CHEMICAL ENGINEERING TRANSACTIONS
VOL. 45, 2015
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216
DOI: 10.3303/CET1545081

Studying Oven Technology towards the Energy Consumption Optimisation for the Baking Process

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A recent guideline from the European Commission declared that several highly energy consuming domestic equipment should be better regulated or avoided at all in the near future. Together with this, several EU nations are abandoning the gas ovens in favour of the electric ones, also due to the home energy rating regulations, that make impossible to get the highest rating with gas ovens. Due to this fact, the study of the technologies related to the energy efficiency in cooking is increasingly developing. The combination of several energy sources (e.g. forced convection, irradiation, microwave, etc.), as well as optimisation of each of them, is an emerging target for oven manufacturers, in matter of oven design and better use of the oven capabilities.
Within this context, an energy consumption analysis and optimisation is targeted in this work, by the application of a bread baking model, validated on experimental data. Each source of energy is given the due importance and the practically applicable process solutions are compared. A basic quality standard is guaranteed by taking into account some quality markers, which are relevant on the basis of a consumer point of view. This work is a part of a more comprehensive study on oven cooking and energy integration, and could lead to practical applications in the design of energy efficient cooking programs.

1. Introduction and scopes

From the energy viewpoint, food cooking can be seen as a process that often requires energy of different kinds to make the raw material subject to chemical and physical transformations, undergoing specific quality constraints (Brenna et al., 1998). Quality can be related to different aspects of food consumption, e.g. microbiological safety, food texture, internal and surface colour, nutritional value, controlled origin, authenticity, etc. (Capozzi and Bordoni, 2013).
Commercial electric ovens are part of the domestic equipment that requires a huge amount of energy to pursue the mentioned transformation, through the use of few technologies such as forced hot air convection, irradiation and, sometimes, microwaves. New technologies to increase the energy efficiency of ovens, for instance, pulsed electric fields (PEF) (see application on carrots (Gachovska et al., 2008) and apple (Wiktor et al., 2013) drying), ohmic heating (Russo et al., 2014), jet impingement (Brenna et al., 1998) are very promising techniques, which are still under investigation at prototype level, but almost never reached the market due to relative technological issues (e.g. production cost). For this reason, while many researchers are focusing on the new technologies, some are more interested in optimising the food processing based on the consolidated technologies (Khatir et al., 2012). This could be made through the assessment of the energy demand of food together to that related to the process itself, belonging to a combination of energy sources. A possible approach could consider this assessment and the related optimisation to be subject to selected quality constraints, based on a specific application, i.e. bread baking, and taking advantage of an appropriate model, validated on experimental data in a previous paper from the authors (Papasidero et al., 2015a). The quality parameters related to the constraints can be identified

Please cite this article as: Papasidero D., Corbetta M., Pierucci S., Pirola C., Manenti F., 2015, Studying oven technology towards the energy consumption optimisation for the baking process, Chemical Engineering Transactions, 45, 481-486 DOI:10.3303/CET1545081

from the topic-related literature to take into account the effects of the process to the product (Hadiyanto et al., 2007).

While the study of consolidated energy sources application, as well as the choice of a single bakery product, could seem limited, the presented approach could be easily extended to the new cooking facilities (and technologies) and to different food (see for instance the paper from Papasidero et al. (2015b) on roast beef cooking) by assessing on one hand the related impact, on the other hand the specific quality constraints based on markers identification (Papasidero et al., 2014).

2. Model assumptions and equations

The bread baking process is here described considering the following assumptions:

- Bread volume is considered constant during the process
- Bread is treated as homogenized multiphase medium (Quang et al., 2011) (i.e. separate mass balances for liquid water and water vapour)
- Thermal properties are calculated based on a mixture approach taking into account food macro-composition (water, fibres, fats, carbohydrates, proteins). (Choi and Okos, 1986)
- Evaporation can occur in the whole bread volume when the local temperature exceeds 100 °C. This phenomena is taken into account by directly coupling mass and thermal balances, meaning that a plateau phase is locally reached at 100 °C until all the available water is evaporated (generally experimentally well-acquainted, e.g. (Nicolas et al., 2014)). Two numerical step functions are applied to activate/inactivate the evaporation term in the balances, as function of temperature and water availability.
- Water diffusion is only dependent on a concentration gradient by considering an effective diffusivity.
- The process conditions are accounted by the introduction of a convection heat exchange coefficient and of an irradiation term to be used in the boundary condition for the thermal balance.

The resulting model equations are:

$$\frac{\partial C_w^l}{\partial t} + \nabla \cdot (D_w^l \nabla C_w^l) = \kappa_T \kappa_C (-I_v) \tag{1}$$

$$\frac{\partial C_w^v}{\partial t} + \nabla \cdot (D_w^v \nabla C_w^v) = \kappa_T \kappa_C I_v \tag{2}$$

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (\lambda \nabla T) = \kappa_T \kappa_C I_v H_{ev} \tag{3}$$

The first and the second equations represent the liquid water and the water vapor mass balances, while the last represents the thermal balance. The parameters κ_C and κ_T are step functions to take into account the evaporation condition at temperatures higher than 100 °C.

The boundary conditions are:

$$\mathbf{n}_w^l \cdot \mathbf{n} = 0 \tag{4}$$

$$\mathbf{n}_w^v \cdot \mathbf{n} = K_m (C_w^v - C_{w,ext}^v) \tag{5}$$

$$\mathbf{Q} \cdot \mathbf{n} = h(T - T_{air}) + \sigma \varepsilon (T_{coil}^4 - T^4) \tag{6}$$

K_m represent the vapour mass exchange coefficient, h the heat exchange coefficient, σ is the Stefan-Boltzmann constant and ε the emissivity of the bread, supposed to be equal to 0.9. For concision, the initial conditions and the supporting equations to calculate the mixture proprieties are not shown here, but can be found on the original paper.

3. Energy Impact

To define an optimisation strategy it is essential to define the objective function. In case of energy evaluation and optimisation, one could refer to a life cycle assessment (LCA) approach, where the potential impact related to identified energy and material inputs and environmental releases is evaluated, to have a full perspective on the process (Sørensen, 2011). Anyway, a simpler application could basically be founded on the evaluation of the power needed by the product to be opportunely cooked, and a "cooking program" could then be based on the combined use of the specific energy sources, rather than on different global variables, that could require the identification of the geographical origin of the input

sources. By the way, both of the approaches can exploit the same (and more) quality constraints, representing a target range that should not be overstep, to fulfil the consumer's acceptability.
The authors prefer to focus on the simpler approach, mainly to address the methodology, while they recognize the relevance of the LCA analyses as a powerful tool for the attainment of the same purpose from a more comprehensive perspective (Van Holderbeke et al., 2004).
Within this context, the energy input is calculated based on the time integral of the heat flux on the bread surface. Even though this evaluation should be more comprehensively based on the effective consumed energy of the oven, since the focus is more on the energy needed to process the dough to become bread, the calculations are based on the heat absorbed by the bread itself.

4. Quality constraints

As stated in the previous sections, some quality constraints should account for the acceptability of the product. Among the possible attributes to take into account, two were selected to be representative: surface browning and crumb formation.
The first is a consequence of the chemical reactions producing coloured compounds from sugars (caramelization, see (Quintas et al., 2007)) and from sugar and aminoacids interaction (Maillard reaction, see (Ledl and Schleicher, 1990)). It was stated in literature that some compounds coming from that reactions can be referred as color markers. Otherwise, a general approach could describe the surface lightness (the "L" parameter, dimensionless and ranging from 0 to 100, from the standard CIE L*a*b color scale) to be dependent on a kinetic law itself. For this reason, we took into account the use of a first-order kinetic law from a recent paper (Purlis and Salvadori, 2009) to describe the lightness dynamics avoiding, for the moment being, the formation of coloured chemical compounds:

$$\frac{dL}{dt} = -k_{light}(L) \tag{7}$$

where $k_{light} = k_{light,0}\exp(-A/T)$ (min^{-1}), with $k_{light,0} = 7.9233\times10^6 + 2.7397\times10^6 / a_w$ and $A = 9.13657\times10^3 + 49.4738 / a_w$, being a_w the water activity.
The first part of the activation energy parameter (A) has been increased by 5 % with respect to the original value to better take into account the differences from the present case from the literature one.
The second attribute, crumb formation, was addressed to be a consequence of the state transitions of the dough in the inner part. Starch gelatinization is potentially representative of this transition. A kinetic law that permit to assess a gelatinization degree (dimensionless) is taken from literature (Zanoni et al., 1995):

$$\frac{d\alpha}{dt} = k_{gel}(\alpha_{\max} - \alpha) \tag{8}$$

with $k_{gel} = 2.8\times10^{18}\exp(-139{,}000/RT)$ (s^{-1})
In this case, a maximum gelatinization degree was considered based on (Hadiyanto et al., 2007), as a function of the dough composition (in term of free sugars, starch, water content and possible water-binding compounds).
Obviously, the surface colour has a range of acceptability, which ends with dark brown before the bread gets burned. Within this sense, a minimum and maximum lightness is identified and used for calculations. On the contrary, the internal crumb formation is given a minimum gelatinization degree condition to get to satisfactory attributes, while the upper bound is considered to be acceptable (see Table 1).

Table 1: Upper and lower values for the optimisation constraints

Attribute	Marker	Lower Bound	Upper Bound	Units
Browning	Lightness, L	40	60	(dimensionless)
Crumb Formation	Gelatinization Degree, α	0.65	-	(dimensionless)

5. Optimisation procedure

Bread baking is a batch process, like many other food processes (see for instance Cisero et al. (2000) for microbial generation of aroma and Khatir et al. (2013) also related to the bread baking process). Several strategies could be applied to get a reasonable dynamic optimisation (see for instance the paper from Kameswaran and Biegler (2006) for a review of innovative strategies of general dynamic optimisation and

that of Pérez-Correa et al. (2008) for a specific reference to food processes). Among these, the easiest to implement concerns the division of the time domain into discrete intervals, every of which has the possibility to turn convection or irradiation on or off by changing the air and coil temperatures in order to use convection, irradiation or both of them within a selected range of operation. Indeed, this is just a simplification, since the best solution would be achieved by selecting continuous functions instead of discrete stepwise functions. In addition, an optimisation strategy should include the possibility to stop the process if a satisfactory condition is reached.
Within this context, the authors chose to apply this simplified approach to get a reasonable result without relevant calculation times, due to the fact that every step of the model solution could need minutes.
Due to these considerations, the optimisation strategy will consist in the following steps:

1. The time domain is divided into N intervals of the same size.
2. An initial set of temperatures, $T_{conv,j}$ and $T_{irr,j}$, is selected as the starting values in the N intervals.
3. The model is solved and the objective function at the end of the process is evaluated
4. The variable related to the constraints are analysed to evaluate the acceptability of the product
5. If the product is acceptable, the procedure is iterated from point number 2 by opportunely changing the temperatures of each interval, until the objective function reaches a minimum.

The boundaries for the convection and irradiation temperature are listed in the table below:

Table 2: Boundary values for the optimisation variables

Variable	Marker	Lower Bound	Upper Bound	Units
$T_{conv,j}$	Convection Air Temperature	120	250	°C
$T_{irr,j}$	Irradiating Coil Temperature	120	250*	°C

*except from $T_{irr,0}$, with an Upper bound equal to 223.15 °C, due to numerical instability of the solution.

The numerical implementation has been made through the use of the software COMSOL Multiphysics 4.3a (COMSOL-AB, 2012) , enabling the solution of the PDE model with a finite element approach. The optimisation is based on the optimisation module from the same program and based on N = 4 equal time intervals of 600 s (the total process time is 2,400 s).

6. Results and discussion

The base case is represented by a baking process with the same process time (2,400 s) and a constant temperature of 180 °C in the oven (both for irradiation and air). It has been compared to the optimised case to analyse the results (see figures below). As showed from Figure 3, the optimisation procedure suggested to use a higher temperature both for convection and irradiation in the initial phase of the optimised case. In this phase, the dough gets heated but the surface temperature is still not too high to cause browning. Gelatinization, on the other hand, starts at lower temperatures, approaching the requested values in the first half of the baking process. When the surface temperature reaches about 80 °C browning phenomena get started, the reaching a considerable browning rate at approximately 120 °C (first time step, 600 s).

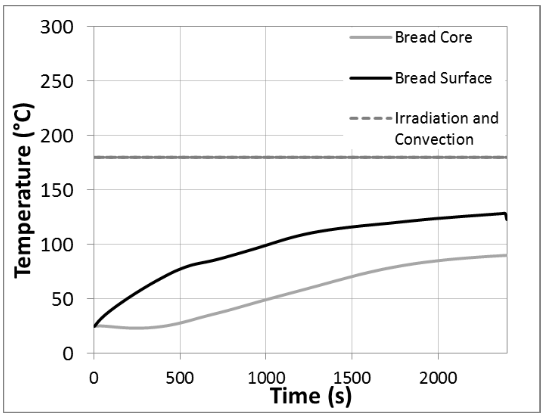

Figure 1: Bread and oven temperature profiles (base case)

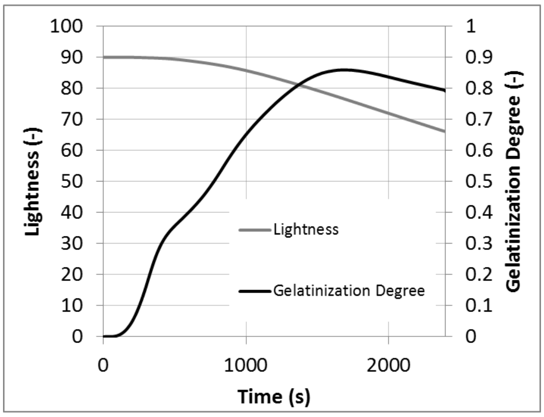

Figure 2: Lightness and Gelatinization degree (base case)

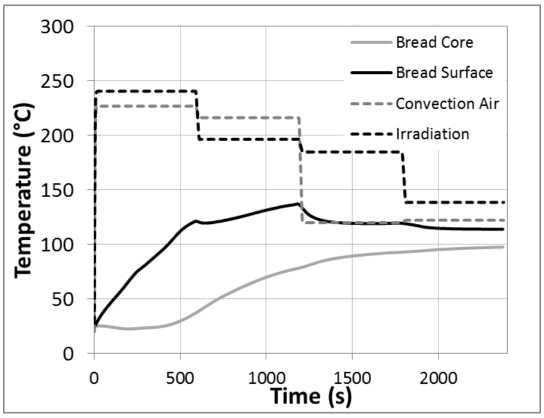

Figure 3: Bread and oven temperature profiles (optimised case)

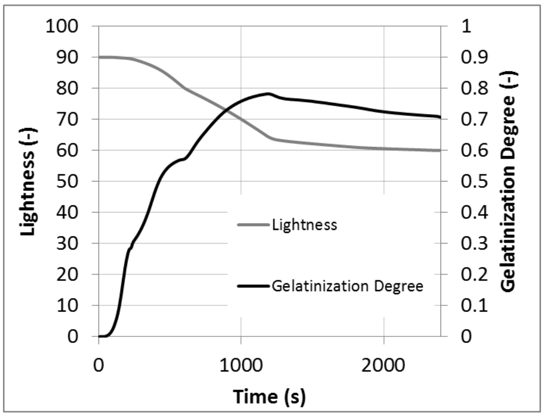

Figure 4: Lightness and Gelatinization degree (optimised case)

To avoid excessive lightness decrease, the algorithm suggests for a decrease in temperature in the next step. The second part of the process shows a drop in the convection air temperature, indicating that the surface temperature is adequate for browning, but since the gelatinization target is already reached, no need for higher gelatinization degree. In this case, we see a temperature drop for the surface, indicating that while the heat is still penetrating due to the Fourier's law (by thermal conduction), the surface does not need for higher temperatures. In the last time period both of the temperatures lower to minimize the energy transferred to the product. It is interesting to think that with a different approach that could include the stop of the baking process, one could predict a lower cooking time. In addition, the gelatinization degree shows a decrease in the last part due to the change in the maximum degree associated with a water activity decrease. The energy absorbed by the bread for the optimal solution is 1.40 MJ, with a 20 % save with respect to the base case, which leads to an absorbed energy value of 1.75 MJ, In that case the final gelatinization degree is 0.791 and the lightness value is equal to 66.2 (see Figure 2 and Figure 4). The optimal values for the temperatures in the four time periods of 600 s are reported in Table 3, as well as the initial values used for the simulations.

Table 3: Initial and optimal values for the temperature profiles (convection and irradiation)

Temperature (°C)	$T_{conv,0}$	$T_{conv,1}$	$T_{conv,2}$	$T_{conv,3}$	$T_{irr,0}$	$T_{irr,1}$	$T_{irr,2}$	$T_{irr,3}$
Initial Value	200	200	200	200	200	200	200	200
Optimal Value	240.5603	196.4859	184.8986	138.6634	226.85	216.2981	120	122.2969

It is important to consider that this procedure would benefit for the use of many shorter time period to get a discrete profile more similar to a continuous one. Indeed, the optimisation could have reached just a local minimum, and further considerations on how to improve the model and the optimisation could be made.
A single iteration for the optimisation requires between 3 and 4 min with an Intel™ Core-i7® processor and this led to a total optimisation time of 12 h with about 150 iterations.

7. Conclusions and perspectives

The present work shows an approach to optimise the total energy absorbed by the product, in this case bread, in a batch process with different energy sources. The optimisation shows that the highest temperatures and the most important energy contribution is related to the initial dough heating part, while the final part is more related to reach the quality targets and require less energy. Indeed, the made assumptions limit the practical applicability of the procedure to real processes, but give some indications on how to proceed for the next steps. A dynamic optimisation procedure that includes continuous temperature profiles rather than a discrete one and that could predict the stop of the process in case of achieved quality targets would be beneficial to get a higher energy saving. The possibility to include a LCA analysis to get a more comprehensive objective function could extend the interest of the purpose, and could be applicable to different food processes. The use of other energy sources can be taken into account, as well.

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