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Heat and Mass Transfer during Baking: Product Quality aspects

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Abstract
Most food product qualities are developed during heating processes. Therefore the internal heating and mass transfer of water are important aspects in food processing. Heating of food products is mostly induced by convection heating. However, the number applications of convective heating in combination with microwave heating are growing. Convection heating only promotes heating on the surface while microwave induce internal heating. This paper focuses on effect of convection heating sources to changes of quality properties in bakery products such as brownness and texture. Heat convection and conduction, and moisture migration due to diffusion and convection are the key to changes (transformations) in physical, chemical and structure properties in products. A 2D model for heat and mass transfer within bread is presented and a numerical FEM approach is used to solve the model and to predict the product qualities.

1 Introduction

Baking is the most important stage in bakery production, where a number of complex mechanisms occur. During baking a chain of physical, chemical and biochemical changes take place in the product. Thermal and gas expansion, color formation, starch gelatinization, formation of porous structure, and crust and crumb formation are the main product transformations [6]. These transformations are the result of simultaneous heat and mass transfer within the product; in other words, heat transfer and moisture migration are dominating factors for product quality.
Several studies have been done to find correlations between product quality and baking settings from experimental experiences. Zanoni et al. [10] indicate that the temperature of a bread centre tends asymptotically to 90-100^{o}C while the surface tends to the oven temperature and no constant drying rate period is found. Furthermore, it is suggested [10] that crust and crumb are determined by the formation of an evaporation front at 100^{o}C. Crust is obtained at the high temperature side of the front where the temperature tends to oven temperature and crumb is formed at the temperatures in the range of 90-100^{o}C. The effect of heating sources, radiation and convection, during baking to browning

formation of cookies has been studied [7]. A linear correlation in rate of browning with temperature was found. De Vries et al. [1] propose a mathematical model for heat and water transfer in dough and crumb considering evaporation-condensation in the gaseous phase and conduction in the liquid phase. The expansion of air in dough was proposed to influence heat and water transfer in the product.
These studies are either focused on finding experimental correlations between baking conditions and the final quality or focused at the internal heat and mass transfer. The objective of this paper is to present a link between heat -mass transfer and product quality during heating process.

2 Model

2.1. Heat and Mass transfer inside product

Heat and mass transfer are considered as the main governing processes during baking process. As in other thermal processes, heat in the oven is transferred from the heating unit to product in mainly two ways: (a) convection that is caused by hot air around the product, and (b) radiation, which does not depend on the air velocity and air temperature.
The model is developed with the following assumptions:

- Constant product volume during heating,
- Homogeneous composition in the product,
- All physical parameters (conductivity, diffusion, heat and mass transfer coefficient etc.) are constant
- Initial conditions are uniform,
- No interaction from quality parameters to heat and mass transfer.

Heat is transferred to the product surface and then followed by conduction inside the product towards the geometric centre. The equation for heat transfer (eq 1) is derived from energy conservation in the product and is a function of conduction, water evaporation and gases (water vapor and CO_2 gas) convection. When heating is started up, the water (water concentration: ρ_w –kg/m^3) in the liquid phase partly diffuses towards the product surface and evaporates partly to vapor phase. In addition, due to the temperature difference between surface and centre, part of water vapor condenses backward to coldest region in the product. Therefore, liquid water conservation can be derived from diffusion Fick's law of liquid water, condensed water vapor and vapor convection in the product (eq 2)

Table 1. Heat and mass transfer models

Component	Models	eq
Energy	$\rho.c_p \frac{\partial T}{\partial t} = \nabla.(\lambda \nabla T) + H\frac{\partial \rho_w}{\partial t} - \nabla.(m_v H_v) - \nabla.(m_g H_g)$	(1)
Water liquid	$\frac{\partial \rho_w}{\partial t} = \nabla(D_w \nabla \rho_w) - \frac{\partial \rho_v}{\partial t} - \nabla(m_v)$	(2)
CO_2 gas	$\frac{\partial \rho_g}{\partial t} = \nabla(D.\nabla \rho_g) - \nabla m_g$	(3)
Water vapor	$\rho_v = \frac{M_w \varepsilon}{RT} k_1 e^{-k2/T} \frac{1.05\rho_w}{(0.09R_{ds} + \rho_w)}$	(4)
Total pressure	$P = p_v + p_g$	(5)
Gas flux	$m_i = -a(\frac{\rho_i}{\rho_i + \rho_j} \nabla P)$	(6)

Water vapor (ρ_v –kg/m^3) in the vapor phase is assumed to follow gas ideal law and the correlation with water liquid and temperature is obtained through the product sorption isotherm (eq 4). The CO_2 gas (ρ_g –kg/m^3) is only a function of diffusion and convection in the gas phase and caused by the internal pressure differences, CO_2 gas is forced to move towards to the surface (eq 3). The total pressure (P – Pa) is considered as the sum of partial pressure of water vapor and partial CO_2 gas. Eq 6 presents the gas flux for CO_2 and water.

2.2. Model of product qualities

In this paper, a heat-mass transfer model is coupled with a model for product quality, which is derived from qualitative information. Here, the development of brownness and texture of bakery product are considered. Because of the qualitative character of the available information, the output of the product qualities are defined on a minimum-maximum scale (ranging from 0 to 1) to describe how the quality properties develop due to heat and mass transfer.

a. Model of Browning reaction

Colour in food products is formed by the non-enzymatic reaction that is also known as the Maillard reaction, which follows a zero order reaction kinetic for formation of melanoidines (b-amount/kg):

$$\frac{db}{dt} = k_o.\exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_o}\right)\right] \tag{7}$$

$$k_o = 4.9.10^{-3}.\left(\frac{\exp(9a_w)}{2.10^3+\exp(11.3a_w)}\right) \quad \text{and} \quad a_w = \frac{1.05\rho_w}{0.09\rho + 0.91\rho_w}$$

Where a_w is water activity and T_o =363 K.

Brownness is considered to have an exponential correlation with the degree of melanoidines:

$$browness = 1 - \exp(-0.23b) \tag{8}$$

b. Model of texture formation

During baking the elastic dough transfers into a fixed structure due to a phase transition of starch (gelatinization). At this moment crumb, which is the main texture quality, is formed. The degree of gelatinization is a function of temperature (gelatinization due to temperature: α_T) and water content (gelatinization due to water availability: α_w). The values of α_T and α_w range from 0 to 1 [10]. The total degree of gelatinization is obtained from the product of the separate terms:

$$\alpha=\alpha_T.\alpha_w \tag{9}$$

Gelatinization takes place in a limited temperature range. It starts just before the gelatinisation temperature (T_α) and ends just above this temperature. From experimental observations [5] it was derived that

$$\alpha_T = \frac{\exp(0.4(T-T_\alpha))}{1+\exp(0.4(T-T_\alpha))} \tag{10}$$

It must be noted that T_α changes with changing sugar concentrations [4].

The amount of water ($W = \rho_{wo} / \rho$) in the initial dough has a major effect on gelatinization. It is reported that in the dough, one-gram starch (S) and other fat free components (C) will bind 0.5 gram of water. The rest of water is available for gelatinisation. Roos [5] states for the starch-water system, minimal 60% of water is needed to have full gelatinisation and one gram of water is needed to gelatinise one gram of starch. The maximum gelatinisation fraction follows from the ratio between water that is available for gelatinisation and total water in the product. These rules give eq.11 as a result:

$$\alpha_w = \begin{cases} 0 \quad \text{if } \ W<0.5(S+C) \\ \dfrac{(W\text{-}0.5S\text{-}0.5C)}{S} \quad \text{if } \ 0.5(S+C)<W<0.5(3S+C) \\ 1 \quad \text{if } \ 0.5(3S+C)<W \end{cases} \tag{11}$$

The total degree gelatinisation is a measure for crumb formation. For products without gelatinisation there is no crumb, the maximum level for crumb is one. Between these levels a linear relation between crumb and gelatinization is used:

$$\text{crumb} = \begin{cases} 0 \quad \text{if } \ \alpha = 0 \quad \text{(no crumb)} \\ 2\alpha \quad \text{if } \ 0 < \alpha < 0.5 \quad \text{(moderate crumb)} \\ 1 \quad \text{if } \ 0.5 < \alpha < 1 \quad \text{(crumb)} \end{cases} \tag{12}$$

Softness and crispiness of bakery products depend on the difference between product storage temperature (T_r) and glass transition temperature (Tg): δT=Tr-Tg. The glass transition temperature is derived as a function of the product water content. For a bread product with sugar: starch ratio = 0.05, Tg is given in equation (13)

$$T_g = 407.89 - 0.383\left(\rho_w\right) \tag{13}$$

Crispiness occurs when δT<0, and a maximal level is achieved when all water content is evaporated. The maximum value is obtained when $\delta T = -T_{heating}$ ^oC. For convection heating (oven), the $T_{heating}$ is close to oven temperature.

$$\text{crispiness} = \begin{cases} 0, \quad \textit{if} \quad \delta T > 0 \\ -\delta T / T_{heating}, \quad \textit{if} \quad -T_{heating} < \delta T < 0 \\ 1, \quad \textit{if} \quad \delta T < -T_{heating} \end{cases} \tag{14}$$

Softness is a combined function of temperature and gelatinisation. A soft product is obtained for δT>0, while at the other hand softness is minimal for a gelatinization fraction of 0.3 [3]. A maximum value is achieved when all starch are gelatinized. Several calculations on δT for bakery products have been performed and it can be concluded that softness stands in the range of 0-100^{o}C for δT.

$$\text{softness}(\delta \text{T}) = \begin{cases} 0, & if \quad \delta\text{T} < 0 \\ 0.01 \times \delta\text{T}, & if \quad 0 < \delta\text{T} < 100 \\ 1, & if \quad 100 < \delta\text{T} \end{cases}, \text{ and } \text{softness}(\alpha) = \begin{cases} 0, & if \quad \alpha(t) < 0.3 \\ -\frac{3}{7} + \frac{10}{7}\alpha(t) & if \quad 0.3 < \alpha(t) < 1 \end{cases}$$

$$\text{Softness} = \text{softness}(\delta\text{T}) \times \text{softness}(\alpha) \tag{15}$$

3 Numerical Method

3.1. Baking process

A cylindrical piece of bread dough (size D=H =0.1 m) with composition 45% of water (500 kg/m^3 product), 2% sugar, 37 % starch, 2 % fat, 9% protein and 6% of other components has been used as simulation example. The product was imposed in the oven, which temperature is kept constant at 180^{o}C and radiation temperature at 127 ^{o}C with baking time of 35 min.

3.2. Numerical Method

A numerical computer program for 2-D calculations with FEMLAB 3.0a was developed to solve the heat and mass transfer equations simultaneously. In order to reduce the complexity and because of symmetry, it satisfies to consider the part of the product domain given by the shaded surface (fig. 1) to perform the finite element grids. At Figure 1, the boundaries are specified as symmetrical boundary (c,d) and surfaces boundary (a,b). The symmetry boundary specifies that all fluxes or gradients across the boundary must be zero. It means that all state variables on one side of the boundary must be equal the states variables on the other side.

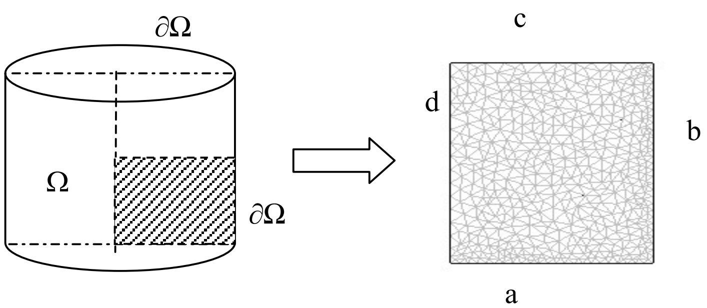

Figure 1. The domain system of the product

The set of mass and heat transfer equations are solved in the general form due to the non-linearity of PDE models and the link with product quality models

$$d_{a1}\frac{\partial u_1}{\partial t} + \nabla.\Gamma = F \qquad on \quad \Omega \qquad \text{(General form)} \tag{16}$$

Where d_{a1} is mass matrix, $u_1 = \left[T \ \rho_v \ \rho_w \ \rho_g \ P \right]$, Γ= conservative flux vector and F =source term. Both Γ and F can be functions of space, time, the solution u and its gradient.

The boundary conditions are given in Table 2:

Table 2. The boundary condition at the surface ($\delta\Omega$)

Variable	-n.Γ	a,b (surface)	Initial
T	$-\lambda\nabla T$	$h.(T_{out}-T_s)+F.\sigma.(T_r^4-T_s^4)+H.k_w.(\rho_{w,s}-\rho_{w,l})$ $+m_v.c_v.(T-273)+m_g.c_g.(T-273)$	293 K
ρ_v	$-D\nabla\rho_v$	$k_v(\rho_{v,l}-\rho_{v,s})+m_v$	0.0153 kg/m^3
ρ_w	$-D_w\nabla\rho_w$	$k_w(\rho_{w,l}-\rho_{w,s})$	500 kg/m^3
ρ_g	$-D\nabla\rho_g$	$k_g(\rho_{g,l}-d_{g,s})+m_g$	0.001 kg/m^3
P	0	P_0-P	10^5 Pa

The model of the Maillard reaction is an ODE model that can be considered as 0-D in two points because there is no space in the equations. For this type of models, the coefficient form in FEMLAB (Eq 17) is suitable for use.

$$d_{a2}\frac{\partial u_2}{\partial t}+\nabla(-c\nabla u-\alpha\nabla u+\gamma)+\beta\nabla u+au=f \quad \text{(Coefficient form)} \tag{17}$$

Where the coefficients refer to FEMLAB use of symbols: c =diffusion coefficient, α=conservative flux convection coefficient, γ=conservative flux source term, f is source term, β=convection coefficient and a =absorption coefficient.
In this case, all coefficients c,α, β γ are set to zero, with u_2=b, da_2 =1 and f expresses the Mailard reaction rate constant. All boundaries are set to Neumann.

The model of texture is an algebraic equation that can be solved directly as output of the heat and mass transfer model.

4. Results and Discussions

4.1. Heat and mass transfer

After placing dough in an oven with constant temperature of 180^{o}C, the product temperature will gradually increase. Figure 2 shows that the temperature raises slower in the centre (point 1) than at the surface (point 3). The temperature in the centre reaches a final temperature of 90^{o}C, while for surface temperature closely to oven temperature.
For the water transport two phenomena take place. First, the increasing product temperature leads to an increase of partial vapor pressure of water, and therefore the partial vapor pressure for water in the region close to surface is higher than in the center. Due to the pressure differences, the water vapor moves both to the centre and to the surface [9]. Secondly, in the centre, with a lower temperature, water vapor condenses and as a result the water content increases. These phenomena are the source for the increasing water content in the centre during the first 1000s. Later on pressure and temperature differences are equalized and from this situation water starts to diffuse from the centre to the surface. Fast dehydration due to surface heating takes place only in the surface, while the water content in the centre decreases only slightly.
During the first 300 seconds the water vapor transport towards the centre is above the internal convection. After this moment the internal convection becomes so high, that the water vapor concentration in side the product starts to decrease. The CO_2 gas decreases rapidly through diffusion from centre to surface.

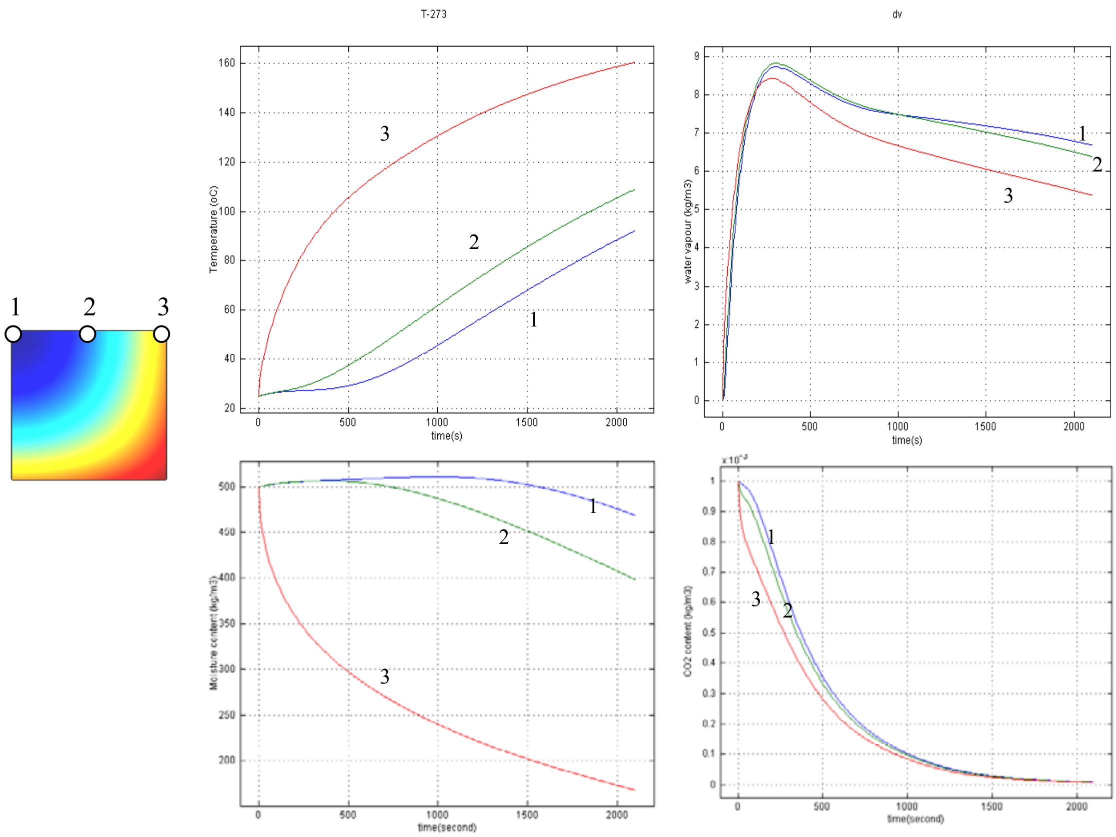

Figure 2 Result of heat-mass transfer simulation

4.2 Product qualities

Figure 3 shows the evolution of simulated value for color at constant oven temperature. Melanoidines formation from Maillard reaction leads to browning of the product. Bread shows significant increase of brownness as well as melanoidines formation at the surface and it reaches maximum scale after 1500s (brownness =1 with melanoidine concentration=70 amount/kg), while brownness in the centre still remains low (brownness=0.05 with melanoidine =2 amount/kg), due to low temperature as a result of the relative high water content.

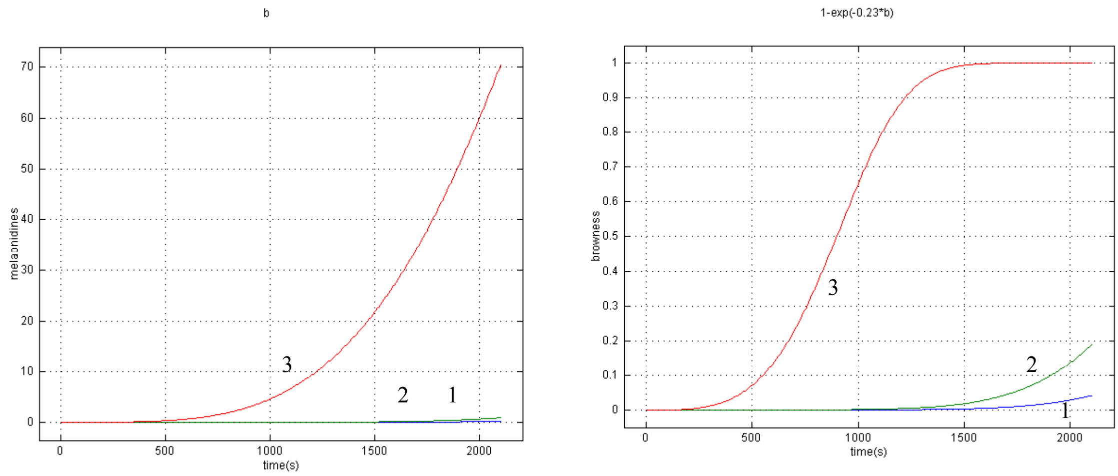

Figure 3. (a) Formation of melanoidines, (b) brownness development

Fig. 4 shows that gelatinization arises when temperature passes 65°C. It is supported also by experiments [8] that crumb was formed when temperature passed the range of 65-70°C. Total gelatinization of bread surface (crust) has reached 52% of scale after 200s of baking and consequently crust has been fully formed after 200s. The centre of the product passes the temperature range 65-70°C at later time, and hence the crumb is formed later.

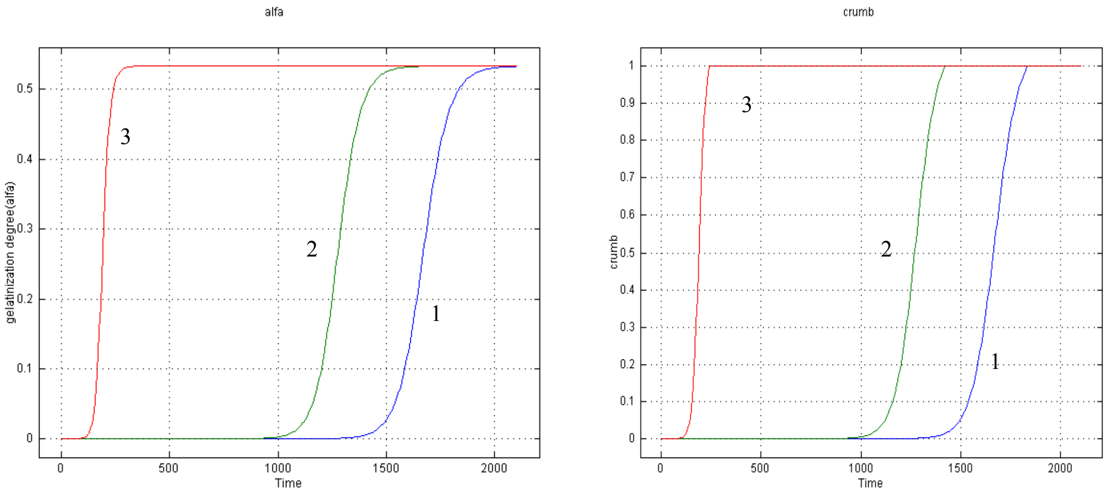

Figure 4. (a) Degree of gelatinization and (b) crumb formation versus baking time

The development of crispiness and softness properties is depicted in Fig. 5. The decrease of water content leads to increase the glass transition temperature, and the difference between room and glass transition temperature (δT) is reduced. In this simulation model, it is assumed that the softness would be minimal if δT <= zero. Softness properties on the surface decrease quickly and follow the pattern of water content, and total gelatinization of 0.52. After about 500 seconds softness is zero and crispiness of the product increases (Fig 5b). In the product center, softness of product remains at a high level due to still presence of the water.

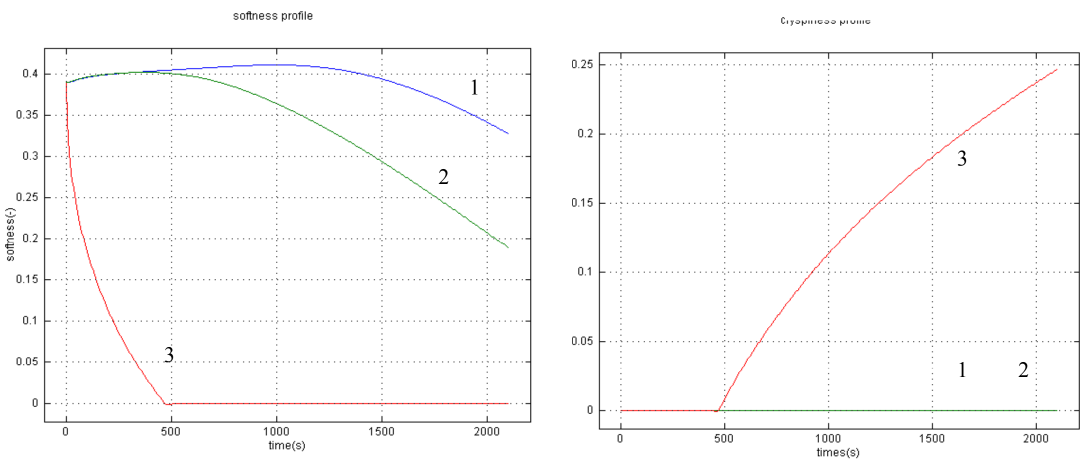

Figure 5. The softness and crispiness of product during heating

5. Conclusions

A model for simultaneous heat and mass transfer in bakery products is combined with models for the development of product quality during baking. The models have been simulated with a FEM approach. From the result follows:

- The simultaneous heat and mass transfer models are adequate to describe the complex mass and heat phenomena inside the product during baking.
- The model for product quality developed from qualitative information is promising to predict the product quality. However, the models need further refinement and validation by experimental works.
- The models are applied with the assumption that all parameters are constant during baking. They can be extended to further work for variable dependent parameters (e.g. temperature or water content).

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