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1 Study of continuous cake pre-baking in a rectangular channel using ohmic 2 heating

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11 12 ABSTRACT

13 An original device dedicated to additive manufacturing was developed to pre-bake cake batter. Its
14 originality lies in the fact that pre-baking is ensured by ohmic heating implemented in a rectangular
15 channel equipped with two parallel electrodes. Experiments and numerical studies were carried out
16 and benchmarked. The rheological properties of the cake batter (non-Newtonian power-law fluid) and
17 the influence of voltage and temperature on electrical conductivity were accommodated in the
18 numerical model. Due to the low velocities of the very viscous products near the solid-liquid interface,
19 it was found that the heterogeneity of the temperature at the nozzle outlet under continuous ohmic
20 heating could lead to nozzle clogging when high temperatures are reached. Hot spots were identified
21 in different areas of the channel, such as corners where the electric field is high and velocity is close to
22 zero. A parametric study was performed on the impact of the thermophysical properties of the batter,
23 showing that specific heat has a much greater impact than thermal conductivity on the accuracy of the
24 temperatures computed. Analysis of the process parameters showed that a stronger electric field leads
25 to a higher temperature gradient in the nozzle section. The temperature gradient decreases with
26 electrode distance (d_{elect}) and nozzle width (l). This model could be used to optimize the ohmic heating
27 nozzle configuration, with the objective of obtaining a continuous flow of pre-baked cake batter, while
28 preventing clogging. Such a system could be used as 3D printing head.

29 *Industrial relevance:*

30 Conventional 3D printing of bakery products is based on the deposition of a batter, followed by a
31 baking. This study proposes an innovative approach based on a printing nozzle equipped with ohmic
32 heating, with the objective of achieving a uniform temperature distribution and of obtaining high mass
33 flow rate. Despite a significant temperature gradient in the baked batter at the exit of the nozzle, the
34 obtained results showed that adjusting the nozzle geometry allows a reduction of the gradient. Further
35 investigations are thus needed to reduce the temperature gradient and to accommodate expansion of
36 the batter in the case of formulation using baking powder. The transfer of such concept for industry
37 application may be doable in a close future.
38

39 **Keywords:** Continuous Ohmic Heating, Baking, Cake Batter, Modeling, Electrical Conductivity,
40 Rheology

41 42 Nomenclature

| | |
|--------------------|---|
| A | Electrode cell area for electrical conductivity measurement (m ²) |
| C _p | Heat capacity (J·kg ⁻¹ ·K ⁻¹) |
| d _{elect} | Electrode nozzle distance (mm) |
| D _h | (4×S ₂)/P, Hydraulic diameter (m) |
| I | Current (A) |

| | |
|-----------------------|--|
| k | Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) |
| K | Constant of Eq. (14) ($^{\circ}\text{C}^{-1}$) |
| L | Nozzle length (mm) |
| l | Nozzle width (mm) |
| L_h | Hydrodynamic entry Length (m) |
| L_{elect} | Electrode cell distance for electrical conductivity measurement (m) |
| m_d | Mass of batter sample (kg) |
| m_i | Mass of batter when weighing immersed in oil (kg) |
| P | Nozzle perimeter (m) |
| m | Consistency index ($\text{Pa}\cdot\text{s}^n$) |
| \dot{m} | $S_2\times V_2$, Volume flow rate ($\text{kg}\cdot\text{s}^{-1}$) |
| n | Flow index (-) |
| P_r | $(\mu C_p)/k$, Prandtl number |
| \dot{Q} | Ohmic heating source ($\text{W}\cdot\text{m}^{-3}$) |
| S | Section (m^2) |
| S_2 | nozzle surface in the normal direction of the flow (m^2) |
| T_{ref} | Reference temperature ($^{\circ}\text{C}$) |
| $T_{\text{m-N}}$ | Nozzle mean temperature ($^{\circ}\text{C}$) |
| T | Temperature ($^{\circ}\text{C}$) |
| V_1 | Piston velocity ($\text{mm}\cdot\text{s}^{-1}$) |
| V_2 | Batter velocity inside the nozzle ($\text{mm}\cdot\text{s}^{-1}$) |
| V | Voltage (V) |
| Greek letters | |
| σ | Electrical conductivity ($\text{S}\cdot\text{m}^{-1}$) |
| σ_{ref} | Reference electrical conductivity at T_{ref} ($\text{S}\cdot\text{m}^{-1}$) |
| ρ_{app} | Batter apparent density ($\text{kg}\cdot\text{m}^{-3}$) |
| ρ_{oil} | Oil density ($\text{kg}\cdot\text{m}^{-3}$) |
| μ | Viscosity ($\text{Pa}\cdot\text{s}$) |
| Δp | Differential pressure (Pa) |
| Subscripts | |
| app | Apparent |
| d | Batter sample |
| elect | electrodes |
| h | Hydraulic, hydrodynamic |
| i | Immersed in oil |
| m-N | Nozzle mean value |
| oil | oil |
| ref | reference |
| 1 | Point to refer to piston region |

43
44
45

1. Introduction

46 3D printing (3DP), also known as additive manufacturing (AM), has undergone rapid growth in the
47 last few years, due to its large scope of application (Ali et al., 2016; Liu et al., 2018). It was first
48 introduced by researchers from Cornell University, using hot-melt extrusion to create personalized
49 chocolate products in complex 3D structures, using a Fab@home printer (Sun et al., 2015). 3D
50 printing applied to food is based on different technologies, as recently reviewed by Le-Bail et al.
51 (2020), and the most important applications are fused deposition modeling (FDM) and soft-material
52 extrusion (Severini & Derossi, 2016). A variety of materials has been used to demonstrate food
53 printing. Most of the existing publications linked to the 3D printing of baked products are based on the
54 deposition of a batter baked after deposition. The earliest application of 3D printing focused on the
55 printing of a “cake mix”, by extruding a batter mixture that consisted of starch, sugar, corn syrup,
56 yeast, and a cake frosting (Lanaro et al., 2017; Yang et al., 2001). However, the biggest challenges are
57 ingredient mixing, the associated rheology, structure accuracy and shape-stability, compatibility with
58 traditional food processing technologies (e.g. baking and drying), and printing speed. Usual
59 approaches to solidify the structure are based on cold extrusion, followed by a post-processing step.
60 Lipton et al. (2010) demonstrated that traditional cookie recipes were compatible with 3D printing.
61 However, extruded products do not retain their shape and structure after post-processing (e.g. baking),
62 due to the presence of high amounts of fat. Two methods can be used to solve the shape stability
63 problem: additives and recipe control (Lille et al., 2018; Lipton et al., 2015, 2010), but solutions
64 consisting of pre-baking the product have not been explored. The challenge consists in solidifying the
65 product while ensuring its flow. **Using a conventional heating system (based on hot walls) would yield
66 a batter to crumb transition starting at the wall with a progressive transfer towards the center of the
67 flow. This may cause several problems, in particular because the baked batter (crumb) would be much
68 harder than the unbaked batter at center of the flow.**

69 This paper focuses on new process solutions like solidifying while printing to prevent shape
70 destruction by implementing ohmic heating in the nozzle head. Ohmic heating (OH) is a thermal
71 process consisting of the internal generation of heat by the passage of an electric alternating current
72 (AC) through a medium with electrical resistance, such as food. In contrast to conventional heating
73 (CH), where the heat of a hot surface is conducted from the outside of a food to its inside, OH is
74 considered to induce heat within the entire mass, i.e. uniformly through the food (Leizeron &
75 Shimoni, 2005). **OH should allow for higher mass flow rate of the printing nozzle, accurate control of
76 the temperature and improvement of the energy efficiency.** This concept is not new and was used in
77 the early 20th century for the electric pasteurization or sterilization of milk and other pumpable foods
78 (viscous or liquid foods), such as fruit and vegetable products (juices, purees, pulps, etc.), and aseptic
79 packaging (De Alwis & Fryer, 1990b; Sarkis et al., 2013; Yildiz & Guven, 2014). OH was also
80 applied to solid foods and significant differences between OH and CH were highlighted. Textural
81 changes can occur following the microscopic and macroscopic changes in food products (Gavahian et
82 al., 2019). The kinetic of textural softening and the product texture could be affected by volumetric
83 heating at high rate. Kamali & Farahnaky, (2015) have also shown that ohmically processed
84 vegetables were characterized by a high textural cohesiveness. OH provides food industries with
85 several benefits such as saving in process time and energy. One of the main advantages is the rapid
86 and relatively uniform heating achieved (Marra et al., 2009). Contrary to classical heaters, whose
87 heating is not homogeneous, due to the nature of heat migration, OH can achieve homogenous
88 warming impossible to accomplish with classical heaters (Shynkaryk & Sastry, 2012). One important
89 key for successful OH is first to identify possible hot and cold spots, in order to eliminate them and
90 ensure the uniformity of heating or to achieve the desired temperature profile.

91 Several studies on ohmic cooking have been performed, but few of them have focused on bakery
92 products. The first application in baking was carried out on bread by Baker, (1939), whose aim was to
93 obtain a baked dough without temperature gradients. Gally et al., (2016) showed the interest of using
94 OH to bake crustless bread in batch conditions. Studies on several applications of OH to the batch
95 baking of cake have been published such as (e.g. Deleu et al., 2019; Luyts et al., 2013; Masure et al.,

96 2019). However, to our knowledge, the baking of bakery products by OH in continuous conditions has
97 never been studied. In such conditions, with a strong change in the rheological properties of the batter
98 during the batter-crumbs transition, OH appears as much more adapted than CH using a heated channel.

99 Mathematical modeling is a valuable tool for the development, understanding, and validation of
100 these emerging thermal technologies (Tijskens et al., 2001). It allows evaluation of the influence of
101 key variables such as electrical field strength and sample conductivity. Initial models of ohmic
102 processes, mainly two-dimensional systems, were developed for continuous flow systems, using
103 liquid-solid mixtures (Marra et al., 2009). Numerical modeling is essential to understand the OH
104 process, due to the difficulty of measuring real internal temperatures during continuous flow, because
105 of the presence of a strong electric field (Sastry & Palaniappan, 1992). Mathematical models were
106 developed and validated experimentally to study the heating patterns of solid-liquid mixtures in static
107 ohmic heaters (De Alwis & Fryer, 1990a; Salengke & Sastry, 2007; Sastry & Palaniappan, 1992; Shim
108 et al., 2010; Zhang & Fryer, 1993). On the other hand, numerical models for multiphase foods in
109 continuous ohmic heaters have been developed, due to the complexity of the parameters (Chen et al.,
110 2010; Choi et al., 2014; Sastry, 1992). Some works have concerned the continuous OH treatment of
111 highly viscous fluids (Shynkaryk & Sastry, 2012). The numerical results have shown the importance
112 of the OH chamber geometry, as it influences both current and fluid flow patterns and thus the
113 uniformity of heating.

114
115 The present study focuses on a new approach, consisting of the partial baking of a cake batter,
116 using ohmic heating embedded inside the printing nozzle head. This study is comprised of three main
117 parts. First, an original printing nozzle device, based on a rectangular canal, was developed to obtain a
118 cake batter pre-baked by OH. Second, the thermophysical and electrical properties of the cake batter
119 were determined, and then a numerical model was developed to model OH in continuous flow, with
120 the objective of understanding the links between the thermophysical properties, the channel geometry,
121 and the temperature profile in the printing nozzle. After validating the numerical model, additional
122 simulations were carried out to establish recommendations to ensure convenient cake pre-baking by
123 continuous OH.

124 2. Materiel and Methods

125 2.1. Materials

126 2.1.1. Rectangular nozzle description

127 A rectangular nozzle was chosen because of its ease of development and versatility. 3D geometry
128 was plotted on Autodesk® Inventor® 2015; the drawing of the nozzle is presented in Fig. 1. It consists
129 of: 1) two parallel stainless steel electrodes (red), enclosed in 2) two rectangular polycarbonate plates
130 (gray), separated by 3) two polycarbonate beams (green) 0.105 m long, with variable width and
131 thickness to allow calibrating the nozzle dimension, and finally, 4) a channel support also made of
132 polycarbonate (A) and (B). Fig. 1 (C) shows the nozzle dimensions, where the nozzle length, L , is
133 equal to 105 mm. The total width of the device, b , is equal to 80 mm; the thicknesses of the electrodes
134 and the polycarbonate plates are equal to 1 mm and 10 mm, respectively. The nozzle section depends
135 on the width, l , and on the distance between the electrodes, d_{elect} , set at 4 cm and 1 cm, respectively,
136 for this paper.

137 2.1.2. System description

138 The complete experimental set-up is presented in Fig. 2 (A). A drive motor (H T23-400D, ORIGA
139 System plus, USA) was used to (1) impose the displacement of the piston at a constant velocity, (2)
140 ensure a flow of batter in the cylindrical container (3), and then in the rectangular nozzle (4). The
141 nozzle was equipped with electrodes to heat and pre-bake the cake batter.

142 The voltage applied between the electrodes (ohmic heating) by the voltmeter (a) (Fluke 45 dual
143 display multimeter, USA) was controlled by an autotransformer (d) (DEREIX S.A, Paris, rotortransfo
144 120 NC, reference R.212). All the data collected from the experiments, especially the temperature
145 variations measured between the inlet and the outlet, were logged by a data logger (c) (AOIP, France)
146 and stored in the PC (f) (logidat program, Samsung computer). The current flowing through the cake
147 batter was recorded with an ammeter (b) (Multimeter MN 5128, AOIP Mesures, France).

148 During each experiment, the velocity applied by the piston (2) and the voltage between the
 149 electrodes were constant, and the temperature of the batter through the nozzle increased due to ohmic
 150 heating.

151 *2.1.3. Experimental procedure and outlet temperature*

152 All the experiments were conducted in such a way that the batter passing through the nozzle did not
 153 solidify. The nozzle dimensions were mentioned in section 2.1.1, and the process parameters were set
 154 to 65 V for the voltage and $V_1 = 0.1$ mm/s for the piston speed. Four thermocouples (T_1 to T_4) were
 155 installed at the outlet of the nozzle (Fig. 2B), and one thermocouple T_5 at the inlet, to measure the
 156 variation of temperature along the nozzle. Four experiments were carried out with the same process
 157 parameters, and the temperature of the cake batter at the inlet was between 16 °C and 22 °C.

158 *2.1.4. Cake batter sample preparation*

159 Cake batter was prepared based on the recipe and cake-making method of Hesso (Hesso et al.,
 160 2014), except that no baking powder was used. The recipe used for the reference cake batter is given
 161 in Table 1. The ingredients of each formula were mixed in a KitchenAid (KSM90, KitchenAid, St.
 162 Joseph, MO, USA) in two stages to obtain the final cake batter. In the first stage, sugar, fat, and liquid
 163 egg were mixed for 2 min at average speed 6, then the wheat flour and salt were added and mixed in
 164 the second stage for 3 min at high speed 8.

165
 166 **Table 1**
 167 Cake batter recipe.

| Ingredient | Origin | Percentage wb(%) | Water content (% db) [ISO 712 : 2001(1998)] |
|------------------------|---|---------------------|--|
| Wheat Flour T55 | Petits moulins de France | | |
| Sugar (S) | Saint Louis, France | 25 | |
| Fat (FA) | | 20 | |
| Liquid Egg (E) | Ovoteam, France | 25 | |
| Salt (SA) | Cerebros, Esco France s.a.s, France | | |

168 *2.2. Batter characterization*

169 *2.2.1. Ohmic heating system and measurement of electrical conductivity*

170 A literature review showed the importance of controlling electrical conductivity during OH of a
 171 food product. In order to correctly design and control the batter cooking process, it was essential to
 172 determine the batter's electrical conductivity under different experimental conditions. All experiments
 173 were carried out in triplicate.

174 The ohmic cell, used to calculate the electrical conductivity of liquid products, was adapted from Gally
 175 et al. (2016), with small changes in cell material and dimensions. The short cell was replaced by a new
 176 polyacetal with an internal diameter of 29 mm and an external diameter of 42 mm.

177 The impact of electric voltage on the electrical conductivity of the cake batter was monitored with
 178 AC voltages (50 Hz) of 100 V, 150 V, and 200 V (22 V/cm, 33 V/cm, and 48 V/cm). The time–
 179 temperature data were plotted to obtain the ohmic heating curves for the batter. Electrical conductivity
 180 was plotted against the corresponding temperature to obtain the electrical conductivity curves.
 181 Electrical conductivity was measured using the following equation:

$$\sigma = \frac{(L_{elect} \times I)}{(A \times V)} \quad (1)$$

183

184 L_{elect}/A denotes the cell constant and is equal to 67.72 m^{-1} . It is calculated from a calibration, using the
185 method of Olivera et al. (2013). Solutions of potassium chloride and sodium chloride were used as
186 references, for which their electrical conductivities are known for their temperatures and
187 concentrations.

188 2.2.2. Measurement of thermal conductivity and heat capacity

189 The thermal conductivity of the cake batter was measured based on the method proposed by Sweat
190 & Parmelee (1978) and also used by Jury et al. (2007), using a line-heat source probe. The probe
191 consists of a hypodermic needle with an external diameter of 0.7 mm and a length of 3.5 cm,
192 containing a heating wire and a K-type thermocouple (OMEGA, Stamford, CT, USA). The thermal
193 conductivity measurements were performed at different temperatures, by placing the samples in a
194 climatic chamber (Froilabo, Meyzieu, FRANCE).

195 The heat capacity was measured by micro-calorimetry, with a micro DSC VII (SETARAM,
196 Caluire, FRANCE), calibrated against the specific heat of saphir. Around 100 mg of batter was
197 installed in a stainless steel pan, which was hermetically closed. A heating rate of $1 \text{ }^\circ\text{C}/\text{min}$ was used
198 from 10 to $120 \text{ }^\circ\text{C}$; the integration of the thermogram provided an enthalpy function whose derivative
199 yielded a specific heat function (provided as a function of temperature). All the thermal conductivity
200 and heat capacity experiments were carried out in triplicate.

201 2.2.3. Density

202 A densimetric method was used to calculate the apparent density of the cake batter (Baker & Mize,
203 1946). A 500 ml beaker was filled with rapeseed oil (density: $935.5 \text{ kg}/\text{m}^3$) and placed on a scale. A
204 holder was maintained in the oil, and the tare was set. The batter was weighed on the scale and then
205 immersed in the oil. Its apparent density was calculated using the following equation:

$$206 \rho_{app} = m_d \times \rho_{oil}/m_i \quad (2)$$

207
208 The density of the oil was determined by the weight/volume method, using a $45.28 \times 10^{-6} \text{ m}^3$ glass
209 cylinder. The cup was filled with oil, leveled on the surface using a spatula, and weighed on an
210 analytical balance. This technique yielded a true batter density, accommodating the possible presence
211 of gas entrapped in the batter during mixing.

212 2.2.4. Rheological properties

213 The hydro-thermal transformations undergone by starch and gluten are the origin of the evolution
214 of the rheological properties of a dough during cooking (Bloksma, 1980). Many models have been
215 developed, leading to a large number of phenomenological models for dough viscosity (Zhou, 2004).

216 The apparent viscosity of batter was determined using a rotational viscometer, 'VT550
217 RHEOWIN' (HAAKE, France). The fluid was placed between two coaxial cylinders with a well-
218 defined imposed shear rate, and the resulting shear stress was measured. Rheological measurements
219 were performed between 25 and $95 \text{ }^\circ\text{C}$, with a precision close to $\pm 1\%$ for the apparent viscosity, using
220 a Ministat 230/Huber with a step of $10 \text{ }^\circ\text{C}$. The variation of the consistency index, m , and the flow
221 index, n , of the batter was determined for a shear rate between 0.9 and 150 s^{-1} in 2 min. These
222 experiments were performed in triplicate.

223 2.3. Numerical models

224 2.3.1. 2D and 3D geometries

225 2D and 3D numerical models were developed on COMSOL Multiphysics 5.4, to study the
226 temperature profile of the cake batter in continuous flow at the nozzle outlet.

227 The 3D model is represented with symmetry along the xz -plane, to decrease simulation time. The
228 2D geometry shows the nozzle in the xz -plane.

229 A mesh independency study for a laminar non-Newtonien fluid flow was performed to determine
230 its effects on the CFD (Computational fluid dynamics) simulation results. It was clear that the
231 simulation time was highly dependent on the number of mesh nodes, and a compromise had to be
232 found between the grid-independent solution and the calculation time.

233 The numbers of domain elements chosen for the 2D and 3D models were equal to 3341 and 36238,
 234 for simulation times of 302 s and 1407 s, respectively.

235 2.3.2. Governing equations

236 Due to the existence of a strong electric field inside the nozzle, the temperature profile was very
 237 difficult to measure experimentally. The fluid temperature was measured at three points at the outlet of
 238 the nozzle. To carry out a stricter validation of numerical models, we made the choice to study the
 239 non-stationary flow, in order to obtain the evolution of the temperature at the nozzle outlet.

240 Navier–Stokes equations were used to describe the incompressible fluid flow, in which flow
 241 behavior is governed by:

$$\rho \partial u / \partial t + \rho (u \cdot \nabla) u = \nabla \cdot [-pI + \mu(\nabla u + (\nabla u)^T)] + F \quad (3)$$

242 where u is the velocity field. From left to right, the different terms in the equation above correspond to
 243 the inertial forces, the pressure forces, the viscous forces, and the gravitational force applied to the
 244 fluid ($F = -\rho g$).

245 Besides the Navier-Stokes equation, the continuity equation was also solved:

$$\partial \rho / \partial t + \rho \nabla \cdot (u) = 0 \quad (4)$$

247 where $\partial \rho / \partial t = 0$, because it is considered to be an incompressible fluid.

249 In the case of the continuous flow ohmic heating process, the product is subjected to temperature
 250 and shear-rate gradients. A power-law model is used to fit the batter viscosity:

$$\mu = m \dot{\gamma}^{(n-1)} \quad (5)$$

253 where μ is the viscosity, $\dot{\gamma}$ the shear rate, m the consistency index which is temperature dependent, and
 254 n the flow behavior index.

255 Heat transfer within the liquid sample was solved and based on the general heat equation with a source
 256 term:

$$\rho C_p \partial T / \partial t + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + \dot{Q} \quad (6)$$

259 where ρ is the density which is constant, C_p is the heat capacity at constant pressure, and k is the
 260 thermal conductivity. C_p and k are temperature dependent, and is the Ohmic heating power source.
 261 The heat, in Eq. (7) is generated by Joule effect, due to the dissipation of electrical energy into heat:

$$\dot{Q} = \sigma \cdot |\nabla V|^2 \quad (7)$$

264 where $|\nabla V|$ represents the modulus of the gradient of electrical potential, and σ is the temperature-
 265 dependent electrical conductivity of the batter.

266 The electrical potential distribution within the batter was computed using the following Laplace
 267 equation:

$$\nabla \cdot \sigma \nabla V = 0 \quad (8)$$

269 2.3.3. Boundary and initial conditions

270 A vertical natural convection condition was considered to exist at all the faces of the nozzle. The
 271 heat losses, due to convection phenomena between the nozzle and the ambience around the sample,
 272 take into consideration the external heat-transfer coefficient (h_{ext}), using COMSOL equations with q
 273 being the convection heat flux ($W \cdot m^{-2}$):

$$q = h_{ext} (T_{ambient} - T) \quad (9)$$

274

275 The initial batter temperature is equal to T_i at $t = 0$ (0 - time injection), and the initial nozzle
 276 temperature is equal to $T_{ambient} = 20$ °C.

277 For the inlet flow conditions, it was shown that a uniform velocity profile at the inlet affects the
 278 temperature profile as well as the pressure drop along the nozzle. An analysis was performed to choose
 279 the right velocity profile at the nozzle inlet and to calculate the hydrodynamic entry length (L_h),
 280 Reynolds number (N_{GRe}), and pressure drop (Δp). The calculation was performed by considering the
 281 mean values of the different parameters at the mean nozzle temperature between the inlet and the
 282 outlet. The power-law Reynolds number used is:

$$N_{GRe} = 2^{(3-n)} \frac{\rho_{app} V_2^{2-n} D_h^n}{m \left(\frac{3n+1}{n}\right)^n} \quad (10)$$

283

284 The hydrodynamic entry length of this region was calculated from:

285

$$L_h = 0,05 R_e D_h \quad (11)$$

286

The differential pressure of power-law non-Newtonian laminar flow is given by:

$$\Delta p = \frac{2^{n+2} \left(\frac{3n+1}{n}\right)^n L m V_2^n}{(D_h)^{n+1}} \quad (12)$$

287

Table 2 shows the analytical results used as boundary conditions for the numerical study.

288

289

290

Table 2

Rectangular nozzle – 65 V – $V_1 = 0.1$ mm/s - analytical study.

| Experience | | T_{m-N} *(°C) | N_{GRe} | L_h (m) | Δp (Pa) |
|-----------------|----|-----------------|-----------|---------------|-----------------|
| V_2 (mm/s) | V | Expe | Eq (10) | Eq (11) | Eq (12) |
| 4 | 65 | 33.33 | 0.0023 | 1.8410^{-6} | 1415.1 |

291

* mean nozzle temperature between the nozzle inlet and outlet.

292

293 The L_h ($1.84 \cdot 10^{-6}$ m) obtained is much shorter than the nozzle length (0.105 m). As a consequence,
 294 the velocity was fully developed at the nozzle entrance section, as this region was much longer in the
 295 laminar flow condition than in turbulent flow (Cengel, 2008). The batter was characterized by a high
 296 Prandtl number ($P_r = 421973$), so that the flow is considered as thermally developing but
 hydrodynamically developed.

297

298 The wall conditions (solid – liquid interface). For the solid-liquid interface, no slip condition was
 299 considered to exist inside the nozzle, and the flow velocity in the immediate vicinity of the surface was
 assumed to be zero.

$$u = 0 \text{ at } \forall t \geq 0 \quad (13)$$

300

301 At the nozzle outlet section, the atmospheric pressure condition was set at $p = 0$ for any time above
 302 the initial time ($\forall t \geq 0$).

303

3. Results and Discussion

304 3.1. Effect of temperature and voltage gradient on electrical conductivity

305 Eq. (1) was used to determine the electrical conductivity of the cake batter and its evolution with
 306 temperature, as shown in Fig. 3 (A), at a voltage gradient of 50 V/cm.

307 Three stages are distinguishable. Zone 1 shows a polynomial curve of the second degree ($R^2 >$
 308 0.999), before starch gelatinization, from 26°C to 80°C; at this stage, the variation of electrical
 309 conductivity can be calculated, using a reference temperature, and expressed by Eq. (14). These results
 310 can be compared with those of Gally et al. (2016), who observed a linear variation of electrical
 311 conductivity, before starch gelatinization, for bread dough. Zone 2 begins at just below 80 °C, which
 312 represents the temperature at the beginning of starch gelatinization. From there, the rate of increase of
 313 electrical conductivity decreases strongly, until the temperature reaches 98°C, and at some stage, it
 314 becomes almost constant. Zone 3 shows a linear variation of electrical conductivity, with a slope
 315 different from that of zone 1. Similarly, Gally et al. (2016) obtained a linear pattern after
 316 gelatinization, with a different slope ($d\sigma/dT$), and attributed it to a change in the product.

317 The changes in the electrical conductivity of batter with temperature, during ohmic heating at three
 318 different voltage gradients, are shown in Fig. 3 (B). For a voltage gradient of 48 V/cm, the onset
 319 temperature of starch gelatinization was 80 °C, that of 33 V/cm was 90°C, and that of 22 V/cm was
 320 100°C. These experiments showed that electrical conductivity increases with voltage gradient. Similar
 321 observations were reported for tomato juice in the range of 50–70 V/cm (Srivastav & Roy, 2014), and
 322 for apricot and peach juices in the range of 20–70 V/cm (Icier & Ilicali, 2005). As the voltage gradient
 323 increased, the heating time of the cake batter, required to reach the prescribed temperature, decreased.
 324 It was found that the ohmic heating time increased by up to 3.6 times, when the voltage gradient was
 325 decreased from 48 to 22 V/cm (Fig. 3C).

326 Electrical conductivity was modeled in zone 1 (before starch gelatinization) and can be written as
 327 follows:

$$\sigma = \sigma_{ref} (1 + K'(T - T_{ref})^2 + K(T - T_{ref})) \quad (14)$$

328 where K and K' are constants, and T_{ref} and σ_{ref} are the reference temperature and electrical
 329 conductivity, respectively. Their values, at the three different electric voltages, are presented in Table
 330 3. Fig. 3 (B) was used to model the variation of electrical conductivity with temperature at different
 331 voltages.

332
 333 **Table 3**
 334 Values of reference temperature, electrical conductivity, and constants K and K' .

| Parameter | 200V | 150V | 100V |
|--------------------------|---------------|--------------|---------------|
| T_{ref} (°C) | 26.3 | 26.3 | 26.3 |
| σ_{ref} (S/m) | 0.048 | 0.051 | 0.055 |
| K (°C ⁻¹) | 0.04 | 0.034 | 0.024 |
| K' (°C ⁻²) | 3.5410^{-4} | 2.110^{-4} | 1.4710^{-4} |

335

336 3.2. Thermophysical properties of cake batter

337 3.2.1. Viscosity profile

338 Fig. 4 (A) and Fig. 4 (B) show the data, in logarithmic form, for the cake batter sample at a
 339 reference temperature of 25°C, and at different temperatures (35°C, 45°C, 75°C, and 85°C),
 340 respectively, where the shear rate varied from 0.9 to 150 s⁻¹. It was found that the power law fits the
 341 apparent viscosity behavior very well ($r^2=0.99$). The results illustrate the power-law non-Newtonian
 342 behavior of the cake batter. It is clear, in Fig. 4 (B), that the viscosity decreases, as expected (Bloksma,
 343 1980), when the batter temperature increases at constant shear rate, before the gelatinization onset
 344 temperature. At a shear rate of 0.5 s⁻¹, the viscosities are equal to 1.4 and 0.8 Pa.s, at 25 °C and 75 °C,
 345 respectively. After gelatinization at 85°C, for the same shear rate of 0.5 s⁻¹, the viscosity increases
 346 again and is equal to 0.95 Pa.s.

347 Flow index, n , is equal to 0.6 ± 0.05 and is considered constant. The consistency index, m , is
348 variable with temperature; it is equal to the viscosity, for a shear rate of 1 s^{-1} , as shown in Fig. 4 (C).
349 Its evolution as a function of temperature is represented by Eq. (15).
350

$$m = 9 \times 10^{-5} \times T^3 - 0,0063 \times T^2 - 0,6672 \times T + 58,203 \quad (15)$$

351
352 It can be seen, in Fig. 4D, that the viscosity decreases with temperature at a fixed shear rate, until it
353 reaches the gelatinization temperature. After that, it increases with temperature up to 95°C at a
354 different shear rate. The viscosity decreases when the shear rate increases at constant temperature. At
355 25°C , it is equal to 18 and 12 Pa. s, at shear rates of 10 and 30 s^{-1} , respectively.

356 3.2.2. Density, heat capacity, and thermal conductivity

357 The cake batter density (ρ) was found to be $970 \pm 8 \text{ kg. m}^{-3}$. The cake batter thermal conductivity
358 vs. temperature could be modeled using Eq. (16); the limit of validity of this equation is 85°C , which
359 is the gelatinization onset temperature.

$$k(T) = 3,8 \times 10^{-5} \times T^2 - 1,27 \times 10^{-3} \times T + 0,21 \quad (16)$$

360
361 The evolution and uncertainty of the cake batter's thermal conductivity and heat capacity with
362 temperature are presented in Fig. 5.

363 Heat capacity and thermal conductivity are responsible for the considerable non-linearity of the
364 numerical model, due to their temperature dependence.

365 3.3. Comparison between numerical simulation and experimental results

366 3.3.1 Outlet nozzle temperatures – voltage 65 V – velocity 4 mm/s

367 The experimental and simulation results for the outlet nozzle temperature vs. time are presented in
368 Fig. 6. 2D and 3D simulations showed good agreement with the experiments for temperature T_1 . In 2D
369 geometry, edge temperature T_2 could not be determined, so a 3D simulation was necessary, which also
370 showed a good correlation with the experiments.

371 The total injection time was 12 min at 65 V, with a batter velocity of 4 mm/s. When the steady state
372 was reached after almost 7 min of injection, the results showed a temperature **difference** between T_1
373 and T_2 equal to 11°C . The transition phase, from 0 to 7 min, showed a small difference between the
374 simulation and the experimental results and was composed of two parts. The first was from 0 to 1 min,
375 where the linear temperature evolutions of T_1 and T_2 with time occurred at the same rate of 0.2°C/s .
376 The second was from 1 min to 7 min, where the temperature evolution was polynomial, and the rate of
377 increase of T_2 was faster than that of T_1 . The temperature difference between T_1 and T_2 , along the x
378 axis, was almost insignificant and equal to 0.2°C .

379 In previous studies, Marra et al., (2009) and Gally et al., (2016) showed the advantage of using
380 ohmic heating in static conditions, with a homogeneous temperature distribution with higher
381 temperature at the center, due to volumetric heating from inside to outside. In the present study
382 involving continuous OH, the temperature gradient between the center and the side of the rectangular
383 channel was reversed, with hot spots in the corners of the channel. To better understand the reason for
384 this heterogeneity, it is necessary to understand what occurs inside the nozzle, with the help of the
385 numerical model.

386 Several simulation results are presented in Fig. 7. Fig. 7 (A) shows the volume electric field. The
387 points where the electric field is the strongest are those at the edges of electrodes. At the center of the
388 electrodes, the electric field is equal to 65 V/cm (in blue). At the bottom of the electrode (horizontal
389 line, parallel to the y axis in Fig. 7 (A) and Fig. 7 (B)), the electric field varies between 200 and 250
390 V/cm , and at the edge line (or vertical line, light blue in Fig. 7 (A)) parallel to the z axis, it is equal to
391 100 V/cm .

392 The xy plane of the nozzle (Fig. 7B) also shows a strong electric field at the corner of the electrode
393 (red zone). It can be seen that, inside the nozzle, the electric field passes through the batter in the
394 perpendicular direction of the two electrodes. It can be seen that the electric field that crosses through

395 the nozzle body (polycarbonate) is negligible. The shear rate inside the nozzle depends on the velocity.
396 Fig. 7 (C) shows that the lowest shear rate, which is almost equal to zero, is at the center of the nozzle,
397 while the highest shear rate, which is parallel to the y axis and equal to 4.89 s^{-1} , is at the outlet edge of
398 the nozzle.

399 The velocity profile tends to zero near the walls (solid-liquid interface) along the y and x axes, as
400 shown in Fig. 7 (D). The residence time and the difficulty to remove heat by convection close to the
401 walls cause temperature heterogeneity and higher temperature at the wall interface. As expected, the
402 latter along the y-axis could cause fouling by clogging, due to starch gelatinization in the batter, in the
403 case of higher voltages.

404 It is important to note the temperature distribution in the xy plane, as shown in Fig. 7 (E). It is
405 obvious that the highest temperatures are at the corners between the electrodes and the polycarbonate
406 beam. The temperature near the electrodes in the x direction is lower than those near the wall in the y
407 direction, although the velocity is zero for both. This could be explained as being due to the strong
408 electric field at these corners (Fig. 7B), along with very high viscosity and zero velocity. Hashemi &
409 Roohi, (2019), have performed numerical modeling of process and bacterial inactivation kinetics with
410 ohmic heating. They have found that the initiation of temperature rise near the regions with high
411 gradient values of electric field was predictable with CFD. Jun & Sastry, (2005) have also found that
412 the electric field strength near the edges of electrodes goes close to the maxima: up to 4985 V/m in
413 their 2D numerical study on the ohmic heating of foods inside a flexible package. They conclude that
414 the electrode configuration could be optimized to ensure uniformity of heating.

415 In summary, the heterogeneity of temperature is a consequence due not only to zero velocity at the
416 wall interfaces, but also to the hot spots that occur at the electrode corners, because of the strong
417 electric field and the very low velocity at these points.

418 In this section, the model developed was validated successfully, showing good agreement between
419 the experimental and predicted temperatures. The main goal here was to predict the temperature
420 profiles of the cake batter inside the nozzle. The results showed heterogeneous temperatures that could
421 cause nozzle clogging at higher temperatures. The challenge now was to flatten and even reverse the
422 temperature profile, by trying different process parameters and by studying the effect of batter
423 properties on the outlet temperature profile. To do that, it seemed necessary to study the influence of
424 certain parameters, and to determine their relative impact on the computed values.

425 3.3.2. Parametric study

426 A parametric study was carried out to monitor the impact of the batter properties and nozzle
427 dimensions on the computed temperatures. In this section, all the results were obtained for stationary
428 flows.

429 A) Thermal conductivity

430 The effect of thermal conductivity was studied first. The results are shown in Fig. 8 (A). The
431 experimental results showed that the thermal conductivity varied from 0.2 to 0.4 W/(m. K) , for a
432 temperature range of 24°C to 74°C . A reference value was set to 0.4 W/(m. K) . When this value
433 decreased by 50%, T_2 increased by 3%, and T_1 decreased by about 2.5%. When the thermal
434 conductivity increased by 50%, T_2 decreased by 2%, and T_1 increased by 2%. It can be seen here that,
435 at a higher thermal conductivity, T_1 at the center and T_2 at the near edge were reversed. It was
436 observed that, when the thermal conductivity was increased by about 50%, the temperature gradient
437 decreased by almost 5%. In summary, when the thermal conductivity increased, the temperature
438 gradient between the center and the near edge decreased; this result was expected, since high thermal
439 conductivity facilitates heat diffusion within the batter, resulting in better temperature equilibration
440 during heat-up. In turn, a reduced temperature gradient was observed.

441 These results showed that the accuracy in determining the thermal conductivity of the batter had a
442 minimal impact on the computed temperature, as a 50% increase in this property yielded only a 2% to
443 3% uncertainty in the temperatures.

444 B) Specific heat

445 The impact of specific heat was investigated in a similar way. It was observed that, when the
446 specific heat increased, temperatures T_1 and T_2 tended to decrease, the lowest specific heat resulting, as
447 might be expected, in the highest temperatures. When the heat capacity was decreased by 8%,

448 temperatures T_1 and T_2 increased by 4%, and when the heat capacity was increased by 19 %, T_1 and T_2
449 decreased by 7%. A further result was that the specific heat had no effect on the temperature gradient,
450 because T_1 and T_2 were affected at the same rate.

451 The temperature profile was not reversed, as had been shown in the previous study on the impact of
452 thermal conductivity. The main finding was that greater accuracy in the determination of specific heat
453 was needed, compared to that for thermal conductivity. For example, a deviation of 8% for specific
454 heat led to a 4% deviation in the computed temperatures. However, the accuracy of specific heat was
455 sufficient to conveniently predict the profile temperatures.

456 C) Density

457 The reference density of the cake batter was 980 kg/m³. The density of the gas-free batter (obtained
458 by computation) was 1200 kg/m³, thus indicating that the batter porosity was 24.3%. For a gas-free
459 batter, the temperature observed at the center (T_1) decreased from 37.7 °C to 34.6 °C, corresponding to
460 a temperature difference of 8%. In contrast, when the batter density was decreased by 50% (from 980
461 kg/m³ to 500 kg/m³), it was observed that T_1 increased by about 13%, based on the initial batter
462 temperature. Here also, T_1 and T_2 were found to change at the same rate with density. Unlike thermal
463 conductivity, but like thermal capacity, the batter density did not flatten the temperature profile.
464 However, it seemed to be important to determine the batter density with sufficient accuracy, at least
465 greater than that of the thermal conductivity, but less than that of the specific heat.
466

467 D) Electrical conductivity and viscosity

468 Fig. 8 (B) shows a parametric study on electrical conductivity and its effect on the temperature
469 profile. The extreme limits of its value were used. Three values were chosen (0.05, 0.125, and 0.2
470 S/m), It can be seen that the higher the electrical conductivity, the higher was the temperature gradient
471 between T_1 and T_2 . **Electrical conductivity plays a major role in the efficiency of the heating process,
472 especially for sweet products, which have a lower electrical conductivity than salty products. Further
473 investigations should be carried out to assess the influence of the cake batter formulation on this
474 property.** The same study was performed on viscosity: three values were studied (40, 25, and 13 Pa. s),
475 namely the limits of variation of the batter viscosity between 20°C and 95°C. The results showed no
476 significant impact of viscosity on the temperature profile.

477 In summary on the impact of batter properties, this study showed the importance of precision in the
478 determinations of electrical conductivity, specific heat, density, and thermal conductivity, as they have
479 a strong impact on the batter temperature profile. Among all the thermophysical properties of the cake
480 batter, thermal conductivity appeared to be the one that most influenced the temperature gradient (the
481 difference between T_1 and T_2). By increasing this property, the temperature gradient decreased, but this
482 change was not sufficient to reverse the temperature profile (the temperature distribution inside the
483 nozzle). Furthermore, it was difficult to control these properties, because they are temperature
484 dependent, making the solution impossible.

485 To summarize this section, it seemed to be difficult to change the temperature profiles by adjusting
486 the thermophysical properties of the cake batter. Hence, this situation led to the idea of studying the
487 process parameters.

488 E) Nozzle dimensions

489 Further work, based on parametric studies, was carried out to assess the effect of nozzle geometry
490 on the temperature profile. To do this, different aspect ratios ($\alpha = d_{elect}/l$) and nozzle dimensions were
491 studied. The temperature distribution at the nozzle exit was determined for several electric field
492 strengths, for the same flow velocity $V_2 = 4$ mm/s. Three channel cross sections were used (presented
493 in Table 4) to determine the effect of nozzle dimensions on the heterogeneity of the temperature along
494 the nozzle outlet along the y-axis.
495

496 **Table 4**
497 Dimensions of nozzle sections.

| | l (cm) | d_{elect} (cm) | α |
|------------------|----------|------------------|----------|
| Section 1 | 2 | 0.5 | 0.25 |
| Section 2 | 4 | 1 | 0.25 |

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Fig. 9 shows the evolution of the nozzle outlet temperature, at 65 V/cm (A) and 100 V/cm (B), for three different nozzle sections, as a function of the dimensionless number $y^* = y/(l/2)$. When the voltage was increased from 65 V/cm to 100 V/cm, for the same nozzle section, T_1 and T_2 increased by 22% and 23.5%, respectively. It can be observed that the increasing rate of temperature T_2 was higher than that of T_1 , which means that, at a stronger electric field, a higher temperature gradient was produced for the same section.

Fig. 9 (A) shows the effect of the nozzle section, at 65 V/cm, on the outlet nozzle temperature. Section 1 (green line), section 2 (red line), and section 3 (blue line) are presented, where section 1 and 2 had the same aspect ratio but different nozzle dimensions. At 65 V/cm, the temperature difference between T_1 (center) and T_2 (wall), for an aspect ratio of 0.5 (section 3), 0.25 (section 1), and 0.25 (section 2), were equal to 13 °C, 8.5 °C, and 15 °C, respectively. For 100 V/cm, the temperature differences between T_1 (center) and T_2 (wall) were equal to 18 °C, 12.5 °C, and 20 °C, respectively (Fig. 9B).

In summary, for different voltages, it was found that the aspect ratio affected temperature heterogeneity along the y-axis. For the same nozzle width l (section 1 and section 3), if the distance between the electrodes (d_{elect}) was decreased from 1 to 0.5, then the temperature difference also decreased from 13 °C to 8.5 °C, at 65 V/cm. In addition, for the same distance between the electrodes (section 2 and 3), when the nozzle width l was increased from 2 to 4, the temperatures difference increased from 13°C to 15°C, for 65 V/cm. Finally, for all the voltages, it was found that section 1 was the most efficient, as it yielded the minimal temperature difference for different voltages, but did not provide a flattened or reversed temperature profile (warmer temperature at the center than in the corners of the channel), which was our final goal, in order to print and pre-bake at the same time.

According to the parametric study, we observed that it was difficult to obtain a homogeneous temperature along the y-axis, by adjusting the dimensions of the nozzle section. Further investigations should be carried out with different configurations because some modifications could result in a reduction of the overheating as in (Shynkaryk & Sastry, 2012). Cooling of the containment walls of the nozzle, which is the practice for some larger industrial ohmic heating systems, could also be part of the solution (Quarini, 1995). As OH is based on volumetric heating from the inside to the outside, a simulation was performed, involving the cooling of the nozzle walls along the y-axis. The simulation in stationary mode, for 4 mm/s and 65 V, showed that we had to remove almost 840 W/m², which was equal to 4% of the total heat power produced in the product, on each side of the walls of the nozzle, in order to make the temperature almost homogeneous along the y-axis.

533 4. Conclusion

534 A new, innovative system was developed to study the possibility of pre-baking a cake batter in
535 continuous flow, by implementing OH in a rectangular channel (nozzle). The study consisted of three
536 main parts, namely the characterization of the thermophysical and electrical properties of the batter,
537 experimental investigations, and CFD modeling of the experimental system, to better understand the
538 links between the geometry of the printing nozzle, the physical properties of the batter, and the
539 temperature distribution in the flow at the exit of the nozzle.

540 The experimental results showed considerable temperature heterogeneity along the y axis, which
541 led to clogging at high temperatures. In-flow ohmic heating and batter baking resulted in heterogeneity
542 in the temperature profile, and the temperature gradient in continuous ohmic heating was reversed,
543 compared to the results obtained in batch conditions. Good correlation between results from
544 simulations and experiments was observed, showing that the temperature heterogeneity along the y-
545 axis was greater than that along the x-axis (electrodes distance). This finding was explained as being
546 due to the presence of hot spots at the nozzle corners and electrode edges, where the electric field was
547 higher than in the rest of the section of the nozzle. Also, the fact that the electrodes represented cold
548 spots could explain why hot spots were found close to the corners of the nozzle, in the vicinity of the
549 lateral walls, which were better insulated against heat transfer than were the electrode surfaces.

550 Different nozzle sections with aspects ratio of 0.25 and 0.5 (electrodes distances/width of nozzle)
551 and voltage conditions were considered with the objective of mitigating the temperature gradient at the
552 exit of the nozzle. The aspect ratio was found to affect temperature heterogeneity along the y-axis
553 (channel width); decreasing the electrodes distance reduced the temperature gradient, while increasing
554 the channel width yielded an increase of the temperature difference between the cold and the hot spots.
555 Further investigations should be carried out with different nozzle-ohmic heating configurations, in
556 order to find a suitable geometry capable of providing cake batter injection and pre-baking, without
557 nozzle clogging. Short additional baking will be necessary to finish setting the structure after
558 deposition. The effect of ohmic heating on food texture could be studied in the future once the
559 partial baking process in a channel has been fully achieved. Once this will be achieved, application
560 to 3D printing will be doable.

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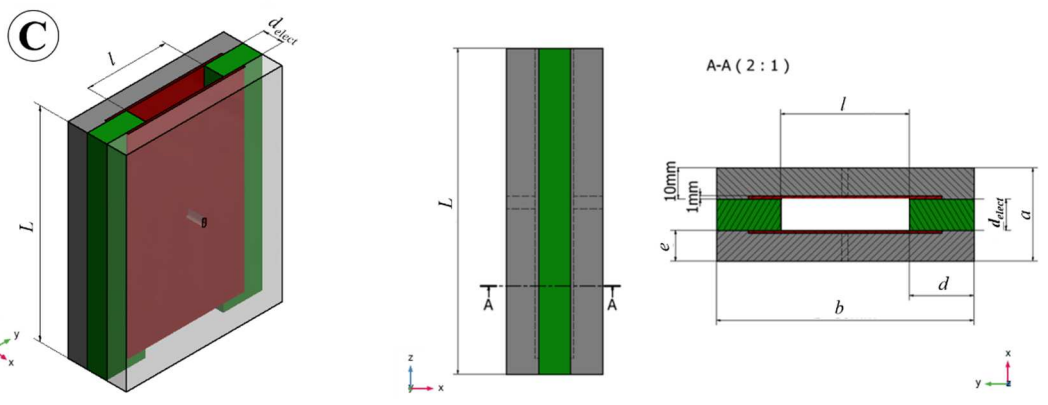
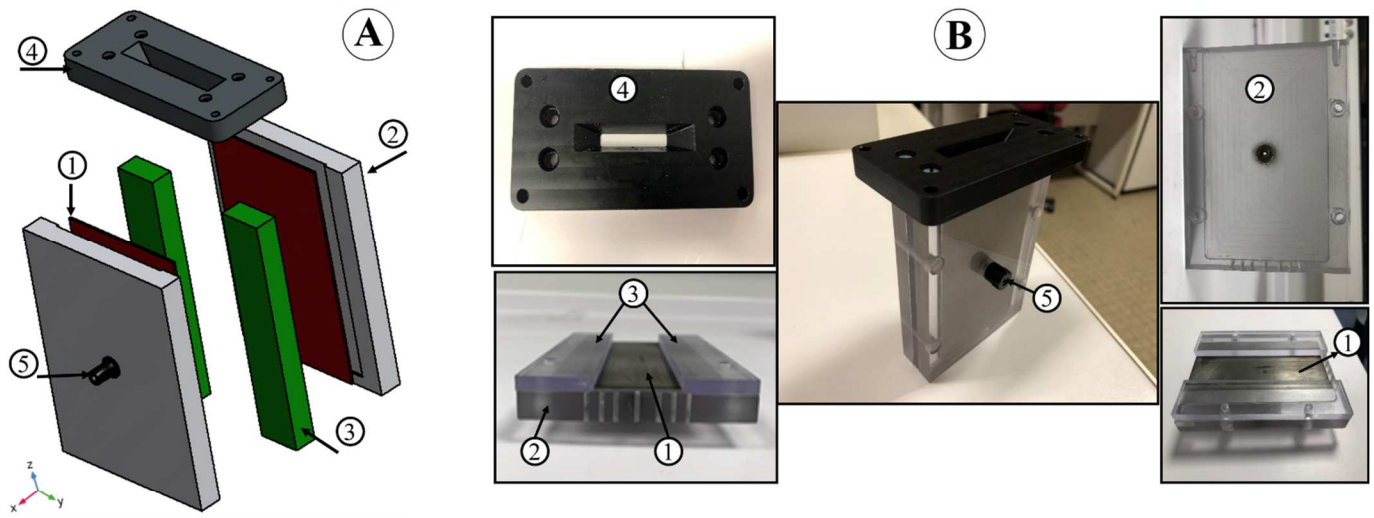
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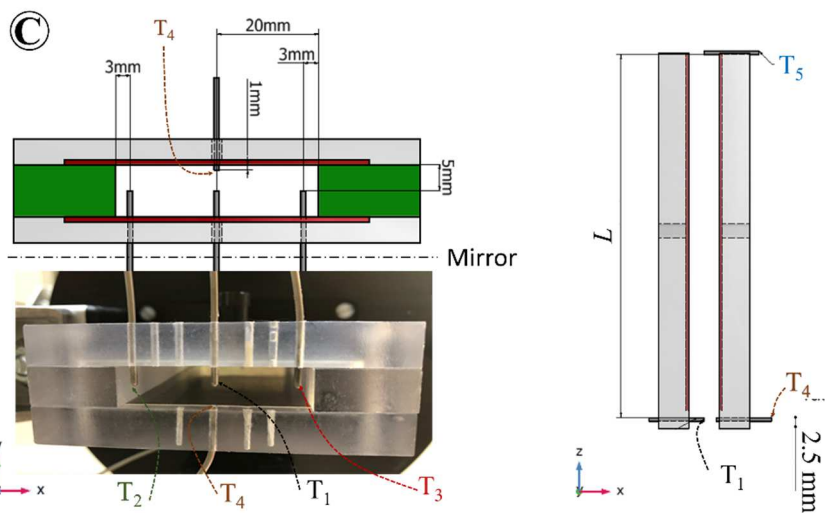
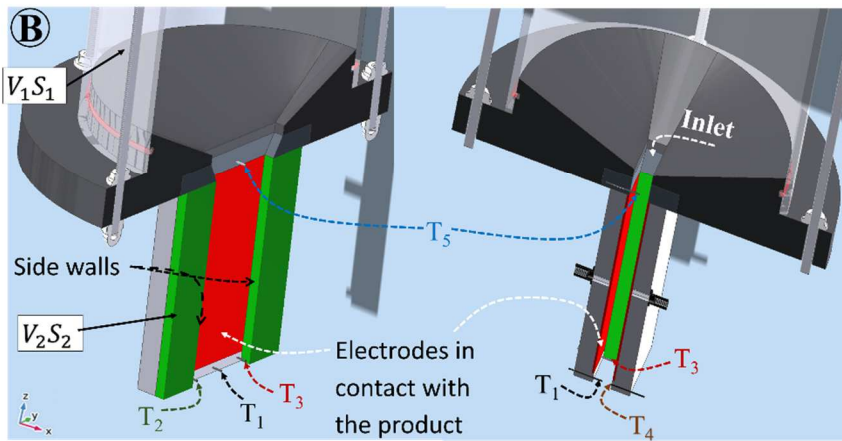
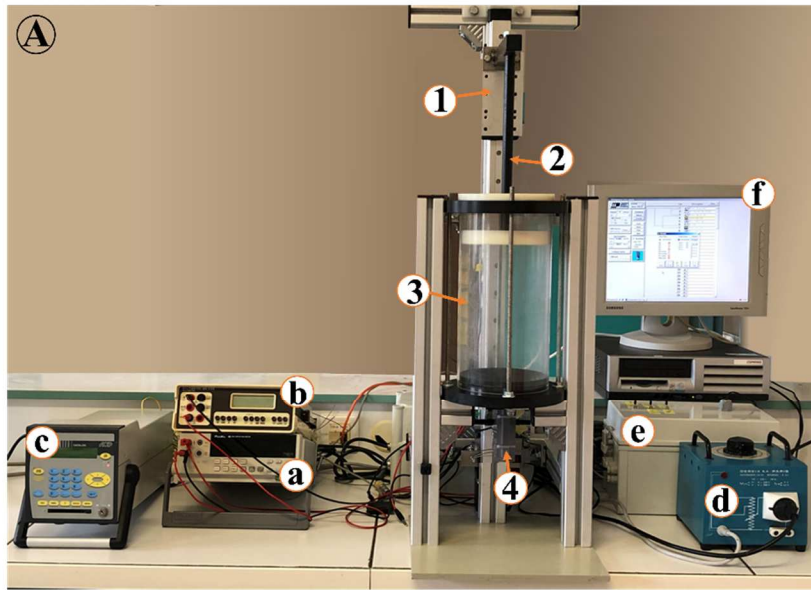
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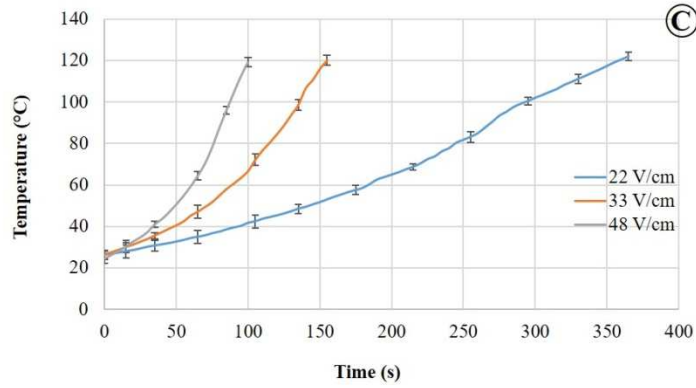
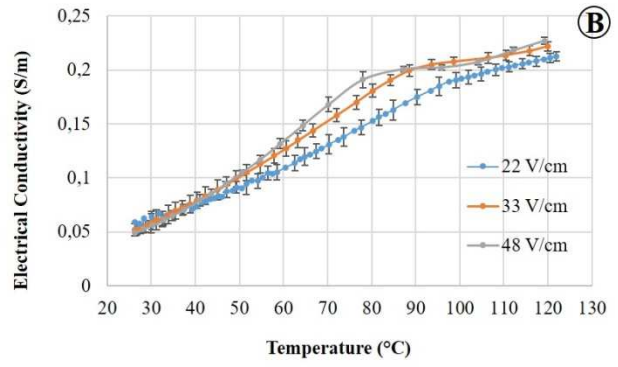
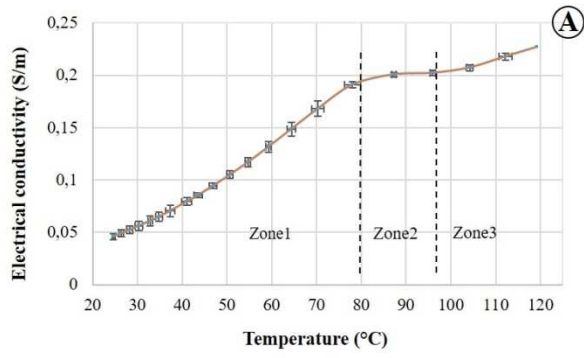
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Fig. 1. (A) Schematic of 3D nozzle geometry, consisted of ; (1) electrodes (red), (2) plates (grey), (3) beam (green), (4) channel support (black), (5) electric relays. (B) Different parts of the reel nozzle, same numbers as in (A). (C) Section views of the rectangular channel, distance between electrodes (d_{elect}) along the x-axis, nozzle width (l) along the y-axis; nozzle length (L) along the z-axis.

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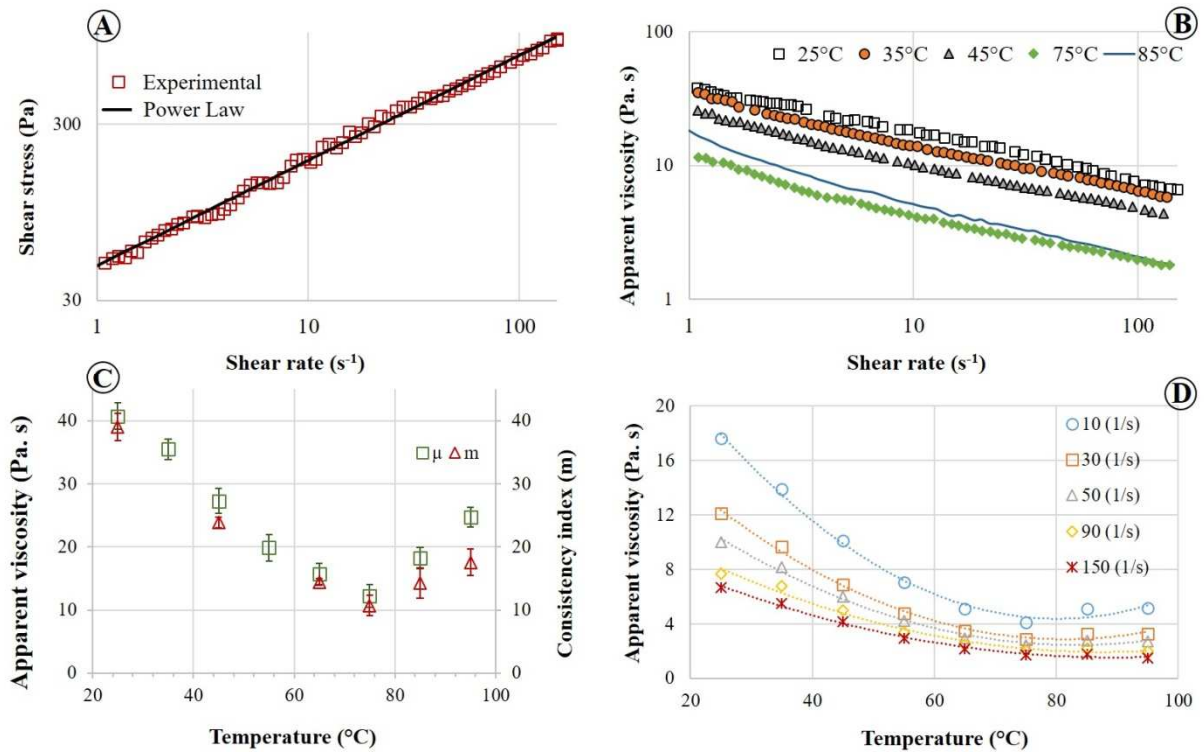
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 703 **Fig. 2.** (A) Overall installation of the system used for experiments, composed of mechanical parts: (1) drive motor,
 704 (2) piston, (3) cylindrical container, and (4) nozzle with ohmic heating, and electrical parts: (a) voltmeter, (b)
 705 ammeter, (c) data logger, (d) autotransformer, (e) motor controller, and (f) PC. (B) **3D views of the location of the**
 706 **thermocouples in the product along the nozzle;** V_1 and S_1 are the velocity of the batter and surface of the cylindrical
 707 container (3), V_2 and S_2 are the velocity of the batter and surface of the nozzle (4). (C) Location of each
 708 thermocouple at the nozzle outlet and inlet.



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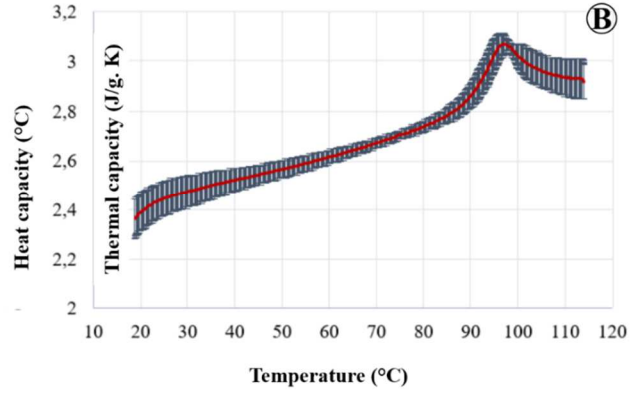
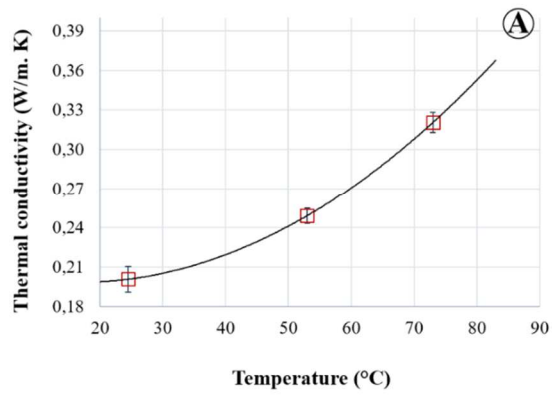
Fig. 3. (A) Electrical conductivity of the batter vs. temperature at a voltage gradient of 50 V/cm, (B) electrical conductivity of the batter vs. temperature at three different voltage gradients (22 V/cm (100 V), 33 V/cm (150 V), and 48 V/cm (200 V)) and (C) evolution of core temperature vs. time for the three different voltages.

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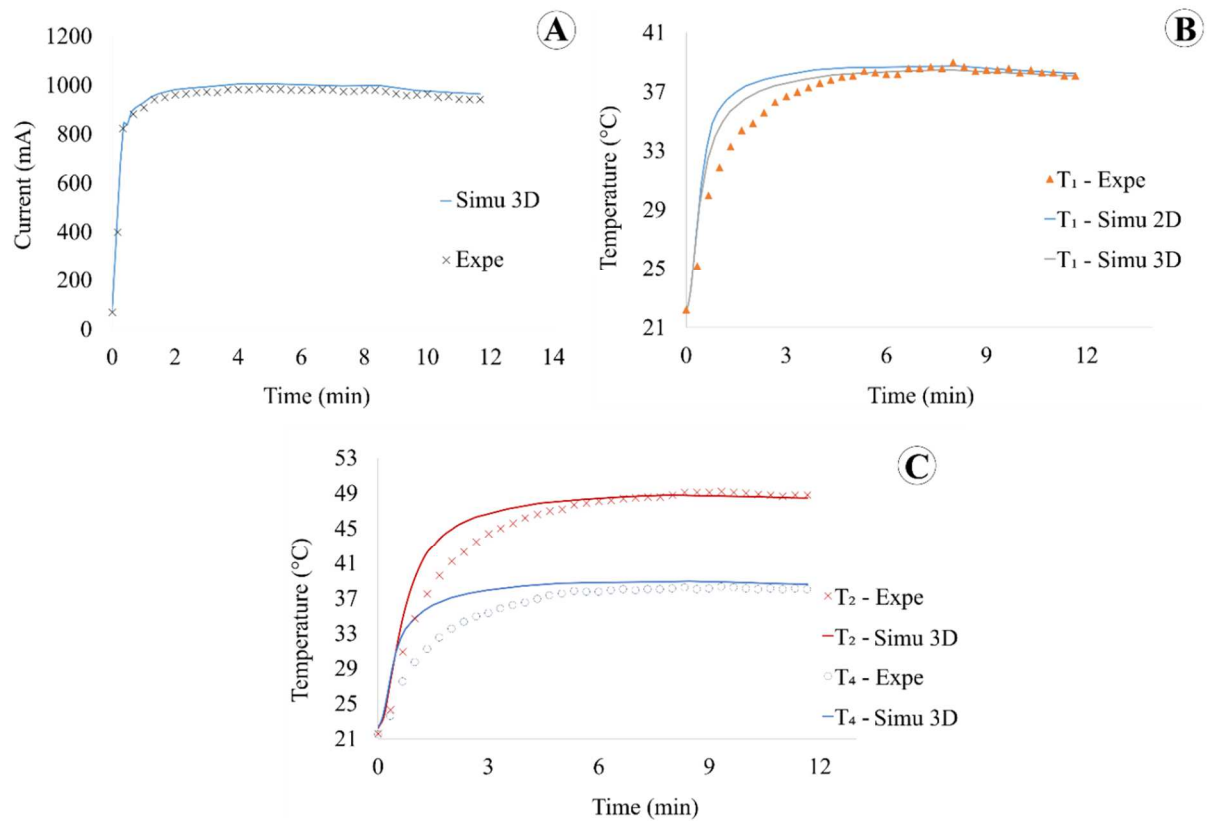
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Fig. 4. (A) Evolution of the batter shear stress vs. shear rate at 25 °C, in logarithmic form, (B) cake batter apparent viscosity vs. shear rate at five different temperatures, in logarithmic form, (C) consistency index and apparent viscosity at 1 s^{-1} vs. temperature, and (D) apparent viscosity vs. temperature at five different shear rates.



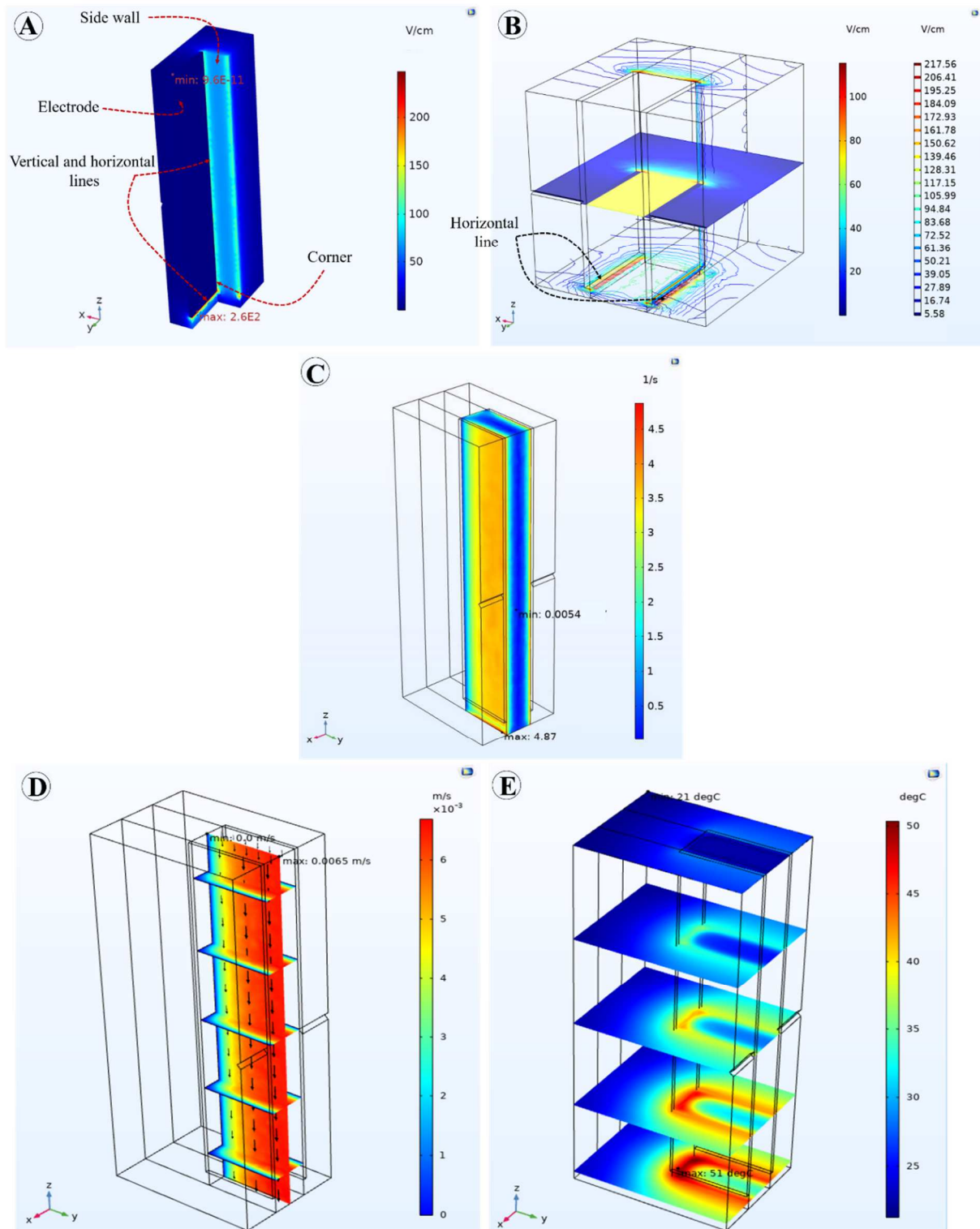
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Fig. 5 (A) Thermal conductivity and (B) heat capacity of the cake batter vs. temperature.



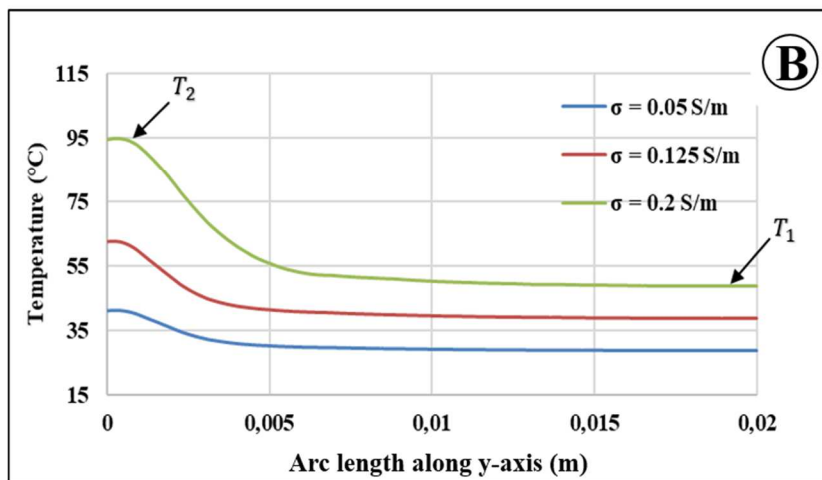
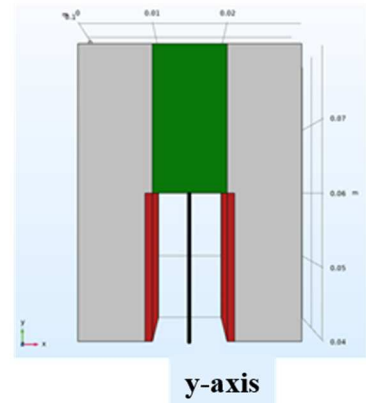
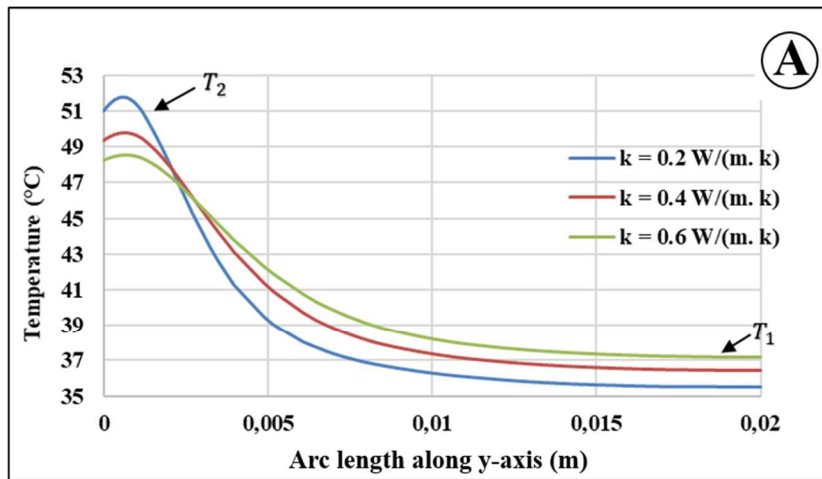
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 734 **Fig. 6** Validation of the model: experimental and modelled data for (A) the current evolution between electrodes,
 735 (B) temperature measurements at the outlet (T_1), and (C) temperatures T_2 and T_4 vs. time at the nozzle outlet for
 736 12 min of injection at 65 V.

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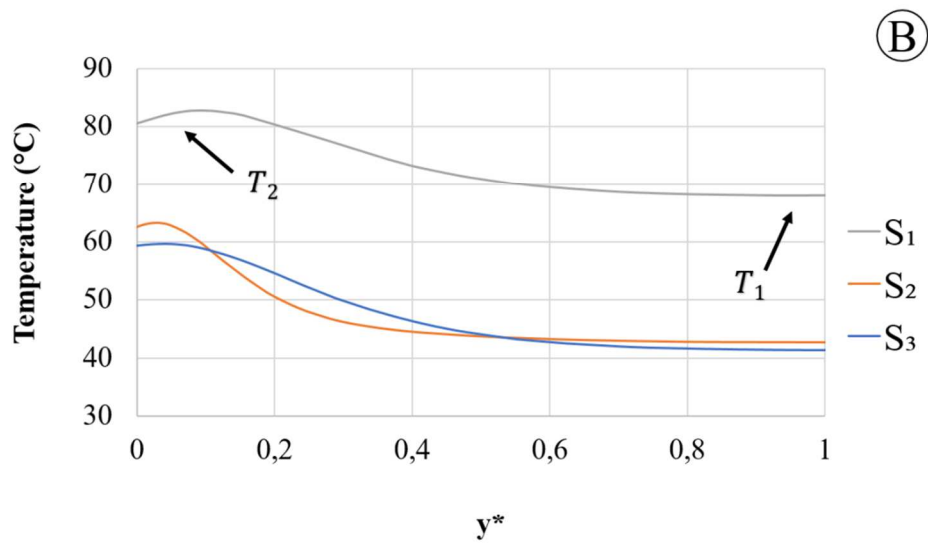
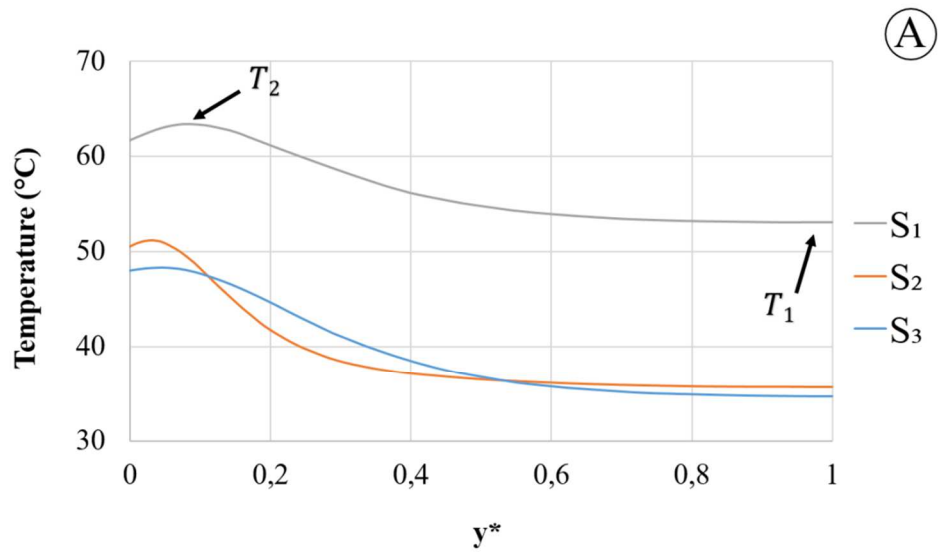
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Fig. 7. Plots for the cake batter after 12 min heating at 65 V and 4 mm/s, for (A) volume electric field; (B) electric field in the xy plane; (C) volume shear rate; (D) velocity along the y axis; and (E) temperature distribution in the nozzle in the xy plane at different location along z axis.



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Fig. 8. Parametric study of (A) thermal conductivity for 65 V – 4 mm/s, (B) electrical conductivity for 65 V- 12 mm/s, and their effects on the outlet temperature profile along the y-axis.



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Fig. 9. Temperature profiles vs non-dimensional coordinate $y^* = y/(l/2)$ for three different nozzle sections: $S_1 = 1 \text{ cm}^2$, $S_2 = 4 \text{ cm}^2$ and $S_3 = 2 \text{ cm}^2$ with aspect ratios ($\alpha = d_{elec}/l$) equal to 0.25, 0.25 and 0.5 respectively, and for two voltages: (A) 65 V/cm, and (B) 100 V/cm, at a velocity of 4 mm/s.