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Bread baking using ohmic heating technology; a comprehensive study based on experiments and modelling

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ABSTRACT

Bread dough baking was investigated using ohmic heating technology. An experimental system was set up for the measurement of the electrical conductivity of bread dough during heating. The influence of temperature, salt content and degree of fermentation (porosity) on the electrical conductivity of dough was investigated. It was observed that it increased linearly with temperature, until starch gelatinisation during which the dough conductivity remained constant or slightly decreased. The conductivity increased linearly again after starch gelatinisation, but at a lower rate. The electrical conductivity of dough had a linear positive dependence on salt content, but decreased with increasing dough porosity. Numerical simulations of temperature increase were carried out and compared with experimental data. For a good correlation between numerical and experimental data, a corrective coefficient was numerically estimated and validated, taking into account mainly the conversion of electrical energy to heat, and geometric uncertainties. Numerical results showed that the linear evolution of temperature with heating time was mainly caused by heat losses.

1. Introduction

Ohmic heating (OH), also known as Joule heating or resistive heating, is a heating process based on the passage of an electrical current through a material, which is used as an electrical resistance (Sastry, 1989). Its main advantages are rapid uniform heating, no residual heat transfer after shut-off of the current, and a high energy conversion efficiency (Sakr and Liu, 2014).

Food containing large amounts of water and ionic salts are the best candidates for OH (Sarang et al., 2008), and previous research has shown that most food contains ionic species, such as salts and acids (Palaniappan and Sastry, 1991).

Bread baking using OH was carried out for the first time by Baker (1939). The purpose of the apparatus that was developed (named an Electric Resistance Oven - ERO) was to bake dough with uniform heating. Using this apparatus, the authors studied starch gelatinisation, as well as the evolution of pressure and volume and gas formation in bread dough (Baker and Mize, 1939a, 1939b, 1941). They found that crustless bread could be produced. Later, bread baking using ERO technology came back to the fore. It was used to study how shortenings and surfactants could improve loaf volume in bread (Junge and Hoseney, 1981), to evaluate the component interaction during heating and storage of baked products (Hoseney, 1986), to study cake baking and its viscosity (Shelke et al., 1990), to evaluate gas retention and bread firming (He and Hoseney, 1991a, 1991b; Martin et al., 1991), and to study the effect of pressure on bread crumb grain development (Hayman et al., 1998). More recently, OH was used by Luyts et al. (2013) to study the impact of moisture migration and amylopectin retrogradation on cake firming, and by Derde et al. (2014) to compare the moisture distribution between bread baked by ERO and by conventional heating. For each of these references, OH was used as a tool to produce bread with an isotropic heating in order to study specific characteristics. It was not considered a baking process as such.

During baking, swelling and gelatinisation of starch occur, which participate in the fixation of the structure (Martin et al., 1991). The detection of starch gelatinisation by OH has been studied by different authors. It was shown that when starch gelatinisation occurs, a noticeable change appears in the electrical conductivity of the sample. Li et al. (2004) and Wang and Sastry (1997) added sodium chloride to the starch suspensions in order to increase the electrical conductivities and observed that during starch gelatinisation, the rate of electrical conductivity increase slowed down. The reason proposed by the authors was that during

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Nomenclature

a_ε	constant of Eq. (10) (S m^{-1})
a_S	constant of Eq. (11) (S m^{-1})
A	electrode area (m^2)
b_ε	constant of Eq. (10) (S m^{-1})
b_S	constant of Eq. (11) (S m^{-1})
Cp	heat capacity (J.kg^{-1}.K^{-1})
E_r	average relative error (%)
ε	porosity (%)
I	current (A)
k	thermal conductivity (W.m^{-1}.K^{-1})
L	gap between electrodes (m)
m	constant of Eq. (9) (°C^{-1})
m_d	mass of the dough sample (kg)
m_ε	constant of Eq. (10) (°C^{-1})
m_i	mass of dough when weighing immersed in oil (kg)
m_S	constant of Eq. (11) (°C^{-1})
P	power (W)
Q_{GEN}	ohmic power source (W)
ρ_0	density of the degassed dough (kg m^{-3})
ρ_{app}	apparent density of the dough (kg m^{-3})
ρ_{oil}	density of the oil (kg m^{-3})
R	resistance (Ω)
S	salt content (% dry basis)
σ	electrical conductivity (S m^{-1})
σ_{25}	electrical conductivity at 25 °C (S m^{-1})
V	voltage (V)
V_{cell}	volume of the sample in the ohmic cell (m^3)

swelling, the volume expansion of the starch granules results in a reduction in the distance between them; consequently, the quantity of unbound water decreases, leading to a reduction in the area for motion of the charged particles. When gelatinisation is completed and while the temperature continues to rise, the granules break down and leach amylose, increasing the amount of free water and causing the electrical conductivity to rise again. On the contrary, Chaiwanichsiri et al. (2001) observed an increase in electrical conductivity during starch gelatinisation. This was explained by the fact that they used pure water, unlike the previous authors. For this reason, the ions contained in the starch granules were released when the granules were disrupted after swelling, resulting in a significant increase in the electrical conductivity of the aqueous solution containing the starch. The background ion concentration after ion release had a stronger impact than that of the decrease in the unbound water content, increasing electrical conductivity instead of decreasing it.

Some modelling studies have been carried out on OH of solid food (Icier and Ilicali, 2005a, 2005b; Marra, 2014; Marra et al., 2009; Shim et al., 2010). However, to the authors' knowledge, modelling bread baking by OH has never been studied. Most of the above-mentioned studies showed that OH is not strictly isotropic, and that some cold points may appear as shown by Marcotte (1999). The hottest spot was located at the centre, while Ito et al. (2014) showed that the "corners" between the electrode and the cell wall may exhibit cold points.

The objective of this work was twofold: first, to study the behaviour of electrical conductivity in bread dough with different parameters (temperature, porosity, salt content). Second, to use a numerical simulation to predict the temperatures and understand the physical phenomena better, in such a way that it could be used for the sizing and, later, the development of an ohmic oven.

2. Materials and methods

2.1. Ohmic heating system

An ohmic cell was designed to measure the electrical conductivity of yeasted and non-yeasted bread dough. The experimental device consisted of a power supply (Rototransfo Dereix SA Paris R212, 0–220 V), two multimeters (AOIP MN 5128 as an ammeter and Fluke 45 as a voltmeter), a data logger (AOIP DATALOG 20) with an acquisition frequency of 0.15 Hz, and a computer. Two types of cell were made of a polypropylene cylindrical container, with an internal diameter of 29 mm and an external diameter of 32 mm. The length of the cell was 98 mm for the first type and 61 mm for the second type. The electrodes were made of 2-mm-thick titanium, with a diameter of 28 mm, maintained in two polyoxymethylene caps of 20-mm thickness (10 mm inside the cell, 10 mm outside), allowing a gap between the electrodes of 78.7 mm (long cell) and 41.7 mm (short cell). Holes were made in both ohmic cells to adapt thermocouples (type K, insulated with a Teflon coating). The long cell had three holes, one at the centre and two at each side, 5 mm and 8 mm from the electrodes respectively. The short one had only one hole at the centre. The cells were put in a vertical position during the experiments. The ohmic cells and device are shown in Fig. 1.

2.2. Sample preparation

The recipe used for the reference dough is given in Table 1. Yeast was removed for the non-yeasted dough recipe. The impact of salt content on electrical conductivity was studied using non-yeasted dough. These samples were prepared with different salt contents (on dry basis): the reference dough (2.66%, following the recipe Table 1), double the reference salt weight (5.30%), 1.5 times (3.98%), 0.5 times (1.33%), and no salt. The dough was kneaded in a spiral mixer (VMI SPI 10, Montaigu, FRANCE) for 4 min at 50 rpm (spiral) and 6 rpm (bowl), and 5 min at 120 rpm (spiral) and 10 rpm (bowl). It was left for 15 min to rest, and then placed in the 78.7-mm cell. Contact was made with both electrodes, and the electrodes were immobilised in a stand to prevent volume change during heating. The electrical conductivity was measured immediately.

The impact of porosity on electrical conductivity was studied with yeasted dough. Five short cells, as described previously, were used. Because of the low electrical conductivity of the yeasted dough, it was necessary to use the shorter cell to obtain approximately the same heating rate with the same voltage as with the non-yeasted dough. Five different samples of yeasted dough were weighed and placed in the cells. The first one occupied the cell fully (contact with both electrodes) and was used as t_0 (no fermentation). The other samples were weighed in a decreasing order for an increasing fermentation time. The porosity was calculated using the following equation:

$$\varepsilon = 100 \times \left(1 - \frac{m_d}{V_{cell} \times \rho_0}\right), \quad (1)$$

with ε the porosity of the dough, m_d the weight of the dough sample, V_{cell} the volume of the cell in which the dough was contained, and ρ_0 the density of the degassed dough. The density of the