ARTICLE IN PRESS

Journal of Food Engineering xxx (2017) 1–14

Contents lists available at ScienceDirect

Journal of Food Engineering

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

A computational study to design process conditions in industrial radio-frequency tempering/thawing process

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ARTICLE INFO

Article history:
Received 19 November 2016
Received in revised form
29 April 2017
Accepted 4 May 2017
Available online xxx

Keywords:
Radio-frequency
Industrial thawing
Mathematical modeling
Design and optimization

ABSTRACT

Conventional thawing processes adopted by food industry are characterized by longer operation times and food quality losses. Recently, batch and continuous radio-frequency (RF) assisted thawing were proposed as alternative and faster process, but their economic feasibility at industrial level is far to be assessed. Undoubtedly, longer penetration depth and ability to generate volumetric heat enable RF assisted heating a very promising technology to apply at industrial scale. On the other hand, most of the RF systems in operation are built following heuristic criteria, more than being designed and tailored on specific products or processes: this has limited the development of RF based system for food thawing as well as the proposal of simple but effective control systems. The literature has contributed with a number of theoretical and modeling based works for RF processes, but design-based studies in general are limited. Therefore, the objective of this study was to present a strategy for virtual design of a continuous RF thawing process. For this purpose, a previously developed and experimentally validated mathematical model was modified to take into account the movement of food product through a continuous RF system, the movement of RF electrode and subsequent effects of temperature and electric field changes. Power uniformity index (PUI) for various proposed configurations was analyzed, and possible scenarios were suggested for an industrial scale process. With this concept, this study was assumed to be significant for design and optimization of industrial RF and RF thawing processes.

1. Introduction

Freezing is commonly applied in food industry to increase shelf-life of food products and preserve their quality during storage and transportation. All frozen food products, with notable exception of ice cream, must be tempered or thawed above their freezing temperature for immediate consumption or further processing. For example, use of frozen meat or fish for further processes in the manufacturing line is a common exercise in the food industry. While the thawing process is to raise the temperature to −2 to 0 °C, tempering consists of increasing the final temperature to −4 to −2 °C (Bernard et al., 2015). At the tempering temperatures, the product becomes still firm to be diced or sliced for further industrial processing (Hassan et al., 2015), and this is somewhat preferred since the objective would not the immediate consumption. Conventionally used industrial thawing/tempering systems work based on convection heat transfer principle, and longer times are experienced with certain quality losses. Upon the start of thawing at the surface of the sample in a conventional system, the thermal conductivity value starts getting lower due to the phase change from ice to water stages (i.e., from ≈1.5 to ≈0.5 W/m-K). The lower thermal conductivity of the thawing front around the surface increases the resistance to heat transfer (which is effective through the 3rd kind boundary condition of heat transfer coefficient). Due to this slowing effect observed in the conventional systems, thawing or tempering of large blocks of frozen commodities (e.g., the frozen tuna steaks for canning industry) using conventional methods take longer times. Besides the increase in thawing time, change in quality attributes (moisture loss – drip losses) and possible microbial growth especially over the surface due to the increase of temperature above +4 °C for longer times represent problems affecting the whole process. To increase the convective heat transfer rate (coefficient) and, then, to reduce the tempering/thawing time, use of water as thawing medium or use of air impingement systems were also preferred,

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http://dx.doi.org/10.1016/j.jfoodeng.2017.05.003
0260-8774/

Please cite this article in press as: Erdogdu, F., et al., A computational study to design process conditions in industrial radio-frequency tempering/thawing process, Journal of Food Engineering (2017), http://dx.doi.org/10.1016/j.jfoodeng.2017.05.003

but all these methods had certain disadvantages. Increased amount of drip losses might result due to the longer thawing times resulting in the adverse changes in texture and significant economic losses. Using water as a thawing medium might result in cross-contamination of the products during the process, and waste treatment of this water becomes an additional cost. The requirement of the larger sized floor space in the conventional systems is another disadvantage for the overall process cost. As also indicated by Farag et al. (2008), there is a high demand from food processing industry for fast and compact systems. Dielectric heating, microwave (MW) and radio frequency (RF), have this potential to reduce tempering/thawing time, lower energy consumption and improved hygiene and quality in industrial use (Bernard et al., 2015). Use of dielectric heating methods for thawing of meat and meat products were first suggested by Sanders (1966). In the dielectric systems, heat generation within the sample is created by dipole rotation and ionic polarization through movement and friction of dipoles and/or ions while an alternating electric field is applied. While, in MW application, dipole rotation is a major contributor at the applied higher frequencies, 915 (industrial) and 2450 MHz (home appliances), ionic displacement is pronounced at the lower frequencies of RF applications (13.56 and 27.12 MHz) (Jones, 1992). Due to longer wave-length of RF (≈22 and 11 m in free space, respectively) compared to the case of MW (≈0.327 and 0.122 m in free space, respectively), higher penetration depth is observed and lower frequency application helps minimizing the run-away heating within the sample (Uyar et al., 2015). Hence, RF process might be accepted to have a potential to improve heating uniformity during an industrial scale process considering the larger sizes of frozen commodities for an industrial process (Taher and Farid, 2001).

During RF processing, besides the size of the sample located between the electrodes and its electromagnetic characteristics (permeability and permittivity), distance between the electrodes, geometrical configuration of the sample, distance between the top electrode and the sample have a certain effect on power absorption (and heat generation within), as well as on the heating rates and temperature uniformity (Uyar et al., 2014, 2016). Temperature uniformity of the samples is a major focus in the recent studies (Ferrari-John et al., 2016), and various approaches have been applied for this purpose including the physical property of the surrounding container (Huang et al., 2016).

Industrial RF systems might run in both batch and continuous modes. Considering that the continuous operation would be more desirable to possibly lower the process cost, movement of the sample within the system might change the electric field distribution within the system resulting in the changes of power absorption and heating uniformity of the sample. Wang et al. (2010) reported the improvement in heating uniformity of some legumes using back-and-forth movement of product within the RF system at a velocity of 0.56 m/min. The improvement of heating uniformity using movement of food product on a conveyor belt during RF processing was also studied for almonds (Gao et al., 2010), coffee beans (Pan et al., 2012) and lentils (Jiao et al., 2012). Zhou et al. (2015) determined the improving effect of moving at 0.21 m/min for temperature uniformity of the rice samples in a container. Chen et al. (2016) used an experimentally validated model to evaluate the effects of conveyor movement on RF heating patterns. In all these studies, while the sample was moving at a constant speed, the distance between the electrode and the sample was assumed to be constant.

The effects of movement in an RF cavity to improve temperature uniformity of the processed foods is a recent trend in the food process engineering literature. However, there is no study yet reported for thawing process. Besides, the design based studies for RF processing in general and for RF thawing is also lacking. Therefore, the objective of this study was to use a previously experimentally validated thawing model to determine the design considerations of a continuous industrial scale RF thawing/tempering process.

2. Materials and methods

2.1. Computer simulations

2.1.1. Mathematical model

A parallel plate RF system (2 kW, 27.12 MHz) with two rectangular metallic electrodes and electrically insulated walls was presumed in this study based on the previously developed and experimentally validated model. Detailed geometrical description of the system was given in Fig. 1. The top electrode position could be changed to adjust the electrode gap while the bottom electrode was fixed with the metallic enclosure of the RF system. The frozen food product (tuna sample) was assumed to be placed on the bottom electrode under both static and moving conditions. Fig. 1 demonstrates the geometry of the RF system with the sample while Fig. 2 shows various configurations for which the simulations were carried out using the described mathematical model.

2.1.2. Mathematical description

The following section summarizes the general equations, initial and boundary conditions solved to determine temperature and electric field distribution change during RF thawing.

2.1.2.1. Governing equations. The solution of the Eq. (1) to determine the temperature distribution within the materials was required to couple with the quasi-static approach of the electromagnetic field equations:

$$\rho\, c_p \frac{\partial T}{\partial t} = \overline{\nabla} \cdot \left(k \overline{\nabla} T\right) + P_{abs} \tag{1}$$

where ρ is the density (kg/m^3), c_p is the specific heat (J/kg-K), k is the thermal conductivity (W/m-K), t is the time, T (K) is the temperature, and P_{abs} is the absorbed power (W/m^3) by sample due to the generation by the electric field distribution. P_{abs} was given by:

$$P_{abs} = 2\,\pi f\, \varepsilon_0 \varepsilon'' \left|\overline{E}\right|^2 \tag{2}$$

where f is the frequency of the radio-wave generator (Hz), ε_0 is the permittivity of free space (8.85E-12 F/m), ε'' is the relative dielectric loss factor of the sample load, and $\left|\overline{E}\right|$ is the modulus of the electric field (V/m). As given in Eq. (2), absorbed RF power (P_{abs}) is governed by electric field strength, relative dielectric loss factor (ε'') and frequency (f). To simplify and by-pass the requirement of solving the Maxwell's equations for the electric field strength, quasi-static approach was presented by Marra et al. (2007) and also applied in this study. In this approach, changes in the electrical field dynamics are assumed to be much faster than the dynamics of heat transfer dynamics due to the longer wavelength of the RF compared to the cavity of a possible RF system (Tiwari et al., 2011). Electric field within the sample and potential between the electrodes were then given by Gauss law, derived from the quasi-static approximation of Maxwell's equations:

$$\nabla\left(\varepsilon \cdot \overline{E}\right) = 0 \tag{3}$$

where ε is permittivity of the load (relative permittivity related to dielectric constant, ε' and dielectric loss factors, ε'', and $\overline{E}$ is the electric field vector (V/m). In fact, electric field strength is a part of the electromagnetic field which is described electric − magnetic field intensities and the electric flux density, and described by