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Modelling the transport phenomena and texture changes of chicken breast meat during the roasting in a convective oven

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ABSTRACT

A numerical 3D model of coupled transport phenomena and texture changes during the roasting of chicken breast meat in a convection oven was developed. The model is based on heat and mass transfer coupled with the kinetics of temperature induced texture changes of chicken breast meat. The partial differential equations of heat and mass transfer as well as the ordinary differential equations that describe the kinetics of the texture changes were solved using COMSOL Multiphysics® 5.2a. The predicted temperature, moisture and texture (hardness, chewiness and gumminess) profiles were validated using experimentally values. The developed model enables the prediction of the texture development inside the chicken meat as function of the process parameters. The model predictions and measured values show the clear effect of changing process settings on the texture profiles during the roasting process. Overall, the developed model provides deep insights into the local and spatial texture changes of chicken breast meat during the roasting process that cannot be gained by experimentation alone.

1. Introduction

Heat treatment of chicken breast meat is a crucial processing step in households, professional kitchens and large-scale food industries to achieve a safe and high quality product. Roasting of chicken meat in a convection oven is a common process that involves simultaneous heat and mass transfer. However, the roasting affects the microstructure (Feyissa et al., 2013; Wattanachant et al., 2005), texture (Wattanachant et al., 2005) and appearance (Fletcher et al., 2000) of the product and, consequently, its acceptance by the consumer.

The texture of the chicken meat is the highest rated quality attribute for the consumer during consumption (Lawrie and Ledward, 2006) and it is mainly influenced by protein denaturation which leads to fiber shrinkage and straightening (Tornberg, 2005; Wattanachant et al., 2005). Consequently, the microstructure is becoming denser with compact fiber arrangements which results in the toughening of the chicken meat during the heating (Christensen et al., 2000; Lewis and Purslow, 1989; Wattanachant et al., 2005). Moreover, the protein denaturation leads to a reduction of the water holding capacity (WHC) of the chicken breast meat. The unbound water migrates into the spaces between the meat fibers which leads to a toughening of the meat and to the loss of water during the roasting process (Micklander et al., 2002; Tornberg, 2005).

The quality of the final product is mainly controlled by the chef or operator through adjustments of the process settings. However, this is still based on the cook-and-look approach, which relies on the experience and skills of the chef or operator. A number of researchers measured experimentally the texture change of poultry meat with temperature (Barbanti and Pasquini, 2005; Wattanachant et al., 2005; Zell et al., 2010) and Rabeler and Feyissa (2018) developed kinetic models to describe these changes with time. However, to gain the relationship between the process conditions and the texture development inside the chicken meat, the spatial temperature and time history during the roasting process is needed.

Mechanistic models of heat and mass transfer (based on fundamental physical laws) are able to predict the temperature and moisture distribution during the cooking process of meat (Feyissa et al., 2013; van der Sman, 2007), beef meat (Kondjoyan et al., 2013; Obuz et al., 2002) or poultry meat (Chang et al., 1998; van der Sman, 2013). However, for the roasting of chicken breast meat only a limited number of mathematical models are available.

Chen et al. (1999) developed a model of heat and mass transfer for convection cooking of chicken patties. In their model they described the transport of moisture inside the chicken patties by diffusion, which is a common approach for modelling mass transfer (Huang and Mittal, 1995; Isleroglu and Kaymak-Ertekin, 2016; Kassama et al., 2014). However, the moisture transport during the cooking process cannot be explained adequately by pure diffusion models (Feyissa et al., 2013; van

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der Sman, 2007). Roasting of chicken breast meat leads to protein denaturation, the shrinkage of the protein network and the reduction of the water holding capacity. This induces a pressure gradient inside the meat and the expulsion of the excess moisture to the surface of the meat.

This approach was used by van der Sman (2013) to model the cooking of chicken breast meat in an industrial tunnel oven. The author showed that the model is able to predict the temperature and moisture development inside the chicken meat for cooking temperatures below the boiling point. However, the presented cooking temperatures (45–100 °C) and times (up to 160 min) are not common settings for the roasting of chicken meat in industrial convection ovens, where hot dry air with more than 150 °C is employed (Chen et al., 1999; Guerrero-Legarreta and Hui, 2010).

Thussu and Datta (2012) showed that by coupling texture kinetics with physical based models of heat and mass transfer, the texture development during the frying of potato stripes can be predicted. However, for chicken breast meat or other muscle foods no attempt was made to couple kinetic models for textural changes with mechanistic models of heat and mass transfer to predict the local and spatial texture changes.

Therefore, the aim of this study is to first develop a mechanistic model to predict the temperature and moisture profiles of chicken breast meat during the roasting in a convection oven. Our hypothesis is then that by coupling the developed model for heat and mass transfer with the kinetic models of heat induced textural changes for chicken meat, the texture profile during the roasting process can be predicted as function of process parameters. Afterwards, the model predictions will be validated against experimental values.

2. Modelling of transport phenomena and texture changes

2.1. Process description and model formulation

Roasting in a convection oven is a thermal process, where the product is heated at high temperatures (150–300 °C) by circulated hot air. The main mechanisms during the roasting of chicken breast meat in a convective oven are illustrated in Fig. 1. Heat is transferred mainly through convection from the surrounding circulated hot air while a conductive heat flux comes from the roasting tray (bottom of chicken breast). The surrounding oven walls are made of polished stainless steel, thus, the effect of radiation is small compared to the convective transport (see section 3.2.1) (Feyissa et al., 2013). The effect of radiation was included in the model by using an estimated effective heat transfer coefficient (combined convective and radiative heat transfer coefficient, see section 3.2.1) (Kondjoyan and Portanguen, 2008; Sakin-Yilmazer et al., 2012; Zhang and Datta, 2006). The heat is then internally transferred by conduction and convection.

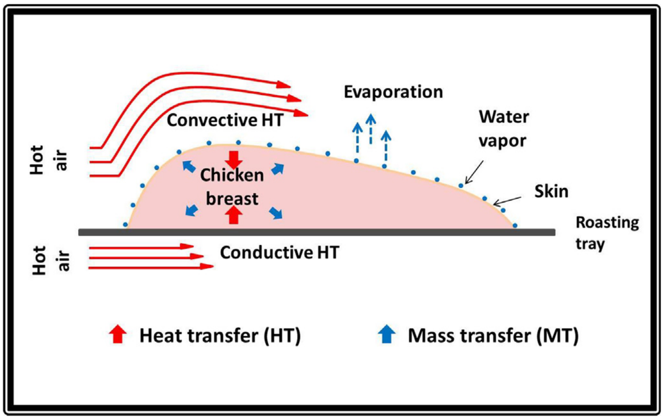

Fig. 1. Schematic illustration of the main mechanisms during the roasting of chicken breast meat in a convection oven.

Water migration within the product takes place by diffusion and convection mechanisms. The latter is a result of the heat induced protein denaturation and shrinkage of the protein network, which results in the decrease of the water holding capacity and a pressure gradient inside the chicken meat. This so called swelling pressure is the driving force for the convective water transport inside the meat and can be described by Darcy's law for flow through porous media (van der Sman, 2007). Liquid water that is expelled to the product surface is then evaporated to the surrounding hot air.

From the measured temperature profiles inside the chicken meat we observed that the temperature stays below the evaporation temperature and only a thin crust is formed during the roasting. Thus, internal evaporation of water was neglected in this study. Furthermore, the following basic assumptions are made to formulate the governing equations for the coupled heat and mass transfer: fat transport inside the chicken meat is negligible (since the fat content is less than 1% in chicken breast meat), evaporated water consists of pure water (no dissolved matter, measured similar to Feyissa et al. (2013)) and no internal heat generation.

2.2. Governing equations

2.2.1. Heat transfer

The heat transfer within the chicken breast meat is given by Eq. (1) (Bird et al., 2007)

$$c_{p,cm}\,\rho_{cm}\,\frac{\partial T}{\partial t} = \nabla(k_{cm}\,\nabla T) - \rho_w\,c_{p,w}\,u_w\,\nabla T \tag{1}$$

where $c_{p,cm}$ and $c_{p,w}$ are the specific heat capacities of chicken meat and water (J/(kg K)), respectively, ρ_{cm} and ρ_w are the densities of chicken meat and water (kg/m^3), respectively, k_{cm} is the thermal conductivity of chicken breast meat (W/(m K)), u_w the velocity of the fluid (m/s), T is the temperature (K) and t is the time (s).

2.2.2. Mass transfer

The governing equation for water transport is based on the conservation of mass and is given by Eq. (2) (Bird et al., 2007)

$$\frac{\partial C}{\partial t} = \nabla(-D\,\nabla C + C\,u_w) \tag{2}$$

where C is the moisture concentration (kg of water/kg of sample) and D is the moisture diffusion coefficient (m^2/s).

Darcy's law gives the relationship between moisture transport and pressure gradient inside a porous medium (in this case meat) and the velocity of the fluid inside the chicken meat can be expressed as

$$u_w = \frac{-\kappa}{\mu_w}\,\nabla p \tag{3}$$

where κ is the permeability of the chicken meat (m^2), μ_w is the dynamic viscosity of the fluid (Pa s) and ∇p is the pressure gradient vector (Pa/m). The swelling pressure is given by Eq. (4) (Barrière and Leibler, 2003; van der Sman, 2007)

$$p = G'(C - C_{eq}) \tag{4}$$

with G' the storage modulus and C_{eq} the water holding capacity of chicken breast meat.

By inserting the expression for the swelling pressure (Eq. (4)) into Eq. (3) the following expression results for the fluid velocity u_w:

$$u_w = \frac{-\kappa\,G'}{\mu_w}\,\nabla(\,C - C_{eq}) \tag{5}$$

The storage modulus varies with temperature and was described by with a sigmoidal function (Eq. (6)) (Rabeler and Feyissa, 2018):