1997; Godsalve et al., 1977; Thorvaldsson and Skjöldebrand, 1996; Wahlby and Skjöldebrand, 2001; Obuz et al., 2002; Van der Sman, 2007a,b). Two main categories of the models about moisture transport have been developed. In the first, convection by Darcy flow and diffusion is considered accounting for pressure-driven moisture flow and diffusion inside the material. In the second, Fick's diffusion accounts for the moisture transport inside the product using an effective diffusion coefficient (Tzempelikos et al., 2015).

The objectives of this work were to model the simultaneous heat and moisture transport during the cooking process of *Semitendinosus* muscle in a steam-assisted hybrid oven, in which steam quantity is less than saturation in the oven chamber, as well as validate that model with the experimental results. Accordingly, the thermal conductivity of muscles and convective heat transfer coefficients were determined experimentally, and the convective mass transfer coefficient was achieved by simulation under real domestic cooking conditions. In this way, cooking times at different cooking conditions would be introduced to the consumers and could offer to manufacturers a facility to develop cooking programmes for products having different cooking degrees (medium-rare, medium, medium-well) at different cooking temperatures in such a domestic steam-assisted hybrid oven.

2. Material and methods

2.1. Material

Semitendinosus muscles were purchased from Pınar Entegre Et & Un Sanayi A.S. (Izmir, Turkey) shortly after slaughter, and stored in vacuum bags at 4 °C for 24 h until cooking. The proximate composition of each fresh muscle was determined before cooking. The average total moisture content using the gravimetric method at 105 °C for 24 h, the average total protein content by Kjeldahl method (AOAC, 1990) and the average total lipid content using the chloroform-methanol method (Folch et al., 1957) were determined as 75 (±1.48, wet basis) %, 20 (±0.60, wet basis) % and 4 (±0.30, wet basis) %, respectively. The total ash content was found to be 1 (±0.07) % using the gravimetric method and heating the sample at 550 °C for 24 h (AOAC, 1990).

2.2. Cooking process

Cooking experiments were carried out in a steam-assisted hybrid oven (Arcelik, 9681 ESLTI), which is a hybrid domestic oven that combines convective cooking with steam application. Its dimensions are 48 × 43 × 25 cm, and an inner steam generator is mounted at the back panel of the oven. The steam generated from ~350 g water was injected through a hole located at the back-bottom of the oven wall between the 3rd and 28th minutes of each cooking process. In every cooking turn, only 1 meat sample was located on a sieved tray, and each sample was obtained by dividing the *Semitendinosus* muscle into 2 equal parts that were 70 mm thick (~400 g). The j-type thermocouples (wire size, 1 mm), one located at the bottom surface, one at the top surface and one at the geometric centre of the sample (Fig. 1(a)), and temperature variation were measured and recorded by a multi-channel data logger (Testo, 177-T4) every 30 s. The cooking process was carried out at 180, 210 and 240 °C oven temperatures until the geometric centre temperatures of the sample reached 65, 72 and 80 °C. All the cooking processes were duplicated.

2.3. Determination of convective heat transfer coefficient, h_c (W/m^2K)

A cylindrical aluminium (Al) block of a similar size as the meat samples was constructed to determine the combined heat transfer coefficient (h_k). The j-type thermocouple was placed in the centre of Al block through a small hole. The oven temperature was set to 180, 210 and 240 °C, and the oven was heated until a constant temperature was reached. At that point, the oven was opened quickly, and the Al block with the thermocouple was placed into the oven. The temperature at the geometric centre of the Al cylinder was recorded every 3 s. According to the lumped capacity method, the combined heat transfer coefficient (h_k) was calculated using the slope of $-\ln(T_\infty - T(t)/T_\infty - T_{ini})$ vs time curve based on Eq. (1), where T_∞ is the oven temperature (°C), T_{ini} is the initial temperature of the material (°C), $A_{surface}$ is the surface area of the material (m^2), V is the volume (m^3), ρ (2700 kg/m^3) is the density and c_p (869 J/kgK) (Singh and Heldman, 2008) is the specific heat of the material, and t is time (s).

$$-\ln\left(\frac{T_\infty - T(t)}{T_\infty - T_{ini}}\right) = \frac{h_k A_{surface}}{\rho c_p V} t \tag{1}$$

Also, the thermocouples isolated with glass wool were fixed on the oven walls to calculate the radiation heat transfer coefficient (h_r) using Stephan–Boltzmann law (Eq. (2)), where T_s is the product surface temperature (K), T_w is the oven wall temperature (K), ε_s, 0.33 (Geankoplis, 1993) is the surface emissivity of the material and σ is the Stefan–Boltzman coefficient (5.676 × 10^{-8} W/m^2K^4).

$$h_r = \varepsilon_s \cdot \sigma \cdot \left(T_w^2 + T_s^2\right) \cdot (T_w + T_s) \tag{2}$$

Then, the convective heat transfer coefficient (h_c) was calculated for each oven temperature using Eq. (3).

$$h_k = h_c + h_r \tag{3}$$

2.4. Determination of thermal conductivity, k (W/mK)

The line heat source method was used to measure the thermal conductivity of muscles that were cooked until the geometric centre temperatures reached 45, 65, 72, 80 and 90 °C. The apparatus used in this work was based on the system described by