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Optimization of temperature profile of cake batter in a ohmic-assisted heater for 3D food printing applications

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Abstract

3D printing of food has great potential for applications such as the design of customized food or the creation of innovative textures. It should also help to reduce the ecological footprint by producing less waste and by using less energy. However, printed products often do not retain their structure due to the composition of the material, especially in the case of cereal products. The objective of this work was to develop, with the help of a numerical model, a 3D cake batter printing nozzle in which ohmic heating is used as a means of baking. The use of a temperature and shear rate dependent viscosity allowed for the solidification of the batter during baking due to starch gelatinization. The numerical model, including heat transfer, cake batter flowing and electric field calculation, made it possible to predict treatment heterogeneities. Preliminary tests have shown that it could be used with optimization procedures to get desired temperature profiles at the outlet of the 3D printing nozzle.

Keywords: ohmic heating, 3D food printing, modelling, optimization

1. Introduction

The growing demand for personalized food has encouraged a period of innovation and experimentation with emerging techniques to customize the texture, shape, size, flavor and nutritional content of foods. Three-dimensional (3D) printing technology is an emerging technology that can meet this demand due to its ability to create complex edible shapes and, at the same time, to allow modification of food texture and nutritional content required by specific diets (Godoi et al., 2019). The first 3D printing of bakery dough was dedicated to making a cake by extruding a batter composed of flour, sugar, corn syrup, yeast, and a cake icing (Lanaro et al., 2017; Yang et al., 2001). The biggest challenges are ingredient mixing, shape stability of the final product, (relatively low) printing speed, associated rheology, and compatibility with current food processing technology (baking or drying). Studies have shown that traditional biscuit recipes can be 3D printed. However, the recipes could not retain their shape and structure after processing due to the large amount of fat. This stability problem can be partially solved by adding additives or by controlling the recipes (Lille et al., 2018; Lipton et al., 2015). Internal heating in the nozzle head could solidify the product and therefore could be a better solution to stabilize the shape and make the cake batter easier to print.

Ohmic heating (OH) is an alternative cooking technology that can be used to meet the challenges of internal solidification and printing speed. Ohmic heating (OH) involves the circulation of an electric current through an electrically conductive product, which will heat up by Joule effect (Ramaswamy et al., 2014). The heat is generated volumetrically and spreads from the inside of the product to the walls. Although viewed as a more homogeneous treatment, temperature difference between the center of the product and the walls is observed in batch configuration. In continuous heating, the temperature gradient is reversed due to the very low velocity of fluid encountered closed to the walls (Khodeir et al., 2021).

In this work, we propose to develop a numerical model of continuous heating of the cake batter by OH allowing to take into account the gelatinization of the batter during this pre-baking step. The challenges are to simulate the flow of the batter through the nozzle as it increasingly solidifies due to starch gelatinization and to find process parameters reducing the temperature heterogeneity at the nozzle exit while maintaining the flowing of the product.

2. State of the art

Ohmic heating is a cooking process that allows for the internal generation of heat by the passage of an alternating electric current inside the product. The concept is far from new as it was used in the early 20th century for the pasteurisation of milk (Jaeger et al., 2016) and other pumpable foods, including vegetable products. De Alwis and Fryer (De Alwis et al., 1990) have described some of the problems observed in the early development of the technique: the product could be contaminated by the electrodes and it was often difficult to get good contact between the electrodes and the product. But the main recognised advantage of OH is rapid heating and, unlike conventional processes, where heating is not homogeneous due to the nature of the heat migration, OH allows for a more even heating (Shynkaryk et al., 2012). To ensure that OH solution is of interest, possible hot and cold spots should be identified to ensure a perfectly safe cooked product.

Transfer modelling is thus a valuable tool for the development and validation of such emerging technologies. It allows, for example, to evaluate the influence of variables such as the electrical conductivity of the product or the intensity of the electric field. Numerical modelling is also essential as it is very difficult to measure real internal temperatures in OH processes due to the presence of a strong electric field. Numerical heat transfer models have often been developed and experimentally validated to study the heating of solid-liquid mixtures in batch systems or continuous systems (Salengke et al., 2007) or solid foods to predict cold areas (Marra et al., 2009).

Some studies have shown that OH could also be used for the production of crust-less bread (Gally et al., 2017) and recently, an original printing nozzle device based on a rectangular canal was developed to obtain a cake batter pre-baked by OH (Khodeir et al., 2021). Numerical models were developed during these studies and simulations were performed to evaluate the suitability of OH process. A parametric study was especially carried out for the development of the printing nozzle, showing the need of cooling the electrodes to ensure the flowing of the batter. However, simulations were performed for low electric field values, resulting in the non solidification of the batter due to too low outlet temperartures. One of the objectives of the presented work is to include the strong variation of the cake batter properties to be able to predict the pre-baking at the outlet of the channel. The second objective is to study the possibility to optimize the temperature profiles with numerical investigations.

3. Materials and Methods

3.1. Device, geometry and mesh

Figure 1 shows a 2D representation of the channel used for pre-baking the cake. The device consists of two stainless steel electrodes between which the viscous batter flows. Two heat exchangers made of copper allow cooling the walls and preventing clogging. Glycol water is used as heat transfer fluid. A thin silicon sheet is placed between the exchangers and the electrodes to electrically insulate the electrodes while allowing them to be cooled. The above materials are surrounded by polyacetal walls. The length of the channel is 10 cm and the gap between the electrode is 1 cm. The application of an electric voltage to the electrodes generate an electric current in the product which heats up by Joule effect.

The nozzle used having a rectangular shape, a 2D model is used for the simulations and the software COMSOL Multiphysics® 6.0 was chosen for its convenience when solving several coupled equations. The heat exchangers constituted of tubes in which the glycol flows, are replaced by two rectangular channels with a counterflow configuration. The 2D representation of the nozzle geometry with its mesh is shown in Figure 2. The geometry consists of 5 domains. It includes polyacetal walls, stainless steel electrodes, silicon plates and 2 fluid domains for the cake batter and the glycol water. The mesh consists of 79,276 triangles, of which 2,172 are boundary elements for 61,7504 degrees of freedom. This mesh is divided into 3 zones:

-Zone 1 (green): It represents the area where the accuracy should be as high as possible. It includes only the product. The maximum size of the elements is 0.02 mm and their minimum size is 0.00324 mm.

-Zone 2 (blue): It includes the stainless steel electrodes. An extremely fine mesh has been applied in this area due to the proximity of the boundary layers and the need to simulate the electric field.

-Zone 3 (light green): It includes the plastic walls, the water flow channel and silicon. The mesh is relaxed in this area as its elements are not in contact with the product.

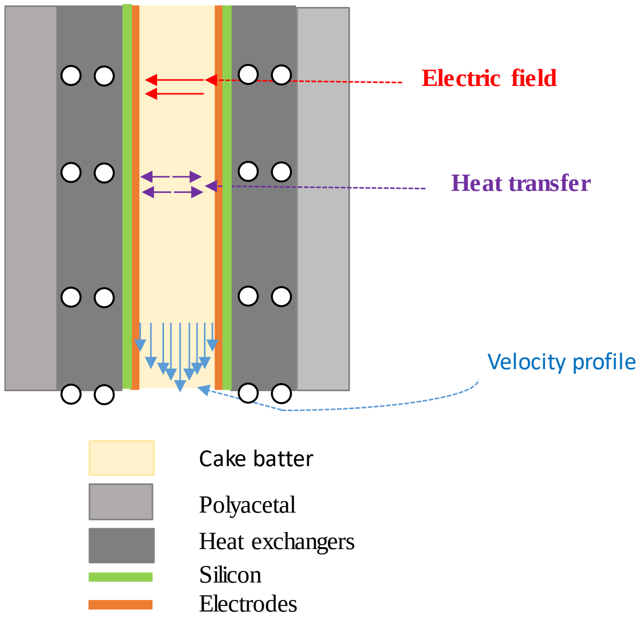

Figure 1. 2D geometry of the device

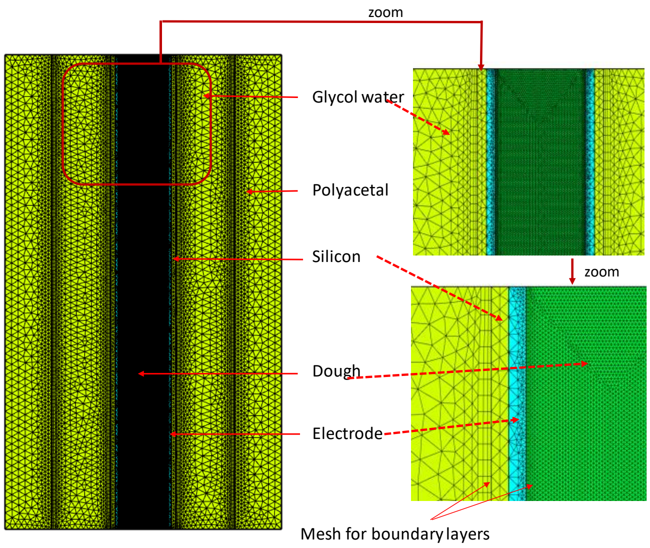

Figure 2. Mesh of the 2D geometry

The properties of the solid materials are shown in Table 1

Table 1. Physical properties of solid materials.

Properties	Polyacetal	Stainless steel	Silicon
ρ (kg.m^{-3})	1410	7850	2329
σ (S.m^{-1})	10^{-12}	$4.032 \cdot 10^{6}$	10^{-12}
k (W.K^{-1}.m^{-1})	0.39	44.5	130
Cp (J.kg^{-1}.K^{-1})	1400	475	700

3.2. Cake Batter recipe

The product used in this study is based on a cake batter recipe (29.5% of wheat flour, 25% of sugar, 20% of fat, 25% of egg and 0.5% of salt) used in previous study (Khodeir, 2020). A baking powder (mixture of Sodium Bicarbonate and Sodium Pyrophosphate Acid) was added to this formula to improve the texture of the cake findings.

3.3. Numerical model

3.3.1. *Electric field*

Ohmic heating is achieved by applying an electrical voltage to one of the electrodes, the other electrode being the ground. This application of voltage creates an electric field that varies spatially in the product. This electric field is obtained by solving Laplace's equation with appropriate boundary conditions. The electric potential is expressed as equation (1).

$$\vec{\nabla}.(\sigma\,\vec{\nabla}V) = 0 \qquad (1)$$

where σ is the electrical conductivity of the product (S/m), V is the voltage applied between the electrodes (V) and the vector $\vec{\nabla}V=\vec{E}$ is the electric field. The knowledge of the electric field makes it possible to calculate the energy used to heat the product (equation 2):

$$\dot{Q}_{gen} = \eta_{conv}\,\sigma||\vec{E}||^2 \qquad (2)$$

where η_{conv} is the energy efficiency conversion.

3.3.2. *Heat transfer*

For ohmic heating of a conductive fluid in steady state, the evolution of the temperature T is described by the following heat transfer equation (3) obtained from the energy conservation.

$$\rho C_p \vec{u}\vec{\nabla}T = \vec{\nabla}.(k\vec{\nabla}T) + \dot{Q}_{gen} \qquad (3)$$

where C_p is the effective heat capacity, k the effective thermal conductivity, ρ the density and $\vec{u}$ the velocity of the flow.

3.3.3. *Flow modelling*

The motion of the cake batter inside the channel and the flow of the glycol water are taken into account using the Navier-Stokes equations.

$$\rho\vec{\nabla}.\vec{u} = 0 \qquad (3)$$

$$\rho(\vec{u}.\vec{\nabla})\vec{u} = \vec{\nabla}\left(-P + \mu_{app}(\vec{\nabla}.\vec{u})^{t}\right) + \rho\vec{g} \qquad (4)$$

where P is the pressure and $\vec{g}$ the gravity acceleration vector. μ_{app} is the apparent viscosity that is temperature and shear rate dependent for the cake batter, resulting in highly nonlinear equations.

3.3.4. *Boundary conditions*

Natural convection and radiation are considered on the external walls but the sensitivity of results to these conditions is negligible. The inlet temperatures are 16°C and 5°C for the cake batter and the glycol water respectively. The electric field is computed in the cake batter and in the electrodes only. External boundaries are electrically insulated except one electrode boundary at potential $V_0 = 110$ V and one another at ground potential. For the flows, no-slip conditions are selected at walls and laminar velocity profiles are chosen as inlet boundary conditions. The mass flow rates are $1.55\ 10^{-4}$ kg/s and $1.83\ 10^{-3}$ kg/s for the batter and the glycol water respectively. The fluids flow in countercurrent.

4. Results and Discussion

4.1. Properties of the cake batter

Particular attention has to be paid to the thermophysical and electrical properties of the cake batter. The most important parameters are the viscosity, because it strongly influences the cake batter flow, and the electrical conductivity for the electric field and the volumetric heat. The other parameters $C_p(T)$, $\rho(T)$ and $k(T)$ were measured in the work of Khodeir (2020).

4.1.1. *Viscosity*

Figure 3 shows results of the viscosity as a function of shear rate for different temperatures (up to 95°C). The curves can be divided into two parts: one where the viscosity changes little for shear rates between 0.01 and 0.1 s^{-1} (except at 95°C where the viscosity increases) and a second where the viscosity decreases for shear rates above 0.1 s^{-1}. The first part constitutes the Newtonian plateau and the second part marks the rheological-fluidizing character of the batter.

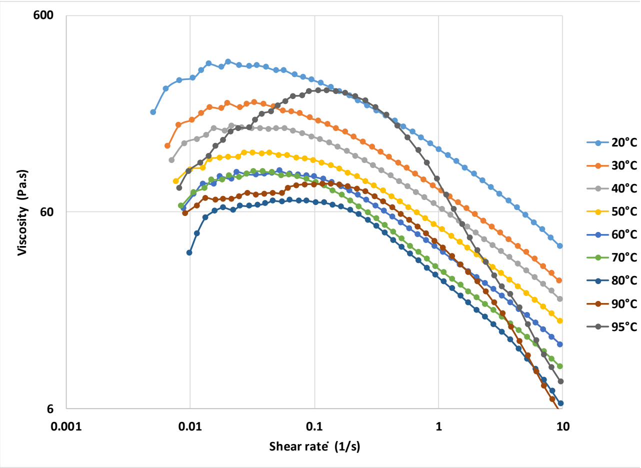

Figure 3. Viscosity of the cake batter vs shear rate for several temperatures

For some low shear rates, it was possible to measure the viscosity of the cake batter beyond 95°C as depicted in Figure 4. The viscosity decreases with temperature up to about 80°C and then increases beyond this value. This increase in viscosity is due to the gelatinization of the starch. All the results on viscosity were implemented in the model to take into account the fact that μ_{app} is strongly temperature and shear rate dependent.

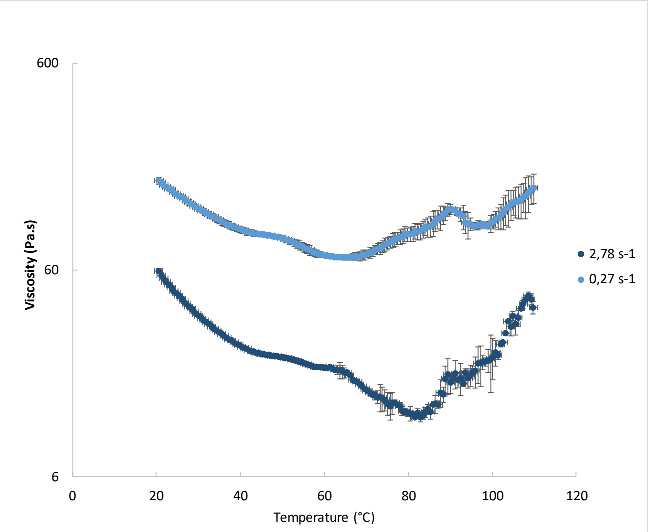

Figure 4. Viscosity of the cake batter vs temperatures for two shear rates

4.1.2. *Electrical conductivity*

The electrical conductivity was measured with a conductivity cell consisting of a polyacetal tube and two electrodes between which the batter was placed. Several electric field were used to measure the electrical conductivity in the baking conditions. From the experiments the following equation was set up to describe the evolution of the electrical conductivity as a function of temperature and gelatinization rate.

$$\sigma = \boldsymbol{\sigma_{25}} + \boldsymbol{K_T}(T-25) + \boldsymbol{K_{T\alpha}}(T-25)(\alpha) \qquad (5)$$

where α it the gelatinization rate, K_T and $K_{T\alpha}$ are empirical parameters and $\sigma 25$ is the electrical conductivity of the batter at 25°C. Before the gelatinization, the electrical conductivity increases linearly with the temperature ($K_T > 0$). A plateau appears as the gelatinization occurs because the parameter $K_{T\alpha}$ has a negative value. Equation (5) is implemented in the model.

4.2. Velocity profiles

As the cake batter flows in the nozzle, its temperature increases due to volumetric heating. Consequently, the batter could solidify due to the gelatinization, resulting in a risk of clogging, hence the need of cooling the electrodes. The influence of the viscosity on the flow can be seen if we look on the velocity profile along the channel. Figure 5 shows the mean velocity profile as a function of the distance between the electrodes at the middle and at the end of the channel. A flattening of the velocity profile is observed as the cake batter flows, reflecting the solidification of the batter center at the channel outlet. The batter close to the walls has a lower viscosity making the flow possible.

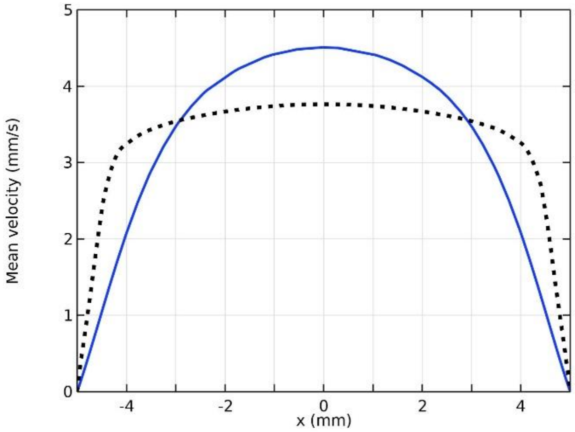

Figure 5. Mean velocity profile at the middle of the channel (blue) and at the outlet (black dotted line)

4.3. Temperature profiles and optimization

The numerical results of the temperature distribution in all domains are shown in Figure 6. The fast heating of the cake batter is clearly highlighted by Figure 6, where the product reaches more than 100°C at the outlet of the 10 cm channel, whereas it had an inlet temperature of 16°C. We can also see the cooling of the electrodes with the increase of the glycol water temperature at the upper part of the figure.

Energy is consumed for cooling the electrodes to ensure the flowing of the cake-batter, while electric energy is also used for heating. For reducing the energy consumption, the temperature profile at the exit of the channel has to be optimized. Figure 7 shows the strong temperature gradients obtained with the process parameters used for the simulation (blue curve). Preliminary tests were done with the glycol water flowrate and the voltage as parameters to be estimated. The Levenberg – Marquardt optimization procedure was chosen to get the parameters giving rise to a temperature profile as close as possible to the desired profile (Figure 7).

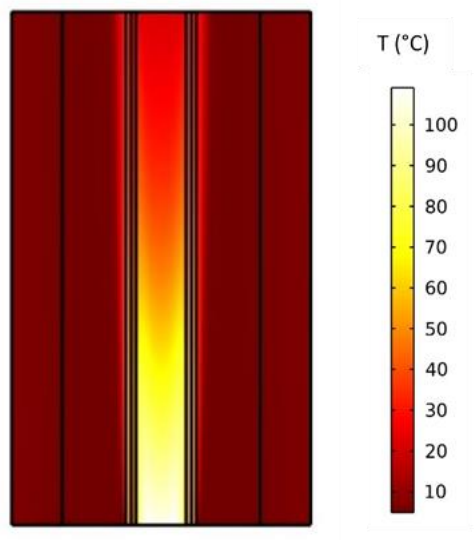

Figure 6. Temperatures in the channel.

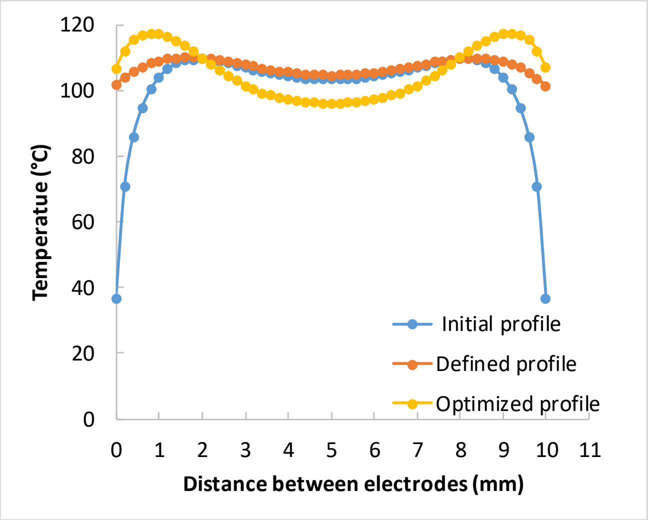

Figure 7. Temperature profiles at the exit of the channel: before optimization (blue), desired (orange) and optimized (yellow).

5. Conclusions

A numerical model was developed with the objective to design a 3D printing head with ohmic heating dedicated to the pre-baking step of a cake batter. Heat transfer and Navier-Stokes equations as well as Laplace equations for the electric field were solved for a product characterized by properties that are highly temperature dependent. Numerical results agree qualitatively with experimental results. The model is able to predict the solidification of the cake batter at the outlet of the channel. Optimization procedure seems to be a promising way to get a more homogeneous pre-baking at the nozzle outlet and to find optimal parameters leading to an energy efficient process.

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