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Energy optimization of bread baking process undergoing quality constraints

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ABSTRACT

International home energy rating regulations are forcing to use efficient cooking equipment and processes towards energy saving and sustainability. For this reason gas ovens are replaced by the electric ones, to get the highest energy rating. Due to this fact, the study of the technologies related to the energy efficiency in cooking is increasingly developing. Indeed, big industries are working to the energy optimization of their processes since decades, while there is still a lot of room in energy optimization of single household appliances. The achievement of a higher efficiency can have a big impact on the society only if the use of modern equipment gets widespread. The combination of several energy sources (e.g. forced convection, irradiation, microwave, etc.) and their optimization is an emerging target for oven manufacturers towards optimal oven design.

In this work, an energy consumption analysis and optimization is applied to the case of bread baking. Each source of energy gets the due importance and the process conditions are compared. A basic quality standard is guaranteed by taking into account some quality markers, which are relevant based on a consumer viewpoint.

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. Quality can be related to different aspects of food consumption, e.g. microbiological safety, food texture, internal and surface color, nutritional value, controlled origin, authenticity, etc. [1]. Energy and exergy analyses are often useful to assess the efficiencies of the production of a certain food, with particular reference to the several steps of conversion starting from the grain cultivation [2] to the food processing [3] and the following waste valorization or disposal [4]. Integration of different technologies can be a solution to achieve energy efficiency. This is particularly effective when the layout of a process or plant can be easily modified without a major technological revision, for instance with the insertion of a new equipment after the analysis of the process streams, as in the case of a cheese production plant presented by Kapustenko, Ulyev [5]. Relevant examples of strategies for the energy optimization of food plants can include the choice of the appropriate ventilation strategy for a large-scale ripening room [6] as well as the implementation of simple best practices the refrigeration rooms to minimize the process energy consumption, such as an appropriate product distribution, the regular check and maintenance of the machinery and the replacement of the old devices [7]. The integration of plants with renewable energy sources (solar thermal energy, biomass, solar photovoltaic) may be implemented to contribute to substantial energy savings on the daily basis, despite the payback periods can be long and the use of some sources can have a seasonal variability. One of such applications is that proposed by Yildirim and Genc [8], that promoted a milk pasteurization process assisted by geothermal energy to increase the pasteurization capacity and undergoing a relevant process efficiency. In general, food processes often involve heating or cooling, sometimes with phase transitions. Those processes need for a high energy demand [9]. Then, a process optimization can have a considerable impact on savings [10].

On a smaller scale, commercial electric ovens are part of the domestic equipment requiring a huge amount of energy to pursue the mentioned transformation, taking advantage of few technologies such as forced hot air convection, irradiation and, sometimes, microwaves. New technologies to increase the energy efficiency of

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ovens, for instance, pulsed electric fields (PEF) (see application on carrots [11] and apple [12] drying), ohmic heating [13], jet impingement [14] 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 optimizing the food processes based on the consolidated technologies, usually taking into consideration the oven design step to achieve the best thermal performances [15,16]. The optimization procedure of an existing oven towards the simple implementation of control algorithms, instead of modifying the oven layout, could involve the assessment of the energy demand of food and of the related process [17], belonging to a combination of energy sources as optimization variables. To do so, a possible approach is that of considering this assessment and the related optimization 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 [18]. The quality parameters related to the constraints can be identified from the topic-related literature to take into account the effects of the process to the product [19].

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 heating technologies and to different food kinds (see for instance the paper from Goñi and Salvadori [20] for a multi-objective optimization of roast beef cooking, also modeled by the authors of this paper [21]) by assessing on one hand the related impact, on the other hand the specific quality constraints based on markers identification [22].

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 [23] (i.e. separate mass balances are present for liquid water and water vapor)
- Thermal properties are calculated based on a mixture approach taking into account food macro-composition (water, fibers, fats, carbohydrates, proteins) [24].
- Evaporation can occur in the whole bread volume when the local temperature exceeds 100 °C. This phenomenon 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. Ref. [25]). 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:

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

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

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

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 in presence of liquid water.

The boundary conditions are:

$$\mathbf{n}_w^l \cdot \mathbf{n} = 0 \qquad (4)$$

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

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

K_m represent the vapor 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 assessment

To define an optimization strategy it is essential to define the objective function. In case of energy evaluation and optimization, 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 [26]. Anyway, a simpler application could 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 fulfill 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 [27].

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. This assumption is realized through the definition of the heat fluxes and a surface integral. The absorbed energy is then represented by the integral of the heat flux with respect to the bread surface and of the process time. This results to the following expression:

$$Energy = \int_{time} \int_{surface} J_H \left(T_{oven}, T_{surface}, t \right) dSdt \qquad (7)$$

In case of volumetric heating terms (e.g. microwave heating), this function would also include the integral over time of that term.

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