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

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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.

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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 ($5.67\times10^{-8}\ W/(m^2 K^4)$)

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: