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Experimental validation of product quality model for bread baking process

Hadiyanto

Bioprocess Engineering Laboratory, Chemical Engineering Department, Diponegoro University Jl.Prof. Sudharto,SH-Tembalang, Semarang 50239, Indonesia

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Abstract

Bread product quality is highly dependent to the baking process. A model for the development of product quality of bread products has been calibrated by experiments at a fixed baking temperature of 200°C and in combination with 100 W of microwave powers. The parameters in this model were estimated in sequence procedures: heat and mass transfer, then product transformations and finally product quality parameters. The results showed that there was an agreement between the calibrated model and the experimental data. Furthermore, the microwave input contributed significantly to the internal product properties but not for the surface properties as crispness and color. Despite the limited calibration with fixed operation settings, the model predicted well on the behavior under dynamic convective operation and on combined convective and microwave operation. It was expected that the suitability between model and baking system could be improved further by performing calibration experiments at higher temperature and various microwave power levels.

Introduction

The availability of accurate models to predict product quality is an essential requirement in quality driven food process design. Hadiyanto *et al*. (2007a) use a model to predict the development of product quality during bakery operations and they use the model also to generate design alternatives by calculating dynamic optimal operations (Hadiyanto *et al*., 2007b). This model needs to be experimentally validated.

Baking is a main operation in bakery production which is performed by convective heating system or by combined heating system using convective, microwave and radiation heating. Convective heating exposes the surface to a high temperature and the heat subsequently penetrates the product towards the center. This result in water evaporation and a corresponding increment of the internal pressure which creates a driving force for vapor transport to the environment of the product. In contrast to convective heating, microwave radiation will generate the heat directly inside the product, which results in different moisture and temperature profiles for products in comparison to convective heating. Radiation heating affects the product surface temperature and heat penetration to the product from this source is limited. Combined heating system with convective, microwave and radiation heating increases the flexibility of baking operation whereas the operation time is reduced and a wider range of product quality can be realized (Ni and Datta, 2002; Keskin *et al*., 2005; Sumnu *et al*.,2006; Hadiyanto *et al*., 2007b).

Important quality attributes of bakery products are color, texture, crumb and size. These attributes are the consequence of browning reactions, starch gelatinization, retrogradation and gas expansion. The associated transformations are ruled by the heat and mass transfer within the products which are a result of the imposed process conditions. The model proposed by Hadiyanto *et al*. (2007a) is a sequential model that includes the chain of phenomena starting from heat and mass transfer followed by the state transformations and finally the product quality formation. The heat and mass transfer part of the model was based on well recognized relationships for transport phenomena (Zhang and Datta, 2006). The state transformations and quality formation, however, were derived from qualitative expert knowledge. Several assumptions and simplifications that inevitably had to made, may reduce the reliability of the prediction. As a consequence, to prove the reliability and for the future use of the model, a check on the validity of the model prediction is required.

Several papers reported on model validation of baking processes (for example Zanoni *et al.*,1993; Thorvaldson and Janestad, 1999; Lostie *et al.*, 2002; Zheleva and Kambourova, 2005). However, their

*Corresponding author.
Email: *hady.hadiyanto@gmail.com*

researches were mostly focused on the heat and mass transfer phenomena during baking and missing the link with product quality. Some studies did consider quality aspects and parameter estimation. For example, Lostie *et al*. (2003) studied the effect of volume expansion, and Zanoni *et al.* (1995) reported about brownness development. Our challenge was to extend and put the previous work on a firmer basis by validation of the combined model for heat and mass transfer and a series of qualities.

The aim of this work is to evaluate the model for the formation of bakery product quality (Hadiyanto *et al*., 2007a), and to adapt parameters in the model where necessary. Because the baking model is a sequential model, in the sense that the heat and mass transport is not influenced by the product transformations, the validation can also be done in a sequential way; starting from heat and mass transfer related measurements, then the state transformations and finally the quality measurements. The model is calibrated against experiments with constant operational conditions.

Materials and Methods

Dough preparation

Dough was prepared from a mixture of 500 g flour (C1000 bread mixture for white and ciabatta, with composition per 100 g flour : 50% starch, 8.6% protein, 5% fat, 2% yeast, 0.5% salt) and 300 g water in a dough mixer (Inventum BM20) at medium speed for 3 minutes and 37oC. Then the dough was kneaded for 5 min and the product was placed on the baking plate for 30 min to rise at room temperature. The initial weight of the dough and the height of the formed sample were measured before the sample was put in the oven. The initial size of the dough was the same for all experiments with diameter 0.08 m and height 0.04 m, the initial weight was 250 g.

Equipment set-up

An overview of the baking equipment is shown in Figure 1. The domestic oven was expanded with an external microwave source, which can provide an adjustable power. A monitoring and control system for oven and microwave heating was developed in Labview. This control system monitors the temperatures and allows for a dynamic operation of the convective and microwave heat sources. Here, input trajectories for convective and microwave heating were based on four intervals of piece-wise constant heating input for the oven and microwave system.

Temperatures in the oven and in the product were measured with optical temperature sensors using an optical slip ring (OSR) with multi probes (FISO Technology, Sainte-Foy, Quebec, Canada). The OSR system with four fiber-optic sensors was mounted on the oven such that it was possible to measure the temperatures during processing on a rotating table. The maximum temperature for the sensors was 250°C with accuracy of 1°C.

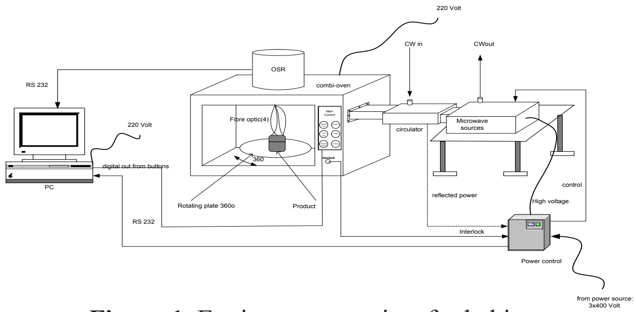

Figure 1. Equipment overview for baking

Baking experiment

Conventional oven baking was performed in the oven at a controlled temperature level (set up at 200°C) and time (set up at 30 min). The oven was preheated for 10 min to reach the setting temperature before the dough was placed in the oven. To follow the development of the product formation during baking, several bread samples with the same initial properties were baked for different time periods. Other experiments were performed for a combination of convective and microwave heating with an adjustable microwave source. For experiments with constant microwave input the dissipated power level was set to 100 W.

Quality analysis

The color of the bread product was measured with a Minolta chromatometer (CR-200, Japan) using the *L*, *a*, and *b* color scale (Hunter method). Triplicate measurements were done at different positions on the bread surface and bread crumb, and then the mean value was calculated. The colour change (ΔE) compared to a calibrated reference was calculated from Eq .1 where the reference color is represented by L_0, a_0 and b_0.

$$\Delta E = \sqrt{(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2} \qquad (1)$$

A texture analyzer for food products (TA-XT Plus, Stable Micro Systems Ltd., Surrey, UK) was used for the instrumental analysis of the bread crust and crumb. Samples of crust and crumb with size 20 x 30 x 30 mm were subjected to a compression test using the SMS P/2 probe (test speed 1.7 mm/s, distance 6.2 mm). The measurements were done 2 hours after baking.

From the resistance of the probe encountered during penetration a force-deformation curve was constructed. Penetration of the crust occurred at about 3.8 s after the probe touched the sample surface and the force-deformation reached a maximum load of 370 g. These peak values are used to represent the crispness of the product surface (Dogan and Kokini, 2007).

The weight loss during baking was determined by weighting the product before and after baking. The relative weight loss was calculated as

$$w_L = \frac{w_o - w_f}{w_0} \quad (2)$$

Where w_o and w_f denoted the initial and final weight of product, respectively. Similarly, the volume extension (*e*) was obtained by measuring the height of the bread product before (h_0) and after (h_f) baking and was calculated as:

$$e = \frac{h_f - h_0}{h_0} \quad (3)$$

Model development

Calculations for the product were done using a 2D spatial model, since the sample breads were much longer than their wide. As the bread samples were symmetric, it was satisfied to do the calculations for a half cross-sectional area. The geometry of the cross-sectional area of the product is given in Figure 2. The evaluated center and surface locations are indicated by point 1 and 2. A symmetry boundary was applied along the center plane and flux boundary conditions were used along the surface of product. The bottom of product was contacted with plate, where it gave conductive heating to the product. The model is a combination of three sequential processes: heat and mass transfer, product transformation and translation to quality, which are explained separately in the following sections. The symbols are explained in the appended notation list.

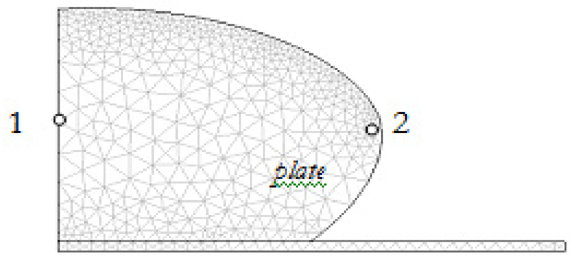

Figure 2. The product domain for simulation. Point 1 and 2 represent the center and surface points of the product for which the results are discussed (height 0.04 m, radius 0.04 m).

Heat and mass transfer

Energy balance

The energy balance covers heat conduction, evaporation and condensation heat, and convection heat transport due to the fluxes of water vapor and CO_2 (eq. 4). The second term is due to the change of product height.

$$\rho_s c_p \frac{\partial T}{\partial t} + \frac{\rho_s \lambda}{1+e}\frac{\partial e}{\partial t} = \nabla.(k\nabla T) - \lambda I_v - \nabla(m_v H_v) - \nabla(m_c H_c) \quad (4)$$

Mass balances

The mass balances for liquid water, water vapor and CO_2 gas are given in Eqs. 5-7. The changes of liquid water in the product are the result of the rates of diffusion and evaporation (Iv). Water vapor is considered as an ideal gas which is in equilibrium with liquid water. The vapor concentration is a function of the rates diffusion and evaporation rate as well.

$$\rho_s \frac{\partial W}{\partial t} + \frac{\rho_s . W}{1+e}\frac{\partial e}{\partial t} = \nabla \phi_w - I_v \quad (5)$$

$$\rho_s \frac{\partial V_v}{\partial t} + \frac{\rho_s . V_v}{1+e}\frac{\partial e}{\partial t} = \nabla \phi_v + I_v \quad (6)$$

$$\rho_s \frac{\partial V_c}{\partial t} + \frac{\rho_s . V_c}{1+e}\frac{\partial e}{\partial t} = \nabla \phi_c + I_c \quad (7)$$

-The flux equations

Flux equations for Eqs. 5-7 are:

$$\phi_w = \rho_s D_w \nabla W \quad (8)$$

$$\phi_v = \rho_s D_{vc} \nabla V_v - m_v \quad (9)$$

$$\phi_c = \rho_s D_{vc} \nabla V_c - m_c \quad (10)$$

The convective mass fluxes of water vapor (m_v) and CO_2 (m_c) depend on local pressure differences, kinematics viscosity (v) and permeability of the product:

$$m_v = -\frac{\kappa}{\nu}\frac{V_v}{V_v + V_c}\nabla P \quad (11)$$

$$m_c = -\frac{\kappa}{\nu}\frac{V_c}{V_v + V_c}\nabla P \quad (12)$$

Hereby the pressure in the product is the sum of partial water vapor pressure and CO_2 pressure which follow from the gas ideal law.

Constitutive relations

Water vapor and CO_2 are considered as an ideal gas and their material balances are derived from Fick's law. The liquid water concentration and water vapor pressure are assumed to be in local equilibrium described by an experimentally derived sorption isotherm (Weijts, 1995) (Eq 13).

$$\frac{P_v}{P_{sat}(T)} = \frac{1.05W}{0.09+W} \quad (13)$$

The evaporation rate (I_v) can be eliminated by combining Eqs 4, 5 and 6 with Eq 13. For the production of CO_2 by yeast or baking soda the empirical expression proposed by Zhang and Datta (2006) is used:

$$I_c = R_{CO}\rho_s \exp\left(-\left(\frac{(T-T_{ref})}{\Delta T_{CO}}\right)^2\right) \quad (14)$$

With R_{CO} is the CO_2 production at $T_{ref.}$ and ΔT_{CO} determines the width of the Gaussian shape function.

The change of product size is represented by the relative extension (*e*) and is caused by the increasing pressure in the gas cells in the dough due to the release and expansion of water vapor and CO_2 from baking powder or yeast (Fan, Mitchell and Blanshard, 1999; Zhang and Datta, 2005). Hadiyanto *et al.* (2007a) considered bread as a Kelvin-Voigt visco-elastic material for which the rate of deformation is proportional to the pressure difference between the internal product pressure (*P*) and the ambient pressure (P_{atm}) minus the elastic strain. A similar expression was proposed by Lostie *et al.* (2002). The two parameters involve in this expression are viscosity (η) and the elasticity (*E*) of product.

$$\eta\frac{de}{dt} + Ee = P - P_{atm} \quad (15)$$

The initial values for heat and mass transfer are given by:

$$T(0)=T_0 \qquad W(0)=W_0 \qquad e(0)=0 \quad P_c(0)=P_{amb}-P_v(0) \quad (16)$$

The boundary conditions of model are given by Eq 17-19. At the boundary, the evaporation is mainly caused by the moisture gradient due to convective heat.

- Fluxes at the surface

$$k\nabla T = h_c(T_{oven}-T_s) - \lambda.\rho_s.D_w\nabla(W_s) \quad (17)$$

$$D_{vc}\nabla V_v = h_v(V_{ext} - V_{v,s}) \quad (18)$$

- Symmetry at the center of the product

$$\nabla T = 0 \qquad \nabla W = 0 \qquad \nabla V_v = 0 \qquad \nabla V_c = 0 \quad (19)$$

The weight loss in the model was determined by calculating the average water content of product, as:

$$w = \frac{\int W\,dV}{\int dV} \quad (20)$$

Where V is volume of product considered for the model calculations.

Brownness

The Brownness of bakery products is mainly the result of the Maillard reaction which produces melanoidins (m_e) as coloring compound. The Maillard reaction can be approximated as a zero order reaction of which the reaction rate depends on the temperature and the water content (Van Boekel, 2006; Hadiyanto *et al.*, 2007a). In the rate equation 21, kme is the Maillard reaction constant and T_o=363 K.

$$\frac{dm_e}{dt} = k_{m_e}\frac{\exp(9a_w)}{2.10^3+\exp(11.3a_w)}.\exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{To}\right)\right] \quad (21)$$

Hadiyanto *et al.* (2007a) used equation 22 to establish the non-linear correlation between the amount of melanoidins and the degree of brownness.

$$brown = 1-(1-brown_0)\exp(-k_{br}\,m_e) \quad (22)$$

Where $brown_0$ is the initial brownness of the dough and k_{br} is a brownness scaling factor. Both k_{me} and k_{br} are empirical values and therefore these two parameters will be adjusted by fitting the model in experimental data estimation.

Crispness

Crispness and softness of bakery products is related to the texture of the product during consumption and are complicated sensory qualities, depending on the product rigidity/elasticity and structure. However, to have an indication of the relative performance of these attribute in the total framework of the model, we propose to simplify the system and link the degree of crispness and softness only to the amount of gelatinization (α) and the difference between the product temperature and the glass transition temperature of the starch in the product (δT=T_r-T_g). The glass transition temperature depends on the moisture content and the sugar/starch ratio (S/Z) for which an empirical relation (Eq. 23) given by (Hadiyanto *et al.*, 2007a) is available.

$$T_{g/m} = 457.1 - 396.32\left(\frac{S}{Z}\right) - 653.21W + 716.76\left(\frac{S}{Z}\right)W + 430.27\left(\frac{S}{Z}\right)^2 + 778.44W^2 - 1424.71\left(\frac{S}{Z}\right)^2 W^2 \quad (23)$$

Products with a negative value for δT are crispy products and crispness reaches a maximum normalized value (crispness=1) when all water is evaporated which occurs for $\delta T = -\delta T_{max}$. For the degree of crispness between $\delta T=0$ to $\delta T=-\delta T_{max}$ a linear expression is used. The parameter, $-\delta T_{max}$ will be adapted to fit the maximally encountered texture range.

$$crispness = \begin{cases} 0, & if \quad \delta T > 0 \\ -\delta T/\delta T_{max}, & if \quad -\delta T_{max} < \delta T < 0 \\ 1, & if \quad \delta T < -\delta T_{max} \end{cases} \quad (24)$$

Results and Discussions

Optimized parameters

The results of parameter estimation are listed in Table 1. The obtained parameter values are compared to literature values. Thermal conductivity is 0.373 W/m K and corresponds to the values obtained by Jury *et al*. (2007) who reported thermal conductivity values for bread in the range 0.1-0.4 W/m K. The value of the heat transfer coefficient, which is strongly linked to the bread surface temperature, is 26.09 W/m^2 K and is close to the value obtained by Zanoni *et al.* (1995) and also in the range (20-50 W/m^2 K) for natural convection heating reported by Demirkol *et al*. (2006). This parameter depends on equipment characteristics (like air circulation around the product) and therefore may differ from oven to oven. Rask (1989) reported for bread with water content in the range 33-45% specific heat values between 2151-2626 J/kg K. The estimated the value from our experiments falls in the middle of this range.

The parameters for the quality model are also presented in Table 1. For the Maillard reaction (k_{me}) and brownness constants (k_{br}) are estimated from E measurements. The obtained values for these parameters are slightly below the previously reported values, just as the maximum temperature difference for the glass transition temperature (δT_{max}). The estimated elasticity coefficient (ΔE) is above the literature value for a cake type of product.

Table 1. Estimated parameters value and literature references

Parameter	Estimated value	Literature/start value	References
c_p [J/kg.K]	2361.2	2151-2626	Rask,(1989)
k [W/m K]	0.373	0.1-0.4	Jury *et al.*(2007)
h_c [W/m^2.K]	26.09	20-50	Demirkol *et al.*(2006)
		30	Zanoni *et al.*(1994)
D_w [m/s]	$1.7 10^{-10}$	$1.3\text{-}3.5.10^{-10}$	Karathanos*et al.*(1995)
k_{me} [-]	0.0039	0.0049	Hadiyanto *et al.*(2007)
k_{br} [-]	0.2241	0.23	Hadiyanto *et al.*(2007)
E [N/m^2]	1.09E6	1.5E5	Marcotte and Chen (2004)
dT_{max} [^{o}C]	138.9	150	Hadiyanto *et al.*(2007)

Evaluation of the temperature trajectories

Figure 3 shows the development of the temperature at the crust and in the product center for convective baking and the combination of convective-microwave baking. Both experiments show that the product temperature at the surface increases rapidly at the beginning. This implies that evaporation at the surface is quick and the surface temperature goes quickly towards the oven temperature. During the full baking time there is enough water available in the product center to sustain a water activity near 100% and therefore the product temperature in the center increases only slowly to the boiling temperature (100^{o}C). Application of combined microwave and convective heating enhances the water evaporation in the product and results in a faster temperature rise in the center than with only convective baking (compare Figures 3a and 3b).

The agreement between experiments and model is in line with the results reported in the literature (Thorvaldsson and Janestad, 1999; Zheleva and Kambourova, 2005; Zhang and Datta, 2006). However, there is systematic deviation between the model and the experiments. This indicates that there is potential for further model improvement; for example to include the temperature and moisture dependency of parameters for specific heat coefficient, thermal conductivity and diffusivity as shown by work of Lostie *et al.* (2003) and Zheleva and Kambourova (2005). Furthermore it should be noted that the gas permeability was assumed to be constant, which should actually be a function of the product porosity, which changes during the baking process.

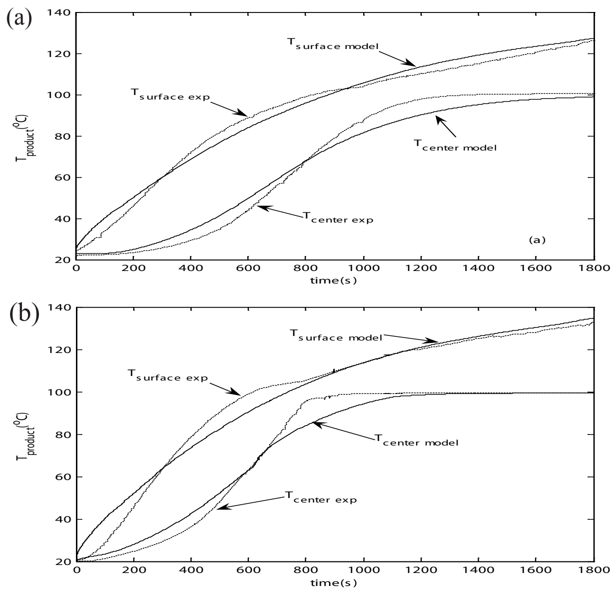

Figure 3. Product temperature during baking experiments (dashed line) and for model calculations (solid line) with convective heating (a) and the combination of convective and microwave heating (b).

Evaluation of Weight loss

The weight loss is due to the amount of water evaporated from the product during baking and depends on the baking processes. The weight loss for the two distinct baking operations is given in Figure 4. In total 10-20% of water is evaporated during baking. The weight loss for convective heating is small in the initial phase and increases exponentially after 900 seconds when the temperature in the product center exceeds 70°C. During combined heating baking water evaporation is enhanced. After already 600-700 seconds the temperature in the center of the product is around 70°C, after which the weight loss starts to increase. Microwave heat accelerates the evaporation of water in the product and might be used to control the water content inside the product. There is a good correspondence between experiment and model after adjustment. However, the evaporation rate is overestimated for product temperatures in the range 70-95°C (600-1200 s), which is the same period where the temperature is overestimated by the model.

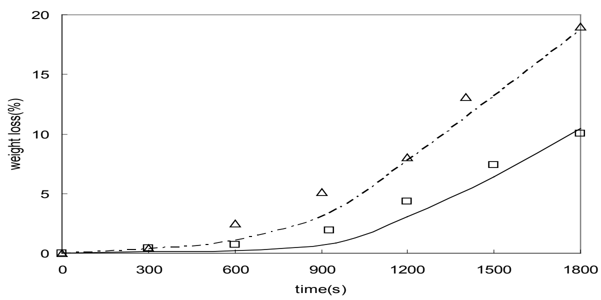

Figure 4. Product weight loss during baking with convective heating (□ : experiment; solid line: model) and combined microwave–convective heating (Δ: experiment; dashed line: model).

Evaluation of Height extension

The product size was measured for different baking times (see Figure 9). The size increases gradually until 1000 seconds of baking. The extension is result of the increase of internal pressure caused by the CO_2 gas production and the evaporation of water. Model predictions and experimental results are reasonably well. After 1200 seconds the size of product starts to decrease as a result of the decreasing pressure in the product and other non-modeled factors such as the change in gas permeability, but the results are not accurate enough to conclude that this is an essential effect.

Figure 5 shows that combined heating gives a faster development of product size, which is possible due to the increased water evaporation rate (see also section of weight loss). For convective heating at 200°C the product size increases up to 1.2 times above the initial size, while the microwave heating 100 W yields a size around 1.4 times above the initial size.

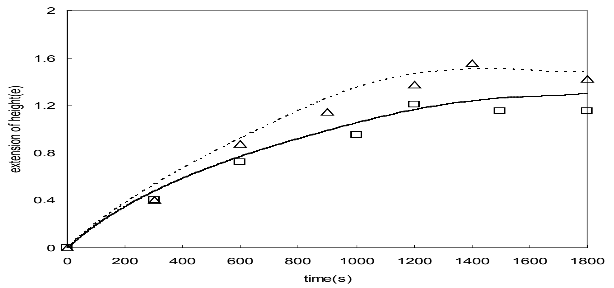

Figure 5. Height extension during baking with convective heating (□: experiment; solid line: model) and combined microwave–convective heating (Δ: experiment; dashed line: model).

Brownness development

Product brownness is mainly the result of the Maillard reaction. The intensity of the color, which ranges from pale yellow to very dark brown, depends on the intensity of this reaction (Henares *et al.*, 2006). Measured brownness values are in the range of ΔE = 24.35 for the initial dough color (pale), to ΔE = 67.12 for the highest value for a black product (Figure 6).

ΔE = 24.35 27.37 37.19 43.57 57.0 67.12

Figure 6. Formation of color during conventional baking. The ΔE value is indicated

Figure 7 shows the correlation between the predicted brownness from the model and color measurement based on the Hunter method (Zanoni *et al.*, 1995). The fair correlation implies that after parameter adjustment brownness is predicted satisfactorily and that the proposed relations (Eqs 21 and 22) can be considered valid.

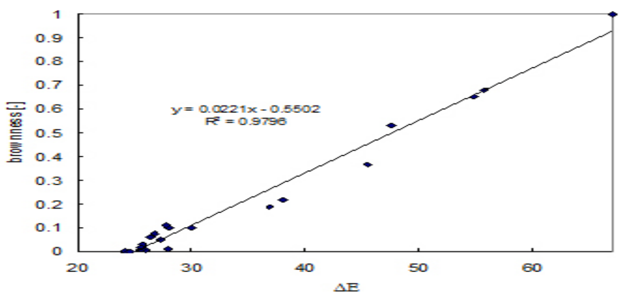

Figure 7. Correlation between brownness and measured ΔE values

In Figure 8 the brownness development during baking is given. The color development for the surface is significant; in the center the color changes are small. The difference in color formation between convective and combined heating operations is

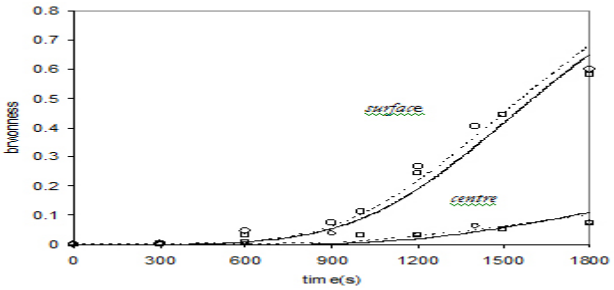

Figure 8. Color developments during baking in the center of the product and at the crust. Results for convective heating (□: experiment; solid line: model) and combined microwave–convective heating (O: experiment; dashed line: model).

minimal. These results are in agreement with the observations reported by Sumnu *et al*. (2001) and Icoz *et al.* (2004).

Crispness

The degree of crispness is in this study directly coupled to the maximum force required to break bread samples by the texture analyzer. Loads in the range 27 g to 512 g are linearly mapped to a crispness range from 0 to 1 (see Figure 9). The scaling is obviously dominated by one extreme loading, but the high correlation with the other measurements indicates that the use of the glass transition temperature in equations 23 as a predictor for the penetration force is a proper choice.

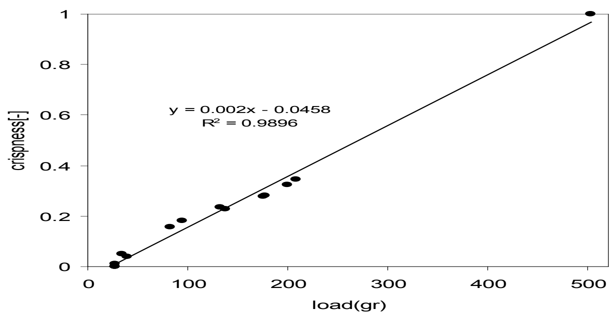

Figure 9. Correlation between crispness and load values

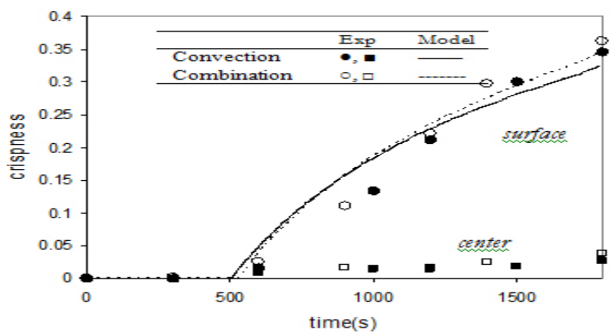

Figure 10. Crispness as a function of baking time. Experimental results (marker) and model simulation (line) for convective heating and combined heating inputs in the surface and center of product.

The crispness as a function of baking time is given in Figure 10. Compared to convective heating, the combination of convective heating and microwave gives only a small difference in crispness. This effect is result of the use of the microwave which generates heat inside the product and only partly affects the surface.

Conclusions

The calibration set was obtained from baking experiments performed under constant baking temperatures and constant input of microwave power during 30 minutes and for a dynamic operation for 2.5 hours including a cooling period. The product quality was measured as a function of baking time at different positions (center and near surface) in the product.

With adjustment of the key parameters in the heat and mass transfer formulation, the model could predict the internal and surface temperatures well. The volume extension could be predicted well for most of the baking process, but still showed some deviation on the observed volume reduction in the final stage of the process. The product quality attributes brownness (based on zero order production of melanoïdines) and crispiness (based on the offset of the predicted glass transition temperature) could be well correlated with color and penetration (texture analyzer) measurements, respectively. Moreover, it was shown that microwave heating hardly affects surface properties as color and crispness, but is an effective tool to control the water content of products.

Nevertheless, the calibration and validation results show that it is possible with an integrated model, which encompasses the heat and moisture transfer and some important transformation, to predict the relative change and absolute value of some key product qualities, as function of the imposed process conditions. The main benefit is that such a model can thus be used to explore the all the degrees of freedom which are offered by the dynamic variation of process conditions and process design, and to directly show the consequences on the product quality attributes.

Acknowledgement

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