Robust Modelling of Heat and Mass Transfer in Processing of Solid Foods

The study is focused on combined heat and mass transfer during processing of solid foods such as baking and frying processes. Modelling of heat and mass transfer during baking and frying is a significant scientific challenge. During baking and frying, the food undergoes several changes in microstructure and other physical properties of the food matrix. The heat and water transport inside the food is coupled in a complex way, which for some food systems it is not yet fully understood. A typical example of the latter is roasting of meat in convection oven, where the mechanism of water transport is unclear. Establishing the robust mathematical models describing the main mechanisms reliably is of great concern. A quantitative description of the heat and mass transfer during the solid food processing, in the form of mathematical equations, implementation of the solution techniques, and the value of the input parameters involves uncertainty. The objective of this thesis is to develop robust models of heat and mass transfer during processing of solid foods. The study consists of formulating the mechanistic models, solving the models by the Finite Element method (FEM), calibrating and validating the models by experimental data, evaluating the models by an uncertainty and sensitivity analysis. In the study, contact baking and roasting of meat in convection oven were chosen as representative case studies. For both representative cases, the experiments were performed and the relevant data such as product temperature, mass loss, and other process conditions were obtained. For roasting of meat in convection oven, the mechanism of water transport during roasting was studied; a theoretical assessment was made on the change in structure, water holding capacity and shrinkage. The mechanism of water transport was tested by measuring the local water content. For the roasting process, 3D and 2D mechanistic quantitative models describing the coupled heat and mass transfer were developed. The governing model equations are based on the conservation of energy and mass. Further, Darcy’s equation was used to describe the pressure driven transport of water in meat during roasting. The change in elastic modulus, evaporation, and moving boundary were incorporated into the model equations. The arbitrary Lagrangian–Eulerian (ALE) method was implemented to capture the moving boundary during the roasting process. The model equations for coupled heat and mass transfer were solved using the FEM (COMSOL). For the contact baking process, a 1D mathematical model of the coupled heat and mass transfer was developed. The model developed for the contact baking process considered the heat transfer, local evaporation, and multiphase water transport (liquid and vapour). The model equations were implemented in the COMSOL-MATLAB computing environment with the following features: parameter estimations, model validations and uncertainty and sensitivity analysis. The unknown parameters in the model were estimated by comparing the measured and simulated data – using the least square method by comparing the measured temperature against the simulated temperature. Further, the model was validated using the experimental data and a reasonably agreement between the simulated and experimental data were obtained. The uncertainty and global sensitivity analysis method were incorporated for the model of coupled heat and mass transfer. The uncertainty of model predictions due to the uncertainty in input parameters such as thermo-physical properties, heat and mass transfer coefficients, phase change initial and boundary conditions parameters were studied. A Monte Carlo based method of the uncertainty and global sensitivity analysis was used. The sensitivity analysis was performed to determine the relative effect of the different parameters on the model prediction. The relative effects of parameters on the model prediction were indentified, and their relative impact on each model output was ranked. Generally, the developed mathematical models of heat and mass transfer provide better insights about the processes. The proposed robust modelling approach was found to be a useful tool in the model building that help to cope up with different challenges in modelling of heat and mass transfer during processing of solid foods and the potential of using the approach is particularly great for frying and baking operations.