Journal of Food Engineering 137 (2014) 39–50

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Optimal design of bread baking: Numerical investigation on combined convective and infrared heating

Emmanuel Purlis *

Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA – CONICET La Plata), Facultad de Ciencias Exactas, UNLP, 47 y 116, La Plata 1900, Argentina

ARTICLE INFO

Article history:
Received 16 September 2013
Received in revised form 4 February 2014
Accepted 29 March 2014
Available online 4 April 2014

Keywords:
Heat and mass transfer
Optimisation
Modelling
Simulation
Control
Bakery products

ABSTRACT

This paper presents a theoretical approach for optimal design focused on baking, which is based on knowledge about transport phenomena and physicochemical changes occurring during the process. Such approach consists in identifying and defining the critical and quality times of the process, and to find a technological solution to make equal those times. Then, an optimum process presents the same critical and quality times. As case of study, the conventional bread baking process is analysed, where the critical time is the time necessary to complete the dough/crumb transformation, while the quality time is given by the target value of browning development. The use of infrared heating as additional energy source, besides convection and radiation, is proposed here to obtain optimum processes. The proposed solution gives good results in comparison with conventional baking, improving process outputs such as baking time, weight loss, thermal input, and energy input. Finally, the generalisation of the approach is discussed.

1. Introduction

Optimal design and optimisation (of existing processes) are essential tasks for modern industry. In particular, the bread baking process is of great importance regarding food manufacturing; bread is a staple food and thus its production is relevant from a commercial point of view, besides its cultural relevance. In addition, bread baking is an energy-intensive process due to thermal vaporisation of water occurring in the product. In fact, conventional baking demands a high amount of energy, similar to conventional drying, in comparison with other manufacturing and preservation food processes and operations (involving heat application), e.g. chilling, freezing, canning (Le Bail et al., 2010). Furthermore, baking ovens are usually operated in an empirical way using a trial and error approach without a thorough understanding of the process, leading to an inefficient use of involved resources and therefore, to economical losses (Broyart and Trystram, 2002; Zareifard et al., 2006). Since baking is a traditional process with no microbiological risk *a priori* (assuming that good manufacturing practices are accomplished), expert operators *solve* the optimisation problem by adjusting operating variables for the desired product characteristics (sensory attributes) based on their own experience or ''know-how'' (Allais et al., 2007). Consequently, there is a need for a scientific and comprehensive point of view for optimal design and optimisation of the baking process, regarding the relationship between operating variables (equipment settings), process variables (energy consumption, processing time), and product variables (sensory attributes, quality parameters).

Regarding food process engineering, two different approaches have been applied to solve design issues: empirical-based and physics-based, or inductive and deductive (or fundamental) modelling, respectively (Broyart and Trystram, 2003). The empirical approach aims to find a relationship between inputs (operating conditions, product properties) and outputs (quality attributes of final product) using an experimental data set and a mathematical tool (black box model), e.g. response surface methodology, artificial neural networks. The physics-based approach is based on transport phenomena models coupled with models that describe the physicochemical changes in the product as a function of operating variables. Then, different (numerical) techniques can be applied for process design, optimisation and control, using such models as a representation of the real process. Both approaches have been applied in the context of baking: empirical-based, e.g. Demirekler et al. (2004), Sevimli et al. (2005); physics-based, e.g. Hadiyanto et al. (2008, 2009); combined approach, e.g. Broyart and Trystram (2003). Due to the basis of each methodology, it is expected that the deductive approach provides results of general application and the required viewpoint for optimal design and optimisation previously stated, since there is *critical* knowledge involved, i.e. there is an intention for scientific explanation.

---

* Tel./fax: +54 221 425 4853.
E-mail address: emmanuel@cidca.org.ar

http://dx.doi.org/10.1016/j.jfoodeng.2014.03.033
0260-8774/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

a_w	water activity
C_p	specific heat (J/(kg K))
CT	critical time (min)
D	water (liquid or vapour) diffusion coefficient of product (m^2/s)
E_a	activation energy of starch gelatinisation (J/mol)
E_{tot}	total energy input (J/m^2)
h	heat transfer coefficient (W/(m^2 K))
K	rate constant of starch gelatinisation (s^{-1})
k	thermal conductivity (W/(m K))
K_0	pre-exponential factor in Eq. (8) (s^{-1})
k_b	rate constant of browning (min^{-1})
k_g	mass transfer coefficient (kg/(Pa m^2 s))
L^*	lightness
P	water vapour pressure (Pa)
Q	heat uptake in starch gelatinisation (J)
q_{IR}	infrared (IR) heat flux (W/m^2)
QT	quality time (min)
R, r	radius (m)
R_g	universal gas constant (8.314 J/(K mol))
RH	relative humidity (%)
T	temperature (K)
t	time (s)
TI	thermal input (°C min)
W	water (liquid or vapour) content (kg/kg)

Greek symbols

α	degree of starch gelatinisation
ε	emissivity
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/(m^2 K^4))

Subscripts

∞	ambient
s	solid or surface
sat	saturated

Recently, a theoretical approach was presented to design heating strategies with focus on optimisation and control of the baking process (Purlis, 2012). This approach was proposed to avoid obtaining unbaked products while sensory attributes are satisfied, assuming that the end point of baking is assessed in a sensory or subjective manner (a common practice). As a result of applying this approach to conventional bread baking, multiple baking strategies were found, which would produce completely baked breads but not always correctly browned (*feasible solutions*). Therefore, a second design/optimisation problem can be established. Accordingly, the specific objective of the present work was to propose a solution to this *new* problem. As a general aim, this investigation seeks to contribute to a comprehensive understanding of the baking process and therefore to design, optimise, and control the process in a more efficient way by applying the developed knowledge on transport phenomena and physicochemical changes. The methodology implemented in this work is based on modelling and simulation of the baking process, using previously developed and validated models (i.e. physics-based approach).

2. Methodology

2.1. Case of study

The case of study is conventional baking of French bread (without mould or tin, e.g. *baguette*) in a static or batch, indirect oven (e.g. electric baking oven). This is a typical case of traditional bread baking at small and medium scale production (still the major scale production of bread in countries with agricultural tradition, e.g. France, Argentina). In a conventional baking oven, the generated heat is transferred to the product by three modes: conduction, convection, and radiation. Heat conduction occurs from the hot solid surfaces in direct contact with the product. Such surfaces can be a baking support or any supporting device if no mould is used, e.g. sole, tray, grate, conveyor band. In order to obtain conclusions of general application, heat conduction from solid surfaces is not taken into account in this study; there exists a large diversity regarding this aspect of oven design and configuration. On the other hand, convection and radiation contributions can be studied systematically. Furthermore, steam injection during baking is not considered in this study (for similar reasons as for conduction). An introduction to heat and mass transfer during baking can be found elsewhere (Purlis, 2014).

Focusing on the product, bread baking is considered as a simultaneous heat and mass transfer process occurring in a porous medium, where phase change (i.e. water vaporisation) is supposed to take place in a moving front. Amongst all physical and chemical changes that are generated during baking, which actually determine the quality attributes of final product, starch gelatinisation and browning development are taken as reference reactions in this work. The complete starch gelatinisation ensures the sensory acceptability of the product because it determines the transformation of dough into crumb, i.e. a minimum baking (Zanoni et al., 1995a). On the other hand, surface colour is one of the main (and generally the first) quality features considering preference of consumers, and therefore it is often used to judge the completion of baking (Ahrné et al., 2007). In bakery products, surface colour is an important sensory attribute associated with aroma, taste, appearance, and with the overall quality of food, and certainly has a significant effect on the consumer judgment: colour influences the anticipated oral and olfactory sensations because of the memory of previous eating experiences (Abdullah, 2008).

Other product quality descriptors such as specific volume, porosity, and mechanical properties are also important in baking design since they are associated with texture attributes. However, these variables are also affected by product formulation and other stages in bread making. In addition, complex transformations like oven rise and crust formation, which affect texture properties such as crispness retention, are still under study for their elucidation (Hirte et al., 2012). The same happens with the impact of steaming on crust properties (Altamirano-Fortoul et al., 2012). Nevertheless, the developed approach for baking design is still valid and allows the incorporation of other quality aspects; this will be discussed later.

2.2. Formulation of the design/optimisation problem

The problem to be solved in this work is formulated from results previously reported, which were obtained by the application of a theoretical approach for optimal design/optimisation to conventional bread baking (Purlis, 2012). In such approach, two different times are defined:

- *Critical time* (CT): time necessary to complete the dough/crumb transition.
- *Quality time* (QT): time required to achieve the established target value of a given quality attribute, e.g. browning development.

The CT represents a minimum requirement of the baking process, i.e. to provide products completely baked. On the other hand, the QT is associated with quality aspects determining the preference of the product by consumers. Then, three types of solutions or baking processes are possible:

- *Optimum solutions*: CT = QT; at the same time, all requirements are accomplished.
- *Feasible solutions*: CT < QT; extra time will be necessary (increasing energy consumption) to achieve the sensory quality requirements while the product is already baked (complete dough/crumb transition).
- *Unfeasible solutions*: CT > QT; if quality time is used to determine the end point of the process, unbaked products (incomplete dough/crumb transition) will be obtained. Otherwise, if the process is delayed to complete the minimum baking condition, sensory quality requirements will be different from the target values.

By applying a physics-based or deductive methodology (as defined in Introduction section), a practical criterion based on starch gelatinisation kinetics was established to avoid unfeasible solutions (which are actually possible for various operative conditions): the temperature of the coldest point of the product has to reach 96 °C at least (Purlis, 2011). Afterwards, by utilising the same methodology and this criterion to determine the CT, a wide range of operating conditions were analysed using the CT value to establish the end point of the process instead of the browning development (Purlis, 2012). As a result, feasible solutions are obtained *a priori*; however, if the achieved browning development at the end of baking is equal to the target value (previously established), then a feasible solution is indeed an optimum condition. Nevertheless, most of these optimum conditions would have almost no application since the corresponding baking conditions produce a low degree of browning, e.g. lightness value (L^*) greater than 80, especially for small characteristic length since CT is shorter (Purlis, 2012). Although this situation would be advantageous from the nutritional point of view, typical colour of French bread would not be obtained (Purlis, 2010). In summary, a conventional/traditional baking process (or oven) would lead to feasible solutions mostly, rather than to optimum solutions (if baking time is set to CT). This means that there exists a scope of optimisation of the process under the discussed viewpoint. Therefore, the challenge is to find a way of obtaining optimum solutions for a variety of operating conditions and quality specifications.

2.3. Proposed solution

Taking as starting point a feasible solution (CT < QT), the objective is to reduce QT to CT, i.e. to obtain an optimum solution, for a given set of operating conditions and a target value of browning development. Consequently, the aim is to accelerate the development of browning. To solve this problem, it is proposed to increase the heat input, but only the radiation contribution, not the convective input. That is, if higher values of air velocity are used to increase the contribution of convection to heat transfer, mass transfer rate will also be increased, producing an excessive drying of the product. An alternative for increasing only the contribution of radiation is to incorporate an infrared (IR) heating source in the oven. Infrared heating acts over an external thin layer of the food; this type of radiation cannot penetrate deep in opaque bodies and thus heats up only a few microns inside food so internal heating is not significant (Salagnac et al., 2004). The absorbed energy at surface is then transferred by other mechanisms (e.g. conduction) towards the inside of the sample. For instance, this technology has been applied in combination with microwave heating to overcome browning issues due to low heating rate at surface provided by microwave ovens (Keskin et al., 2004; Krishnamurthy et al., 2008; Rastogi, 2012; Sumnu, 2001; Sumnu et al., 2005).

Therefore, three heat sources are considered in this work: (i) convection, (ii) radiation (default contribution), and (iii) infrared radiation (additional source). Finally, the problem is to find the value of IR heat flux to apply during baking such that QT = CT, for a given set of operating conditions and target quality parameters. The problem and solution procedure (algorithm) are depicted in Fig. 1.

2.4. Simulation of the baking process

Bread baking process is simulated to calculate CT and QT (and other output variables), and to find optimum solutions for several operating conditions (Fig. 1). Temperature and moisture profiles during baking are obtained using a (modified) simultaneous heat and mass transport model, which has been developed and validated previously. Dynamics of starch gelatinisation and browning development are predicted using kinetic models, also reported formerly. The same models (including properties) were used to obtain the results discussed before (Purlis, 2011, 2012). Following, a brief explanation of such models is presented, including the modification made to incorporate infrared heating.

2.4.1. Heat and mass transport model

The transport model includes the main distinguishing features of bread baking, i.e. the rapid heating of bread core and the development of a dry outer crust. Bread baking is considered as a

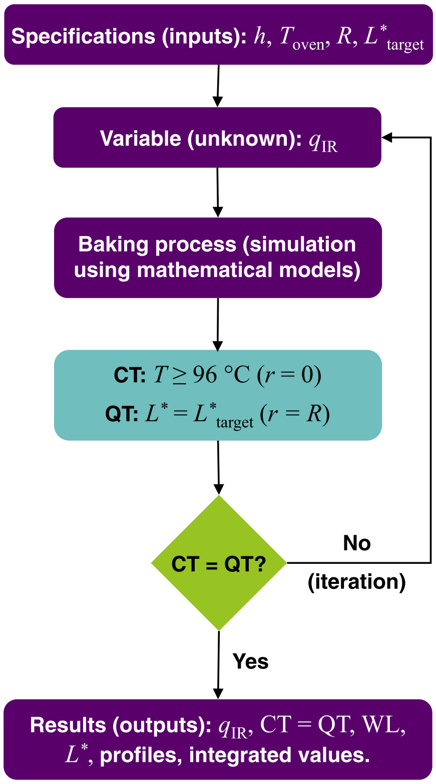

Fig. 1. Scheme of the optimisation problem and proposed solution procedure.

moving boundary problem (MBP) where simultaneous heat and mass transfer with phase change occurs in a porous medium. Bread is modelled as a system containing three different regions: (i) *crumb*: wet inner zone, where temperature does not exceed 100 °C and dehydration does not occur; (ii) *crust*: dry outer zone, where temperature exceeds 100 °C and dehydration occurs; (iii) *evaporation front*: between the crumb and crust, where temperature is ca. 100 °C and water evaporates (liquid–vapour transition).

Mathematically, the MBP is formulated using a physical approach, where phase change is incorporated in the model by defining equivalent thermophysical properties. Major assumptions of the model are the following: (i) bread is homogeneous and continuous; the concept of porous medium is included through effective or apparent thermophysical properties; (ii) heat is transported by conduction inside bread according to Fourier's law, but an effective thermal conductivity is used to incorporate the evaporation–condensation mechanism in heat transfer; (iii) only liquid diffusion in the crumb and only vapour diffusion in the crust are assumed to occur; (iv) volume change is neglected.

Bread (French type) is considered as an infinite cylinder of radius R, so the problem is reduced to a single dimension via the axial symmetry assumption. For initial conditions, uniform temperature and water content are assumed. Governing equations are the following:

Heat balance equation:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) \tag{1}$$

Mass balance equation:

$$\frac{\partial W}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial W}{\partial r}\right) \tag{2}$$

The incorporation of infrared heating is made via the boundary condition for heat balance; it is assumed that penetrative IR energy does not make significant contribution to internal heating, so IR energy is absorbed at surface (Rastogi, 2012; Salagnac et al., 2004). Therefore, the boundary condition at surface for heat balance states that heat arrives to bread by convection, radiation and IR radiation, and is balanced by conduction inside the bread:

$$-k\frac{\partial T}{\partial r} = h(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_\infty^4) + q_{\mathrm{IR}} \tag{3}$$

For the mass balance, water migrating towards the bread surface is balanced by convective flux:

$$-D\rho_s\frac{\partial W}{\partial r} = k_g(P_s(T_s) - P_\infty(T_\infty)) \tag{4}$$

where $P_s = a_w\, P_{sat}(T_s)$ and $P_\infty = (\mathrm{RH}/100)\, P_{sat}(T_\infty)$.

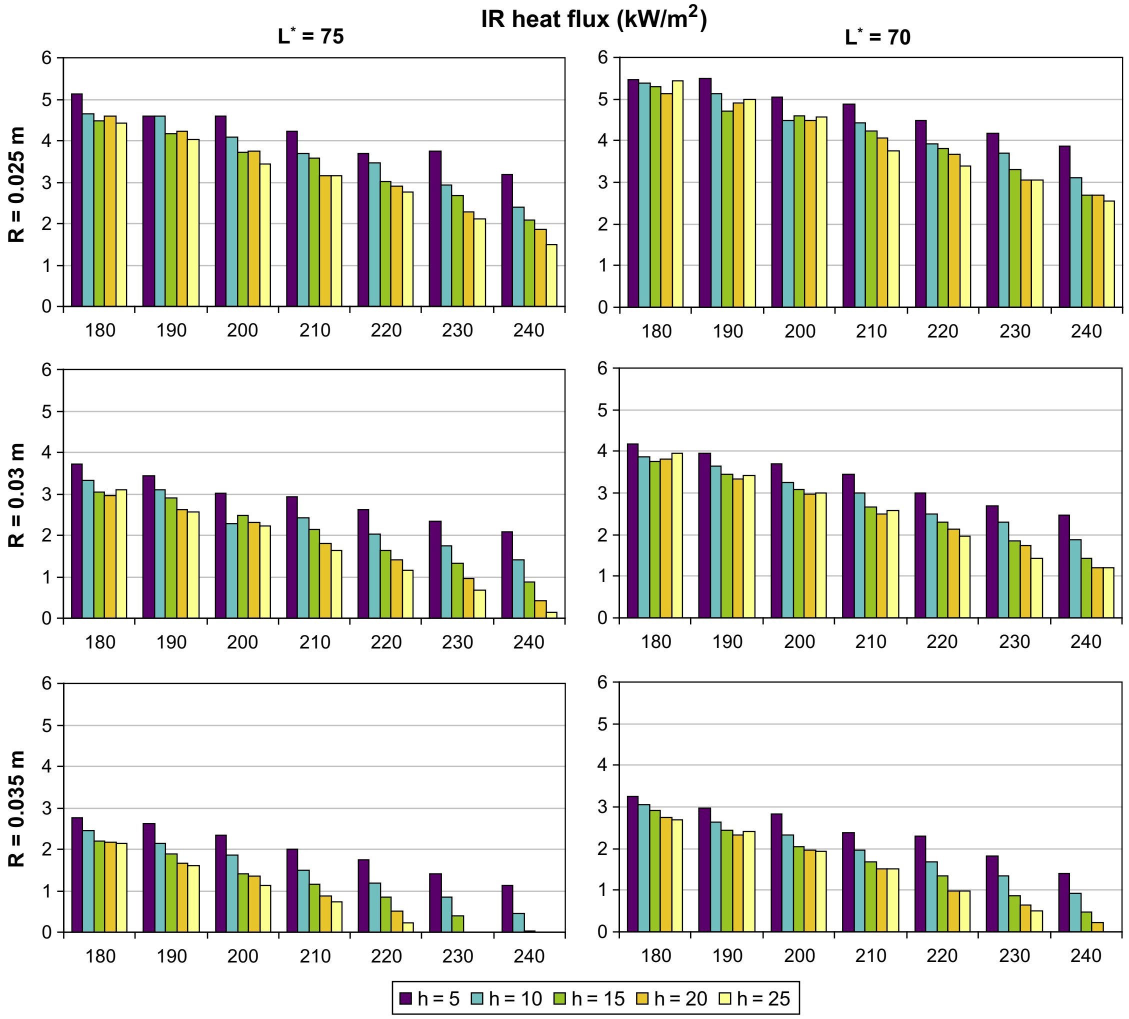

Fig. 2. Values of infrared heat flux for optimum solutions. The absence of a bar (e.g. R = 0.035 m, L^* = 75) indicates that the corresponding condition produces an L^* value lower than the target without application of IR heating (Purlis, 2012).

At the centre of bread, i.e. $r = 0$:

$$\frac{\partial T}{\partial r} = 0 \tag{5}$$

$$\frac{\partial W}{\partial r} = 0 \tag{6}$$

For a more detailed description of the model, including thermo-physical properties, the reader is referred to Purlis and Salvadori (2009a,b, 2010). It is worth noting that this modified model has not been validated directly by using experimental data as the original one. However, in this work we utilise a very similar range of operating conditions (note that application of IR will be significant only when convection and radiation are not important), and indeed the values of temperature and water content obtained by including the IR heating are within the range where the original model (without IR) has been developed and validated.

2.4.2. Kinetic model for starch gelatinisation extent

The extent of starch gelatinisation is computed to verify the complete transition dough/crumb during baking. The model developed and validated by Zanoni et al. (1995a,b) is used for such aim. In this model, the extent of starch gelatinisation follows first-order kinetics and the reaction rate constant is temperature dependent according to the Arrhenius equation:

$$\frac{d(1-\alpha)}{dt} = -K(1-\alpha) \tag{7}$$

$$K = K_0 \exp\left(\frac{-E_a}{R_g T}\right) \tag{8}$$

where $K_0 = 2.8 \times 10^{18}\ \mathrm{s}^{-1}$ and $E_a = 139$ kJ/mol. The gelatinisation degree (α) is defined as:

$$\alpha(t) = 1 - \frac{Q(t)}{Q_{max}} \tag{9}$$

where $Q(t)$ and Q_{max} are the heat uptakes for partially baked and raw dough, respectively. At initial condition, $\alpha = 0$, i.e. $Q = Q_{max}$ (raw dough).

It can be assumed a complete starch gelatinisation when the coldest point of the product achieves a value of $\alpha \geqslant 0.98$ (Zanoni et al., 1995a,b). This parameter is used to verify the assessment of the minimum baking time (CT) by using the core temperature ($\geqslant$96 °C) as a technological solution. It is worth mentioning that this model is applied to crumb but not to crust, where the starch gelatinisation process is more complex due to variation in water content (e.g. Primo-Martín et al., 2007).

2.4.3. Kinetic model for browning development

The advance of browning at bread surface is evaluated using a kinetic model developed and validated by Purlis and Salvadori (2009c), based on a non-isothermal kinetic approach and assuming a general mechanism of browning (caused by Maillard reaction and caramelisation of sugars), which can be described by the variation of lightness (L^* parameter of the CIE $L^*a^*b^*$ colour space). In this

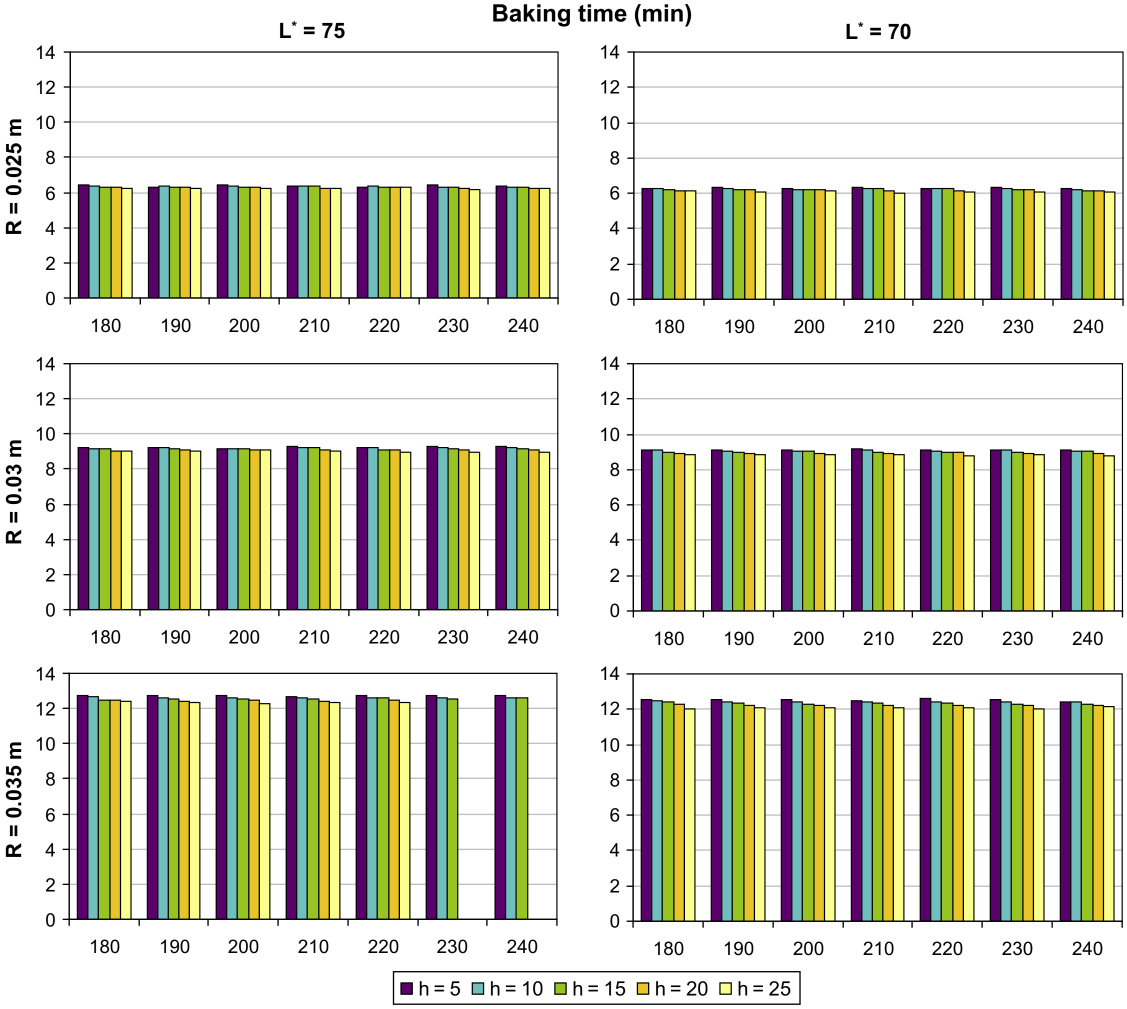

Fig. 3. Values of baking time (CT = QT) for optimum solutions. The absence of a bar (e.g. $R = 0.035$ m, $L^* = 75$) indicates that the corresponding condition produces an L^* value lower than the target without application of IR heating (Purlis, 2012).

model, browning advance is described by first-order kinetics, and the rate constant is a function of temperature and water activity of bread:

$$\frac{dL^*}{dt} = -k_b L^* \quad (10)$$

$$k_b = (7.9233 \times 10^6 + 2.7397 \times 10^6 / a_w) \times \exp\left(-\frac{8.7015 \times 10^3 + 49.4738 / a_w}{T}\right) \quad (11)$$

Browning is initiated when temperature exceeds 120 °C; raw dough has an initial value of $L^* = 85$ (standard recipe for French bread: 100% wheat flour, 54.1% water, 1.6% salt, 1.6% sugar, 1.6% margarine, 1.2% dry yeast).

2.4.4. Solution procedure

The proposed solution explained in Section 2.3 (see Fig. 1) was implemented by using an optimisation routine from MATLAB 7.0 (function *fminbnd*; The MathWorks Inc., USA). Such routine finds the minimum of a function of one variable (i.e. IR heat flux) within a fixed interval; the algorithm is based on golden section search and parabolic interpolation. The solution procedure was applied to the following set of operating conditions: oven temperature (180, 190, 200, 210, 220, 230, and 240 °C), heat transfer coefficient (5, 10, 15, 20, and 25 W/(m^2 K)), product radius (0.025, 0.03, and 0.035 m), and target surface lightness L^* (70, 75).

For baking simulations, initial temperature and water content were assumed to be uniform and equal to 25 °C and 0.65 kg/kg (dry basis), respectively. Relative humidity in oven ambient was assumed to be negligible (no steam injection). The system of non-linear partial differential equations describing the heat and mass transport model was solved using the finite element method. The numerical procedure was implemented in COMSOL Multiphysics 3.2 (COMSOL AB, Sweden). The finite element mesh consisted in 240 elements in all cases. Finally, a medium order Runge–Kutta routine (function *ode45* from MATLAB) was used to solve (numerically) the quality kinetic models from temperature and moisture content profiles obtained through transport model simulation.

3. Results and discussion

3.1. Optimum solutions

As a result of applying the solution procedure, optimum solutions were obtained for the tested range of operating conditions (Figs. 2–5). In practical terms, optimum solutions provide the value of infrared heat flux to be applied for obtaining the target value of surface lightness at the same time that dough/crumb transformation is completed, for a given set of operating conditions (heat

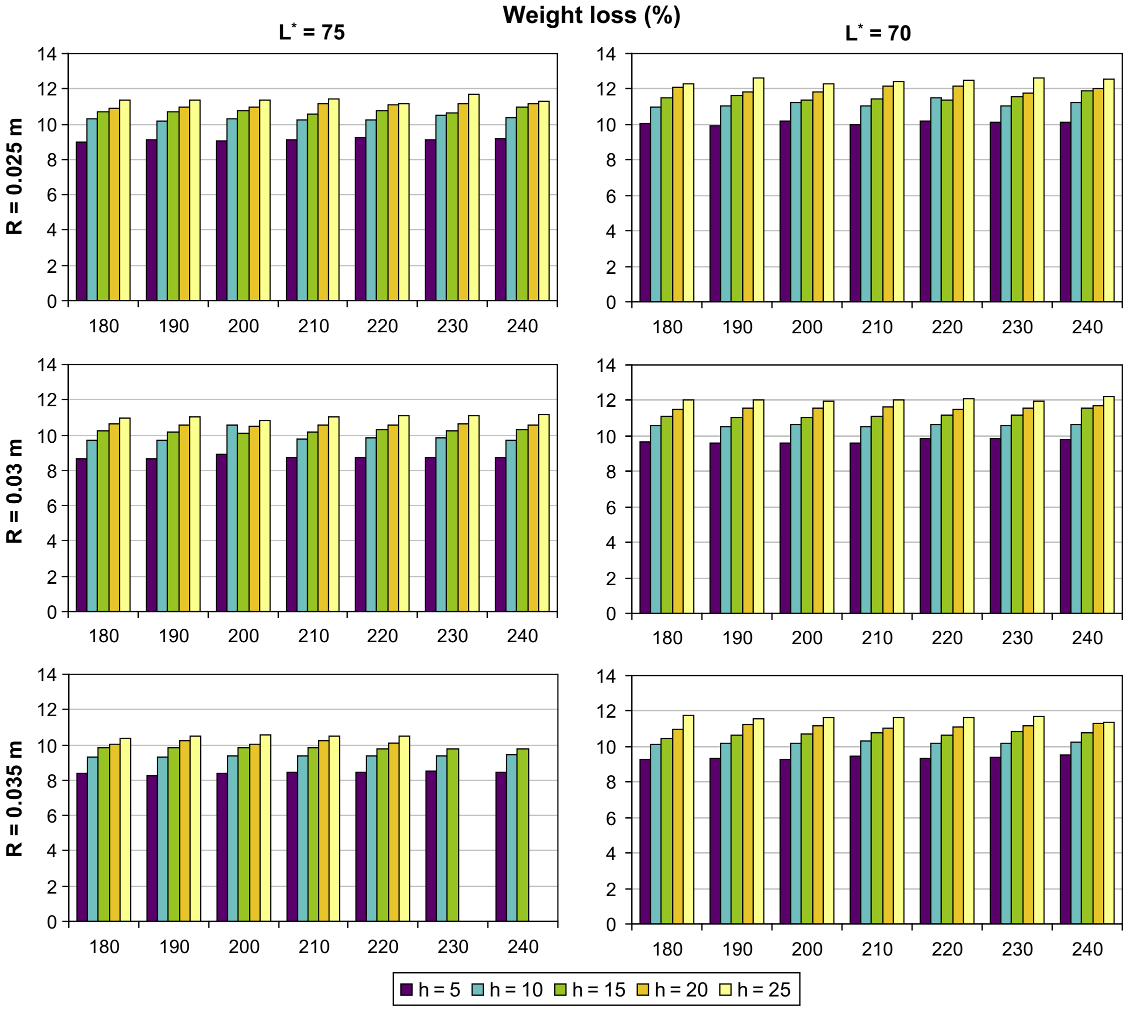

Fig. 4. Values of weight loss for optimum solutions. The absence of a bar (e.g. $R = 0.035$ m, $L^* = 75$) indicates that the corresponding condition produces an L^* value lower than the target without application of IR heating (Purlis, 2012).

transfer coefficient, oven temperature, bread radius). Besides the values of infrared heat flux (Fig. 2) and baking time (Fig. 3, equal to CT and QT, by given definition of optimum solution), a series of outputs can be calculated from temperature and moisture content profiles provided by the transport model. For clarity of presentation, only the final weight loss of the product (Fig. 4) and the contribution of infrared heating to overall heat flux (Fig. 5) are shown here. For microscopic information (profiles) and related discussions, please refer to the corresponding cited articles.

Firstly, it is worth noting that the values found for overall and IR heat fluxes are in the range of measured values by other authors in baking operations (Ploteau et al., 2012; Zareifard et al., 2006). In order to establish a practical reference, the highest value of IR heat flux, ca. 5500 W/m^2, is equivalent to a heat transfer coefficient of 160 W/(m^2 K) approximately, for the tested operating conditions (this value was calculated from the q_{IR} value, the oven temperature and the average surface temperature). A similar result (200 W/(m^2 K)) was reported in the literature for a comparison between IR drying (energy input of 10 kW/m^2) and convective drying (Rastogi, 2012).

For a fixed value of product radius (characteristic length), IR heat flux decreases with the increase of heat transfer coefficient and oven temperature (i.e. convection and "default" radiation contributions to heat flux), as it is expected (Fig. 2). Similarly, a more browned product (L^* = 70) will require more amount of IR heat flux for fixed baking conditions. Regarding the differences with bread radius, a lesser amount of IR input is needed for larger products (fixed baking conditions). This is explained by using the critical time definition: a larger value of radius for a fixed heat flux implies more time to complete the dough/crumb transformation (assessed at the coldest point), so browning can be further developed and thus the additional energy input required for reducing QT to CT is lower. In other words, a larger characteristic length gives more time to browning reactions to advance while the product is being baked. The same reasoning (regarding IR heat flux variation) is valid for the variation of baking time with bread dimension (Fig. 3).

In the same way, the (global) variations of baking time (Fig. 3) and weight loss of bread (Fig. 4) can be explained by basic transport phenomena concepts. Besides the (straightforward) trends of time and weight loss with heat transfer coefficient, oven temperature, and product dimensions, it is interesting to analyse the behaviour of such outputs with increasing degree of browning. For the same radius, a slight decrease in baking time and a more marked increase in weight loss are observed for decreasing L^* values (i.e. more browning). The values of IR heat flux account for this behaviour: a darker surface, for the same radius and baking conditions, will require a higher amount of additional heat input (always for CT = QT), which is translated into a diminution of baking time

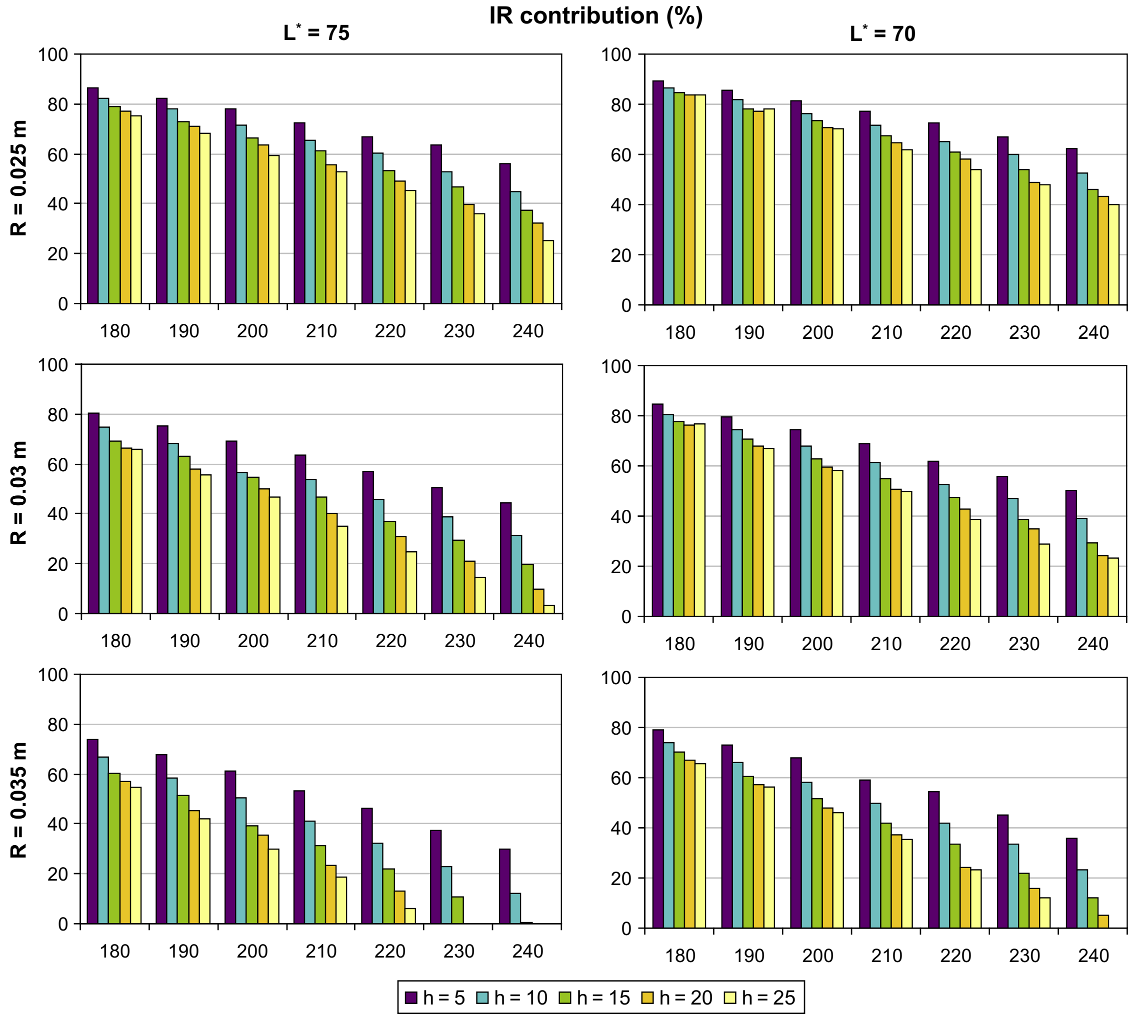

Fig. 5. Values of infrared contribution to overall heat flux for optimum solutions. The absence of a bar (e.g. R = 0.035 m, L^* = 75) indicates that the corresponding condition produces an L^* value lower than the target without application of IR heating (Purlis, 2012).

by increasing the thermal gradient. Simultaneously, mass transport rate is augmented and more weight loss is produced. These changes are accompanied by higher values of surface temperature for darker products (results not shown).

On the other hand, it is possible to compare the obtained optimum solutions with the results corresponding to a conventional baking process without application of IR heating, i.e. optimum vs. feasible solutions. The comparison can be made via process outputs, e.g. baking time, weight loss, etc. The aim of this assessment is to quantify the scope of optimisation initially pointed out. Feasible solutions were obtained by direct process simulation without searching the IR heat flux to equal CT = QT. For these non optimum conditions, the baking time is actually the quality time since the target value of browning has to be reached for making the comparison. Besides baking time and weight loss, two other relevant outputs were evaluated: thermal input (TI, in °C min) and total energy input (E_{tot}, in J/m^2). The thermal input represents the time–temperature history to which the product is subjected during the baking process. This variable is important to evaluate the nutritional quality of bread products regarding the formation of toxic compounds via the browning reactions during baking, in particular, the generation and accumulation of acrylamide. For instance, low oven temperature combined with long baking time do not result in lower acrylamide content than by using high temperature and short time, if the same browning degree is to be achieved (Amrein et al., 2004). So, nutritional quality of the product would be improved with decreasing thermal input values. Thermal input was assessed using the following expression:

$$\mathrm{TI} = \int_t T(r = R)dt \qquad (12)$$

where the function to be integrated over baking time is the time–temperature history at bread surface. The total energy input was computed from the total heat flux and the baking time.

So, the mentioned comparison was carried out by calculating the ratio of a given output value (y), between the ones obtained by feasible and optimum solutions, i.e. $y_{\text{feasible}}/y_{\text{optimum}}$; the corresponding results are shown in Figs. 6–9. As can be observed, all outputs reveals a significant scope for optimisation in the bread baking process, in particular, baking time (Fig. 6) and thermal input (Fig. 8). In most of tested conditions, except for those which produce L^* values close to target (R = 0.035 m, high values of h and oven temperature), the advantages of applying an additional heat flux input are remarkable. In addition to short baking times and low weight loss values provided by optimum conditions (Figs. 3 and 4), lower thermal input, which would result in better nutritional quality due to a reduction in acrylamide formation (Amrein et al., 2004), and energy reduction can also be obtained

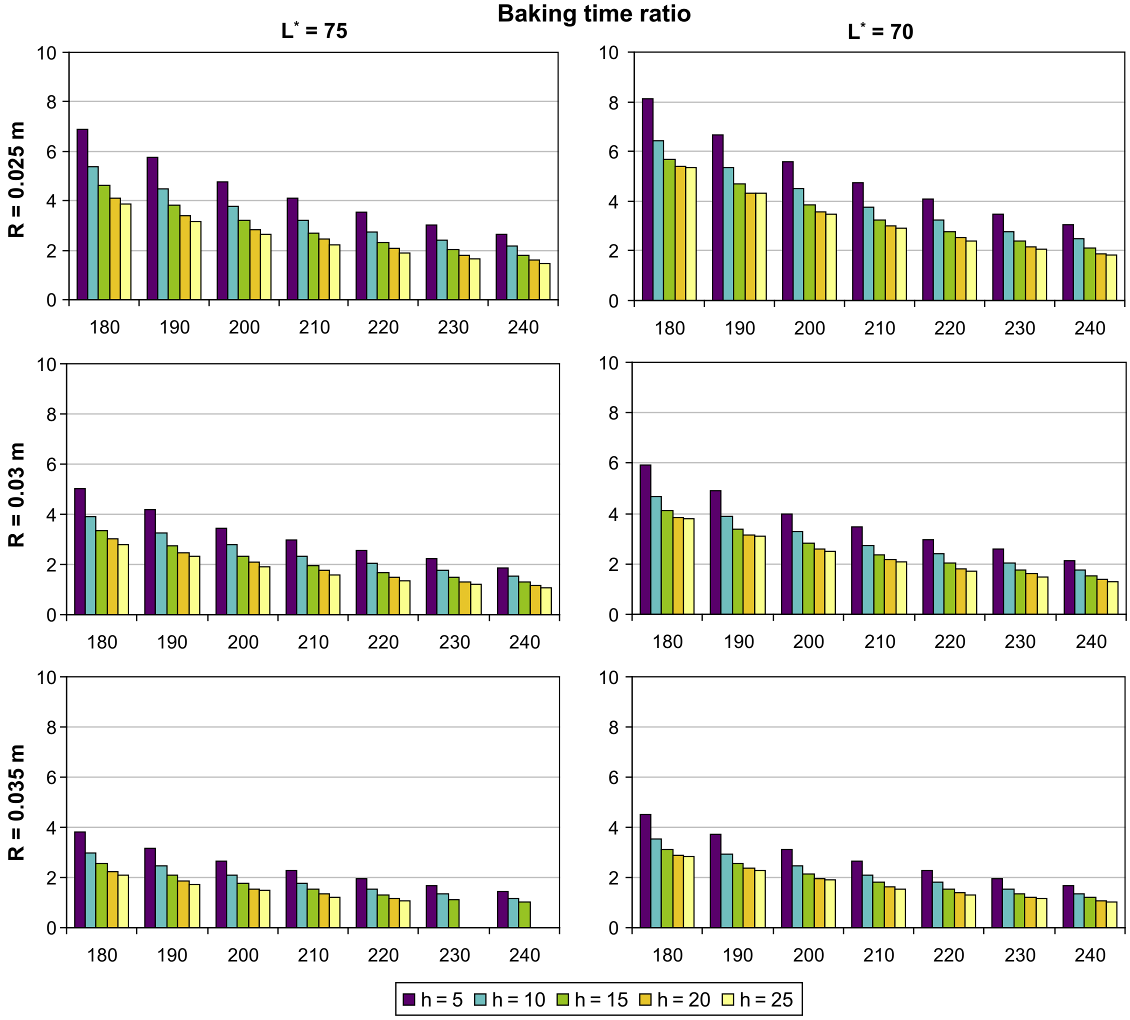

Fig. 6. Comparison of baking time between feasible and optimum solutions; values correspond to ratio feasible/optimum. The absence of a bar (e.g. R = 0.035 m, L^* = 75) indicates that comparison could not be done for the corresponding condition (see Figs. 2–5).

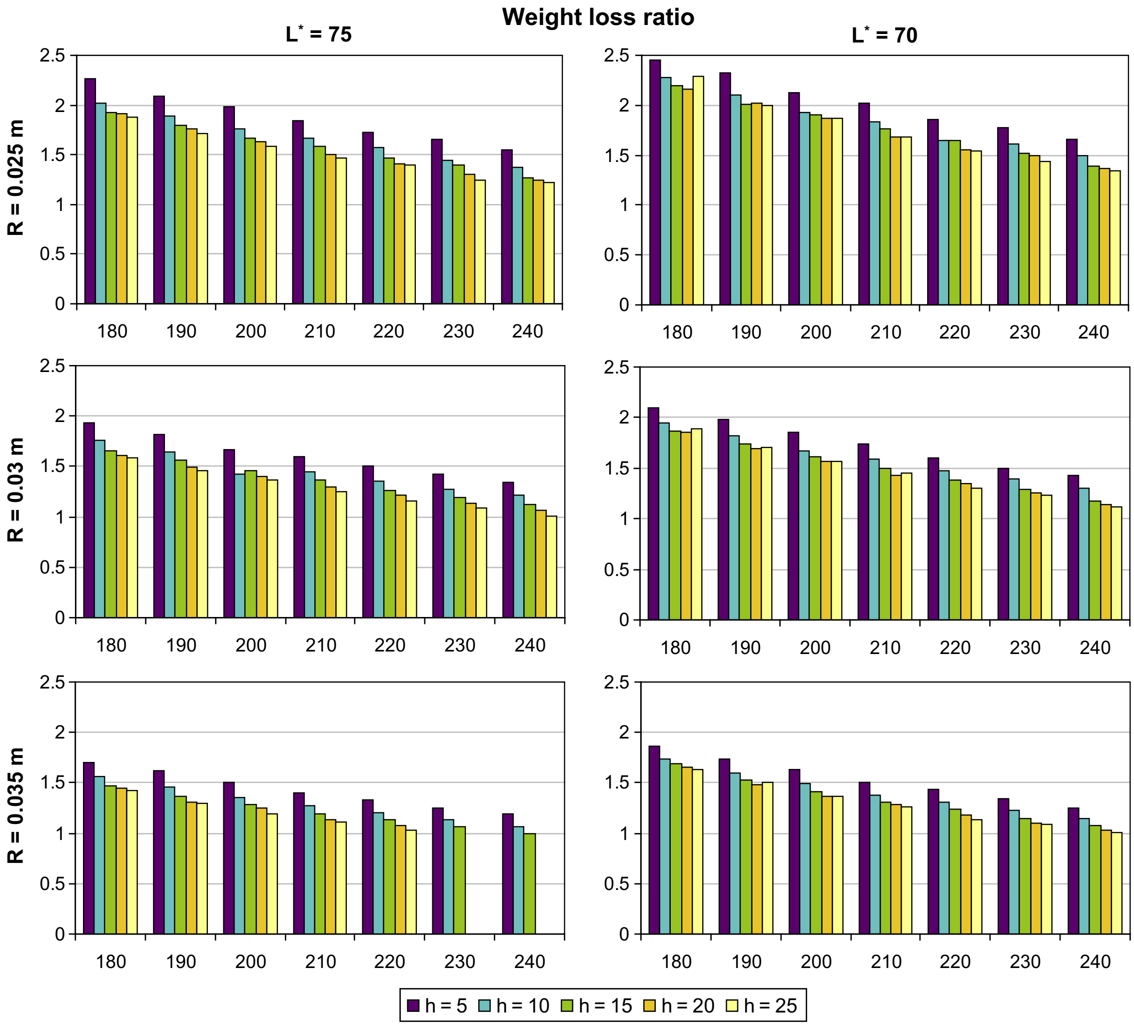

Fig. 7. Comparison of weight loss between feasible and optimum solutions; values correspond to ratio feasible/optimum. The absence of a bar (e.g. $R = 0.035$ m, $L^* = 75$) indicates that comparison could not be done for the corresponding condition (see Figs. 2–5).

(Figs. 8 and 9). These results not only show the potential of the use of infrared heating together with conventional heat inputs for baking, but also the fact that baking can be optimised or improved largely in a relatively simple way.

3.2. Implementation of the proposed solution

The implementation of the obtained results involves the application of an additional heating source to reduce quality time to critical time. In this work, the use of infrared heating has been considered as a possible solution. From the transport phenomena perspective, IR radiation has the advantages of not increasing the convection contribution and to have a low penetration depth, so the contribution to internal heating can be considered negligible (Rastogi, 2012; Salagnac et al., 2004). In this way, the traditional baking process remains the same except for a greater (although not fully convective) heat flux at product surface. Therefore, it appears as a very effective technology for time reduction without other undesired consequences such as excessive weight loss (because of increasing the convection contribution, e.g. air impingement), or modification of characteristic properties of the product (e.g. application of microwave heating). Regarding the equipment for IR heating, it presents fast transient response, associated energy savings and easy accommodation with other heating sources or modes. The main advice is a radiator or radiant emitter; depending on required energy input, there are various types and shapes of IR emitters. Finally, it is important to mention the easy control of IR source by adjusting the power output (Rastogi, 2012).

With respect to the actual practical implementation, some works have been reported that give (experimental) support to the proposed solution. For instance, Skjöldebrand and Andersson (1989) investigated the use of infrared baking in comparison with conventional baking of bread. They found a marked reduction in processing time by using IR equipment and some differences regarding crumb softness and crust thickness features between both processes. Also, they noted the easy and rapid control of IR baking oven and the possibility of controlling separately and simultaneously the formation of crust and crumb in order to complete both transformations at the same time. Finally, they proposed the use of a multi-stage baking oven for applying both IR and conventional heating. More recently, Zareifard et al. (2009) reported that a reduction in energy consumption would be possible if baking oven performance were optimised through the application of a heat flux approach, i.e. to measure different heat fluxes for monitoring and controlling the process. In this way, they showed experimentally that the same amount of heat can be delivered to the product while the contributions of different heating modes are varied, so different quality characteristics can be obtained.

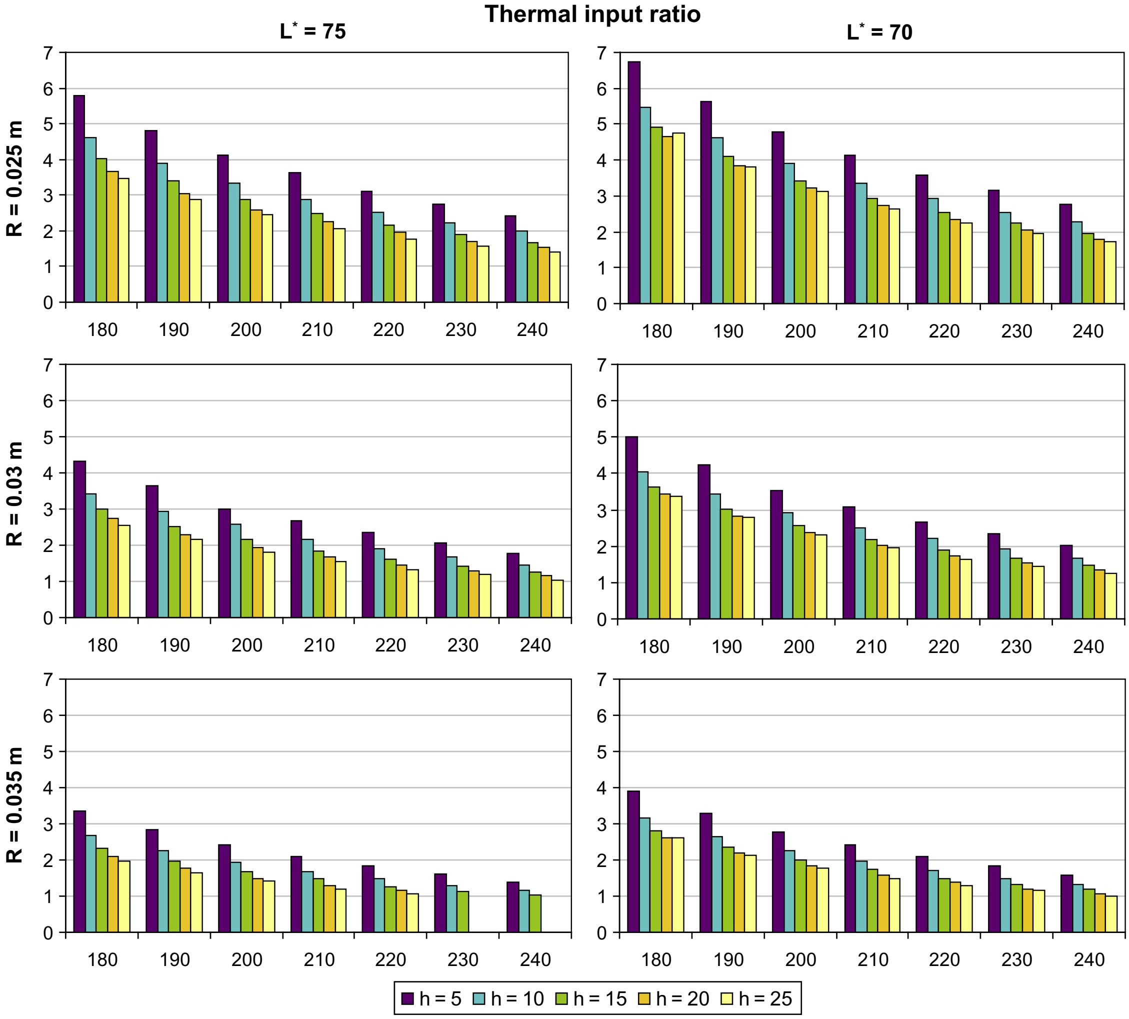

Fig. 8. Comparison of thermal input between feasible and optimum solutions; values correspond to ratio feasible/optimum. The absence of a bar (e.g. $R = 0.035$ m, $L^* = 75$) indicates that comparison could not be done for the corresponding condition (see Figs. 2–5).

Finally, IR heating has been combined with microwave heating to produce breads of comparable quality to the ones obtained by conventional baking (Demirekler et al., 2004). In summary, these previous results give experimental support to the proposed solution of adding IR heating to develop optimum baking strategies and to the approach of designing optimum processes based on controlling the different contributions of heat flux.

3.3. Generalisation of the proposed approach

The ultimate objective of this work is to propose a general idea or conceptual framework for optimal design of food engineering processes. On the one hand, there exist a series of numerical techniques to solve optimisation problems. On the other hand, a considerable number of works have been dedicated to optimise different unit operations and processes. Nevertheless, most of these works solved specific problems and generalisation of results is often difficult to carry out. Then, this work represents also an attempt to address the bottleneck of developing conceptual approaches for optimal design of food processes. This implies identification of the problem, construction of the objective function to be optimised, (mathematical) solution of the problem, and application of results and conclusions.

On this concept, it should be noted that the proposed approach may be valid for other baking technologies, e.g. use of steam injection or steaming. Obviously, if a physics-based approach will be used, different transport models will have to be considered according to baking technology. Also, the approach can be extended in order to take into account other quality attributes, e.g. texture descriptors. So, if each quality attribute is achieved at a corresponding quality time, the proposed approach can be extended such as: $CT = QT_1 = QT_2 = QT_3 \ldots$

Furthermore, the developed approach can be applied to other processes by redefining the critical and quality times. For example, in meat cooking, the critical time may be the time necessary to reach a minimum temperature at the coldest point to ensure microbiological safety; quality times may be associated with texture and colour attributes.

4. Conclusion

This work shows that there is a significant scope for optimising the conventional baking process. A possible way to design optimum baking conditions is by using infrared heating as an additional heat flux input, so all relevant changes in the product are completed at the same time. The use of infrared heating is equivalent to generate high heat transfer coefficients but without the significant weight loss associated with a large contribution of convective heating (and coupled drying). The numerical implementation of this solution to bread baking shows very good results

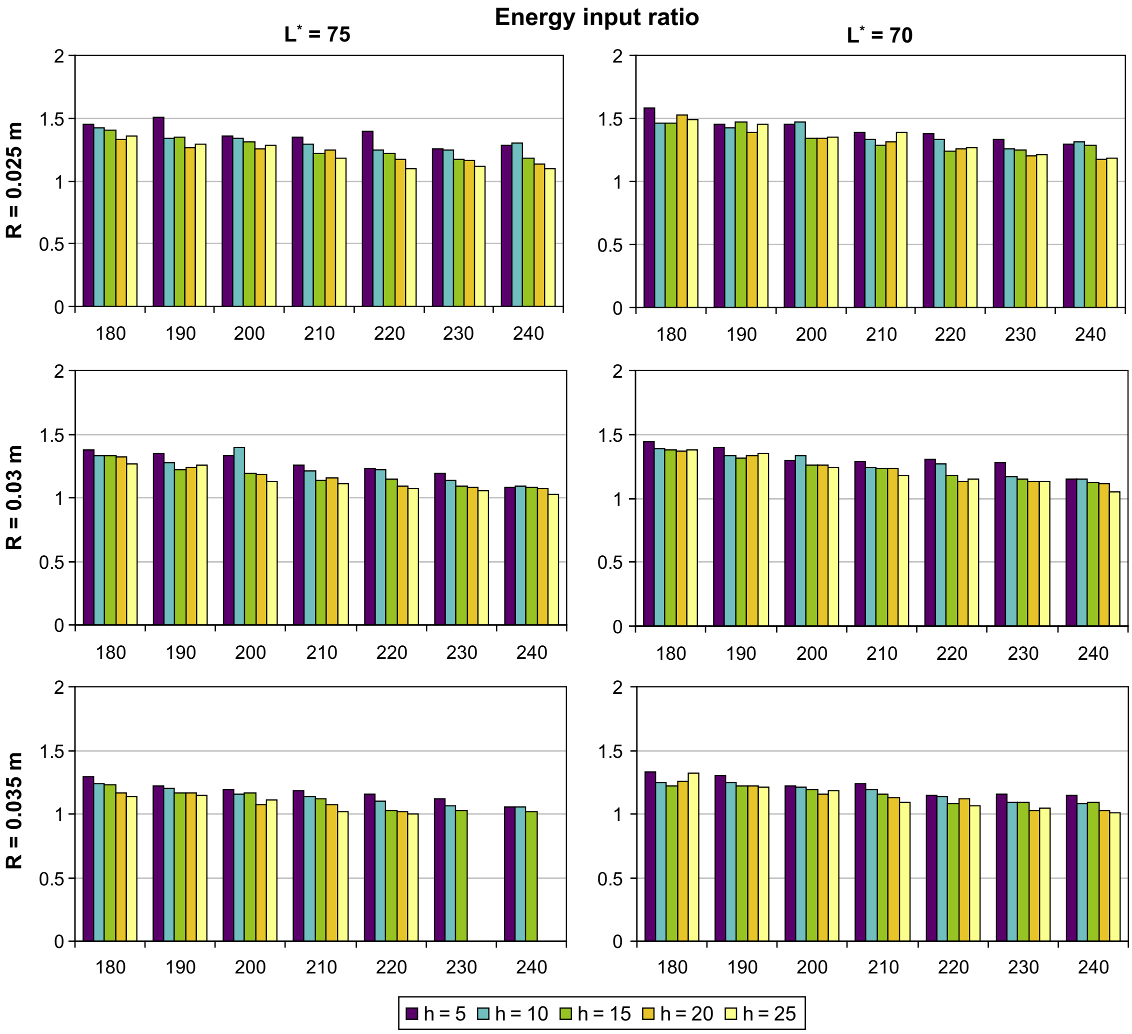

Fig. 9. Comparison of total energy input between feasible and optimum solutions; values correspond to ratio feasible/optimum. The absence of a bar (e.g. $R = 0.035$ m, $L^* = 75$) indicates that comparison could not be done for the corresponding condition (see Figs. 2–5).

involving relevant outputs such as baking time, weight loss, overall energy input, and thermal input to the product. Since the applied approach relies on a conceptual framework for optimal design, it is expected that it can be applied to other processes in food engineering.

Acknowledgements

Author would like to thank to Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), and Universidad Nacional de La Plata (UNLP) for financial support.

References

Abdullah, M.Z., 2008. Quality evaluation of bakery products. In: Sun, D.-W. (Ed.), Computer Vision Technology for Food Quality Evaluation. Academic Press, Burlington, MA, USA, pp. 481–522.

Ahrné, L., Andersson, C.-G., Floberg, F., Rosén, J., Lingnert, H., 2007. Effect of crust temperature and water content on acrylamide formation during baking of white bread: steam and falling temperature baking. LWT – Food Sci. Technol. 40 (10), 1708–1715.

Allais, I., Perrot, N., Curt, C., Trystram, G., 2007. Modelling the operator know-how to control sensory quality in traditional processes. J. Food Eng. 83 (2), 156–166.

Altamirano-Fortoul, R., Le Bail, A., Chevallier, S., Rosell, C.M., 2012. Effect of the amount of steam during baking on bread crust features and water diffusion. J. Food Eng. 108 (1), 128–134.

Amrein, T.M., Schönbächler, B., Escher, F., Amadò, R., 2004. Acrylamide in gingerbread: critical factors for formation and possible ways for reduction. J. Agric. Food Chem. 52 (13), 4282–4288.

Broyart, B., Trystram, G., 2002. Modelling heat and mass transfer during the continuous baking of biscuits. J. Food Eng. 51 (1), 47–57.

Broyart, B., Trystram, G., 2003. Modelling of heat and mass transfer phenomena and quality changes during continuous biscuit baking using both deductive and inductive (neural network) modelling principles. Food Bioprod. Process. 81 (4), 316–326.

Demirekler, P., Sumnu, G., Sahin, S., 2004. Optimization of bread baking in a halogen lamp-microwave combination oven by response surface methodology. Eur. Food Res. Technol. 219 (4), 341–347.

Hadiyanto, H., Esveld, D.C., Boom, R.M., van Straten, G., van Boxtel, A.J.B., 2008. Product quality driven design of bakery operations using dynamic optimization. J. Food Eng. 86 (3), 399–413.

Hadiyanto, H., Boom, R.M., van Straten, G., van Boxtel, A.J.B., Esveld, D.C., 2009. Multi-objective optimization to improve the product range of baking systems. J. Food Process Eng. 32 (5), 709–729.

Hirte, A., Primo-Martín, C., Meinders, M.B.J., Hamer, R.J., 2012. Does crumb morphology affect water migration and crispness retention in crispy breads? J. Cereal Sci. 56 (2), 289–295.

Keskin, S.O., Sumnu, G., Sahin, S., 2004. Bread baking in halogen lamp-microwave combination oven. Food Res. Int. 37 (5), 489–495.

Krishnamurthy, K., Khurana, H.K., Soojin, J., Irudayaraj, J., Demirci, A., 2008. Infrared heating in food processing: an overview. Compr. Rev. Food Sci. Food Safety 7 (1), 2–13.

Le Bail, A., Dessev, T., Jury, V., Zuniga, R., Park, T., Pitroff, M., 2010. Energy demand for selected bread making process: conventional versus part baked frozen technologies. J. Food Eng. 96 (4), 510–519.

Ploteau, J.P., Nicolas, V., Glouannec, P., 2012. Numerical and experimental characterization of a batch bread baking oven. Appl. Therm. Eng. 48, 289–295.

Primo-Martín, C., van Nieuwenhuijzen, N.H., Hamer, R.J., van Vliet, T., 2007. Crystallinity changes in wheat starch during the bread-making process: starch crystallinity in the bread crust. J. Cereal Sci. 45 (2), 219–226.

Purlis, E., 2010. Browning development in bakery products – A review. J. Food Eng. 99 (3), 239–249.

Purlis, E., 2011. Bread baking: technological considerations based on process modelling and simulation. J. Food Eng. 103 (1), 92–102.

Purlis, E., 2012. Baking process design based on modelling and simulation: towards optimization of bread baking. Food Control 27 (1), 45–52.

Purlis, E., Heat and mass transfer during baking. In: Calderón-Domínguez, G., Gutiérrez-López, G.F., Niranjan, K. (Eds.), *Advances in heat transfer unit operations: baking and freezing in bread making*, CRC Press, Boca Raton, 2014.

Purlis, E., Salvadori, V.O., 2009a. Bread baking as a moving boundary problem. Part 1: mathematical modelling. J. Food Eng. 91 (3), 428–433.

Purlis, E., Salvadori, V.O., 2009b. Bread baking as a moving boundary problem. Part 2: model validation and numerical simulation. J. Food Eng. 91 (3), 434–442.

Purlis, E., Salvadori, V.O., 2009c. Modelling the browning of bread during baking. Food Res. Int. 42 (7), 865–870.

Purlis, E., Salvadori, V.O., 2010. A moving boundary problem in a food material undergoing volume change – Simulation of bread baking. Food Res. Int. 43 (4), 949–958.

Rastogi, N.K., 2012. Recent trends and developments in infrared heating in food processing. Crit. Rev. Food Sci. Nutr. 52 (9), 737–760.

Salagnac, P., Glouannec, P., Lecharpentier, D., 2004. Numerical modeling of heat and mass transfer in porous medium during combined hot air, infrared and microwaves drying. Int. J. Heat Mass Transfer 47 (19–20), 4479–4489.

Sevimli, K.M., Sumnu, G., Sahin, S., 2005. Optimization of halogen lamp-microwave combination baking of cakes: a response surface methodology study. Eur. Food Res. Technol. 221 (1–2), 61–68.

Skjöldebrand, C., Andersson, C., 1989. A comparison of infrared bread baking and conventional baking. J. Microw. Power Electromagn. Energy 24 (2), 91–101.

Sumnu, G., 2001. A review on microwave baking of foods. Int. J. Food Sci. Technol. 36 (2), 117–127.

Sumnu, G., Sahin, S., Sevimli, M., 2005. Microwave, infrared and infrared-microwave combination baking of cakes. J. Food Eng. 71 (2), 150–155.

Zanoni, B., Peri, C., Bruno, D., 1995a. Modelling of starch gelatinization kinetics of bread crumb during baking. Lebensmittel-Wissenschaft und-Technologie 28 (3), 314–318.

Zanoni, B., Schiraldi, A., Simonetta, R., 1995b. A naive model of starch gelatinization kinetics. J. Food Eng. 24 (1), 25–33.

Zareifard, M.R., Marcotte, M., Dostie, M., 2006. A method for balancing heat fluxes validated for a newly designed pilot plant oven. J. Food Eng. 76 (3), 303–312.

Zareifard, M.R., Boissonneault, V., Marcotte, M., 2009. Bakery product characteristics as influenced by convection heat flux. Food Res. Int. 42 (7), 856–864.