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Relating Bread Baking Process Operating Conditions to the Product Quality: a Modelling Approach

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Recently, many researchers are focusing their attention to food process modelling as a tool for optimizing not only the energetic and economic aspects, but also the final product texture, flavour and nutritional value. Modelling is also a valid instrument for better understanding the different scales of the cooking process. Due to its wide consumption, bread is one of the most studied foodstuffs, whose estimated production is about 9 billion kg/y (Heenan et al., 2008). The objective of this work is to analyze some of the main phenomena related to bread baking and to characterize cause-effect relationships between selected operating conditions and the final bread quality. From this viewpoint, an important role is played by the identification of the right markers that have to be taken into account for the representation of the bread quality, both from a consumer perception (Gellynck et al., 2009), from a nutritional perspective (Gellynck et al., 2009) and from that of engineers (Mondal and Datta, 2008). In addition to this, it is of relevant importance to properly characterize the most relevant physical and chemical aspects. This step is related to the analysis, choice and implementation of the models for reproducing the dynamics of the main involved phenomena. Heat exchange, water evaporation, weight loss, crust formation and browning, starch gelatinization, odours development, to quote a few, are directly depending from the baking conditions. Some of them have been modelled by several authors with different degree of detail. Assembling some of the literature models, a general model for temperature and water content/weight loss dynamics is obtained and validated with experimental data. Some correlations are used for the representation of other phenomena such as starch gelatinization and other chemical reactions, like those related to protein-sugars interactions and the following compounds development (Maillard Reaction). The present work represents a first step towards the achievement of a more comprehensive study for modeling and understanding food cooking in domestic ovens. A special attention will be addressed to the development of a reliable chemical kinetic scheme.

1. Introduction

Bread Baking is one of the most clear example of food process that involves several chemical and physical phenomena (Mondal and Datta, 2008, Gellynck et al., 2009, Dewettinck et al., 2008). For this reason, the study of this process has been for decades to the attention of several researchers, that focuses on the general problem or to specific issues, such as for example the flavour generation (Mondal and Datta, 2008), the browning development (Schieberle and Grosch, 1989), the water and heat transport (Purlis and Salvadori, 2007), the influence on oven design (e.g. for CFD based design (Chhanwal et al., 2011) and (Purlis, 2012) for a process perspective), the volume expansion (Purlis, 2011), etc.

An important issue with cooking (and baking) processes is that they are almost always batch processes, and dynamic models are recommended for their description, with the exception of the flow field, when the assumption of steady state can simplify the system solution with good approximation. For this reason, very detailed models are often hard to solve and requires very efficient (and robust) solvers, powerful computers and an intelligent algorithm for reducing the computational costs. In addition, some key assumptions can be required to make a simulation enough fast, certainly going to the detriment of the details but getting reasonable results, when compared to the aim of the research.

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For what deals with thermal aspects of food modelling, it’s important to consider both the models for the food itself, and the boundary conditions that, in practice, represent the operating conditions which the food is subject to. In this sense, the first choice is about the consideration of a homogeneous or heterogeneous medium. In both of the cases, every considered phase can be made of only one or more components. Once this has been decided, appropriate mixing rules have to be chosen in order to describe the properties of the components (such as thermal conductivity, heat capacity, density). In addition, when searching for food material literature, one has to face the problem of the specificity of a single food: often, the experiments for its validation and for the properties and coefficients derivation, as well as for the boundary conditions, are designed on a very specific foodstuff and experiment, and a general approach requires to make new assumptions and/or experimental tests to be applied to the specific case. By the way, a general approach is still possible, being careful to develop and utilize equations based on general phenomena, eventually applied to the specific context by modifying some terms and by introducing some parameters (Zhang et al., 2005).

Talking about the boundary conditions for an oven, several papers consider the environment as a source of heat, generally for convection, conduction and, sometimes, radiation (Zhang et al., 2005). Most of the times, where the product itself is the main target, heat exchange coefficients are considered (Nicolas et al., 2012), while when the oven design is the target, the fluid dynamic flow is simulated (Purlis, 2011).

Within this context, the aim of the current paper is to identify a general model for bread (as a product), with specific attention to some key phenomena (i.e. heat transfer, weight loss, starch gelatinization, development of some flavours), considering also a reasonably simplified oven model for the operating conditions. The further aim is to validate first the oven model, then the overall model with experimental data. In the end, a final purpose is to get the possibility to work on the operating conditions in order to work to the product quality and to possible process design solutions.

An extensive review on bread baking and on baking process design can be found in the paper from (Chhanwal et al., 2011) and in the book chapter from (Mondal and Datta, 2008).

2. Experimental configuration

In the introduction it is explained that before considering the whole baking process, it is useful to consider the empty oven model and related experimental data, in order to operate in the correct operating conditions. The data for the model have been taken from a test made on a domestic oven, measuring the temperature in some points of the cavity, in forced convection heating conditions. The temperature has been measured through T-Type thermocouples linked with a data logger for the storage of the dynamic data.

The same configuration has been applied to the bread baking process, where bread dough has been inserted in the oven after a pre-heat phase. The bread was placed on a circular grill instead of a dripping pan in order to minimize the effect on conduction and on fluid flow. Temperature has been measured inside the bread in the centre at two different heights (Figure 1). The bread weight has been measured before and after the cooking phase, with a kitchen scale (Figure 2), that have an uncertainty of 0.5 g on the measured weight.

Figure 1: experimental configuration: bread and thermocouples in the centre

Figure 2: experimental configuration: bread weight measure on the kitchen scale.

3. Model description

3.1 Geometries

With respect to the real geometries of the oven, the model cavity is made by a parallelepiped with the same size. The 4 inlets are represented by the rectangles near the four corners, while the outlet (centre-back part) is designed as a circle. The resulting geometry has been designed with a commercial FEM software and it is shown in Figure 3.

The model that includes the bread respects the same geometries for the oven (Figure 4). The bread is modelled as a truncated ellipsoid, with the constant dimensions measured before the cooking phase (i.e. the volume expansion is neglected for simplification purposes, while several authors suggest to calculate it with the assumption of Newtonian fluid (COMSOL-AB, 2012) or stress-strain relation model for a porous material (Nicolas et al., 2012)).

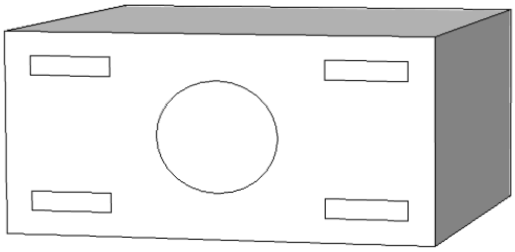


Figure 3: Model geometry: oven cavity (back viewpoint)

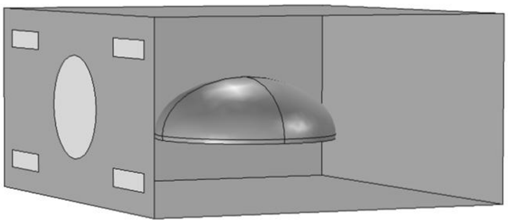


Figure 4: Model geometry: oven cavity with bread (side viewpoint) n.b., side-face is hidden.

3.2 Model: cavity

The cavity is modelled as a box filled with air in a forced convection regime. The wall thickness (and material) is neglected. Continuity (1), momentum conservation (2) and energy conservation (3) equations are here provided:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\rho \frac{d\mathbf{u}}{dt} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left[-p\mathbf{I} + \mu\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I} \right] + F \tag{2}$$

$$\rho C_p \frac{dT}{dt} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) \tag{3}$$

The boundary conditions for the oven (wall thermal insulation (4), forced air at inlet (5), no-slip conditions at the other walls (6), air outlet condition (7) and inlet temperature variable with the time (8)) are:

$$-\mathbf{n} \cdot (-k \nabla T) = 0 \tag{4}$$

$$\mathbf{u} = -u_0 \mathbf{n} \tag{5}$$

$$\mathbf{u} = 0 \tag{6}$$

$$\left[\mu\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I} \right] \mathbf{n} = 0 \tag{7}$$

$$T_{inlet} = T_{inlet}(t) \tag{8}$$

Initial conditions are set on initial temperature and pressure in the cavity and, if considering the dynamic model, zero velocity in the cavity (otherwise, if considering steady state flow, the cavity air flow field is calculated from a steady state simulation).

3.3 Heat and Mass Transfer Model: bread

The bread thermal model comes from the work of Purlis and Salvadori (Zhang et al., 2005), references for the mathematical formulas for bread properties. In brief:

1. the crust development is connected to the formation and advance of an evaporation front. The crust is that part at a temperature higher than 100 °C.
2. Bread is homogenous and continuous, volume change is neglected, bread is motionless.

3. Heat capacity, thermal conductivity and density are effective properties functions of the transition temperature (100 °C), in order to take into account the condensation-evaporation mechanism (Purlis and Salvadori, 2009a, 2009b) and the moving boundary problem (Thorvaldsson and Janestad, 1999).
4. Thermal properties take advantage of smoothed Heaviside and Dirac functions to manage the transition.

Different approaches are being used for the bread thermal model and properties (especially dealing with mixture properties), but they will be included in future works.

The equation for the thermal aspects are bread thermal balance (9) and no-slip bread wall boundary conditions (10):

$$\rho C_p \frac{dT}{dt} = \nabla \cdot (k \nabla T) \tag{9}$$

$$\mathbf{u} = 0 \tag{10}$$

Water transport is considered simple diffusion with a Fick law, with a boundary condition of a surface flow:

$$\frac{dW}{dt} = \nabla \cdot (D_W \nabla W) \tag{11}$$

$$-\mathbf{n} \cdot (-D_W \nabla W) = k_{mat} (W - W_{bulk}) \tag{12}$$

3.4 Kinetic Model: bread starch gelatinization and crust flavour formation

Starch gelatinization is a phenomena often related to the bread degree of baking. Its kinetics has been studied by (Bonacina et al., 1973) and described with a first order kinetic equation:

$$\alpha_g = 1 - \exp(-kt) \tag{13}$$

$$k = k_0 \exp(-\frac{E_a}{RT}) \text{ , with } \mathrm{K_0} = 1.8\ (10^{18})\mathrm{s}^{-1} \text{ and } \mathrm{E_a} = 138\ \mathrm{KJ/mol} \tag{14}$$

Crust flavor is really important when talking about bread quality from a consumer perspective. Its formation is also a kinetic process, widely recognized to be connected to Maillard Reaction, a that regards the interactions between amino-acids and reducing sugar in foods and in biological systems (Zanoni et al., 1995). Despite a great variety of works on the end-products characterization, only few studies focus on the kinetic aspects: the authors direct their attention on a work by (Ledl and Schleicher, 1990), where a 11 reactions scheme (see Figure 5 and Table 1) is produced and validated on data taken from a model system.

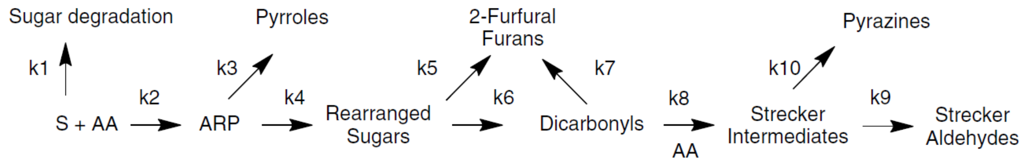


Figure 5: Maillard kinetic scheme, from (Jousse et al., 2002)

Table 1: Kinetic parameters for the simplified Maillard reaction

Reaction	k0 (1/s or L/mol/s*)	Ea (kJ/mol)
R1	0	0
R2*	5.0e12	120.5
R3	6.0e1	35.1
R4	1.5e5	52.9
R5	2.0e11	109.3
R6	5.0e5	66.5
R8*	5.0e11	83.1
R9	1.0e15	116.3
R10	fast	-
R11	1.0e10	99.7

*(bi-molecular reactions)

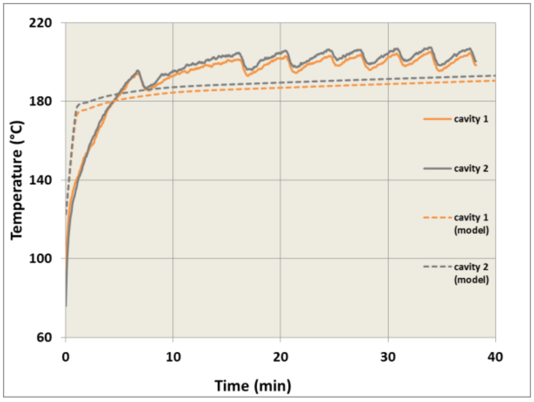
Despite the conditions can be very different from that of the baking process, it is useful to apply a kinetic scheme in order to get the sensitivity of the scheme to temperature and time, resulting in the possibility to study, when experimental test can be available, the real chemical compounds: the characteristic flavours.

4. Model validation and results

The validation for the oven cavity is not shown for conciseness. Hence, the authors present the application of the presented model to the bread baking process.

4.1 Thermal behaviour

The results for the bread baking process are presented in Figure 6 and Figure 7.



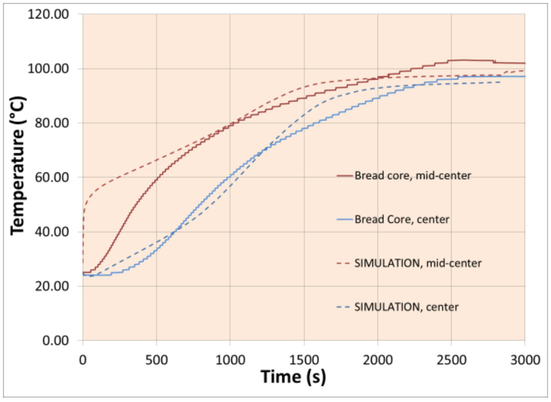


Figure 6: Time/temperature profiles, oven centre-front (cavity 1) and centre-back (cavity 2)

Figure 7: Time/temperature profiles for bread, thermocouples at centre and mid-centre

As one can see, the time/temperature profile is reasonably good for oven, with a maximum temperature that is about 10 °C less than the experimental one, probably due to neglected radiation. The bread model has a reasonably good temperature trend for the centre, while the mid-centre has some differences at the beginning. This is probably due to the fact that the used properties have been developed for a 2-D case, and have to be tuned in order to fit better the real trend. In addition, since the volume growth of the bread, the thermocouple position could have changed, bringing to a slightly different temperature profile.

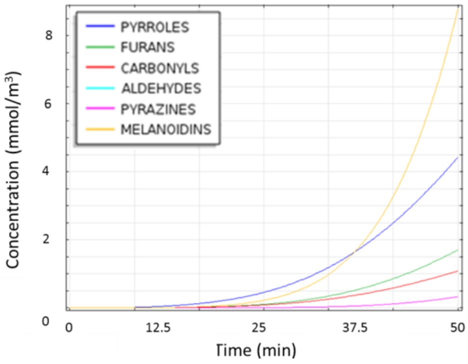
4.2 Starch gelatinization and weight loss

From the simulations, the bread starch is completely gelatinized in about 15 min (almost 1/3 of the baking time). This is reasonable and in agreement with the paper from (Jousse et al., 2002).

Weight loss is associated to water transport: bread dough is dried during the process. The final weight is very close to the experimental one. Due to the page number limit no charts are shown on these aspects.

4.3 Flavour Development

The model presented in the previous section with the parameters reported in Table 1 has been applied to the system. The results can't be validated due to lack of experimental measurements, but can be representative of the possible flavour development for crust and crumb (Figure 8 and Figure 9).



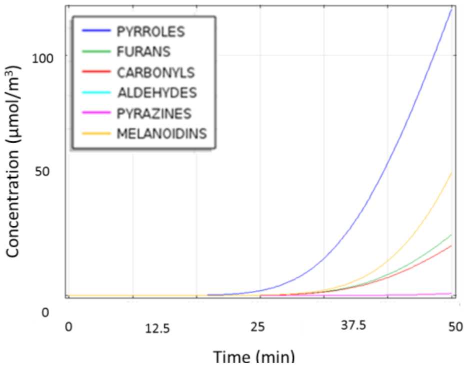


Figure 8: Flavour development in the crust

Figure 9: Flavour development in the crumb

5. Conclusions

The present work presents a fluid Dynamic model applied to a simplified oven design, combined to heat and water transport in the bread case study. Chemical kinetics has also been considered to give more answers to the quality issue. Some markers (Gelatinization degree, Flavours, Weight) have been found and related to the cooking process. Such approach can give the opportunity to find a correlation between baking conditions and the final quality, being also an optimization and design instrument for the oven.

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