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S. Marc, J.-P. Ploteau, P. Le Bideau, P. Glouannec. Transient heat flux estimation during the baking of cereal batter by contact heating. *International Journal of Heat and Mass Transfer*, 2020, 155, pp.119848 -. 10.1016/j.ijheatmasstransfer.2020.119848 . hal-03490196

HAL Id: hal-03490196

<https://hal.science/hal-03490196>

Submitted on 20 May 2022

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Transient heat flux estimation during the baking of cereal batter by contact heating

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Abstract

In many applications, it is essential to evaluate the heat flux transferred by contact between two materials. Heat flux sensors must be properly designed to reduce sources of measurement bias while maintaining a high sensitivity without disrupting the flux itself. The aim of this study is to estimate the heat flux exchanged between two materials in contact at different temperatures. When materials are rapidly brought into contact (less than one second) the heat flux exchanged presents large variations. In this study, the heat fluxes transferred are computed using an inverse heat conduction problem. Initially, a particular attention is focused on the numerical analysis of the method and its reliability. A first experimental study is conducted on a prototype where an elastomer plate is suddenly placed on a hot iron disk. Based on temperature measurements recorded in each medium, the heat flux exchanged is estimated by two ways and the results are compared with each other. These first results show the efficiency of the method and its ability to extract information from temperature measurements. Then, a second experimental study is carried out with a cereal batter spread on the iron disk.

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The estimation of the heat flux from cast iron temperatures is compared with that deduced from an energy balance performed on the batter. The energy balance takes into account the sensible heat, the mass losses and the heat flux exchanged by radiation and convection with ambiance.

Keywords: Direct contact heating, Inverse Heat Conduction Problem, Experiment, Heat flux density, Baking, Experimental test bench

Nomenclature

Normal

c_p	specific heat $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
h	convective heat transfer coefficient $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
k	thermal conductivity $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
L_v	latent heat $\text{J}\cdot\text{kg}^{-1}$
m	masse kg
R_c	thermal contact resistance $\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$
T	temperature K

Greek letters

α	thermal diffusivity $\text{m}^2\cdot\text{s}^{-1}$
ϵ	emissivity
ρ	density $\text{kg}\cdot\text{m}^{-3}$
σ	Stefan Boltzmann constant $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$
φ	heat flux $\text{W}\cdot\text{m}^{-2}$

Subscripts

amb ambient

ci cast iron

cond conduction

conv convection

e elastomer

exp experimental

imp imposed

m metallic mass

pyro pyrometer

rad radiation

1. Introduction

The optimization of cooking appliances is becoming a priority for many sectors of the food processing industry [1–4] such as for cooking systems by contact [5]. Heating or cooling by direct conduction can involve high heat transfers. This cooking method is widespread around the world [6, 7] but knowledge in this field is generally empirical and based on know-how rather than on technical and scientific knowledge. In the case of cooking where a product, whose initial temperature can be between -30°C and room temperature, is placed directly on a hot metal plate between 100°C and 300°C , it is essential to know the heat flux transferred from the hot surface to the product to optimize the heating system and control the quality of the end

12 product [8]. A non-exhaustive literature survey reveals that many studies
13 focused on the estimation of heat fluxes exchanged during the contact of
14 two products initially at different temperatures. Some of them rest on the
15 cooking processes [9–12] but a large amount of these studies dealt with other
16 fields such as metallurgy [13, 14], plastics [15] and glasswork [16]. For all
17 these processes, the heat flux transferred, which is a function of the thermal
18 contact resistance and contact temperatures, can vary greatly. For indus-
19 trial productions, a perfect knowledge of heat flux and contact resistances
20 is required to ensure the quality and the repeatability of the production.
21 The estimation of heat flux, contact resistances or contact temperatures can
22 be performed by solving an Inverse Heat Conduction Problem (IHCP) [17].
23 Many studies have been conducted in recent years to solve different problems
24 that can be mathematical [18] or more applied such as controlling the occur-
25 rence of irregularity in heat curing composites [19], heat flux identification
26 in a reduced scale braking system [20] and the estimation of the incident
27 radiant heat flux in an infrared oven [21]. In the field of cooking by direct
28 conduction, Sanz-Serrano [22] proposed a study on the estimation of power
29 distribution in a pan by analyzing surface temperatures and using an inverse
30 model according to different heating systems: induction, electric resistance
31 and gas. However, whatever the configurations, the pan is considered empty,
32 without any food, that which could not be representative of the real heat
33 flux transferred from the pan to the foodstuff.

34 The purpose of this article is to present a methodology to design a
35 heat flux sensor composed of a metallic mass instrumented with thermo-
36 couples and directly integrable inside a hot plate. The procedure rests on

37 Inverse Heat Conduction Problem (IHCP). In the first part of this article,
38 the methodology used is described. A 2D numerical model is developed and
39 the conditions for optimal instrumentation for the resolution of the inverse
40 heat conduction problem are presented. A description of the characteriza-
41 tion of the thermophysical properties of the materials used is then given.
42 Subsequently, the numerical results are discussed. A sensitivity analysis is
43 performed to quantify the impact of materials properties and sensors loca-
44 tion on the estimation. Finally, experiments are carried out to evaluate the
45 estimation method on the basis of real measurements.

46 Two configurations have been studied, the first one with an elastomer to
47 simulate the future presence of the batter, but with a medium not subjected
48 to shrinking and the second one corresponding to the baking experiment.
49 First tests are performed with an elastomer plate in order to calibrate and
50 validate the transient method and avoid approximations relating to food
51 products, such as encountered by Cernela [8]. Then, the proven method is
52 used to estimate heat flux transmitted to a cereal batter during its cooking.

53 **2. Problem statement and numerical development**

54 The objective of the study is to measure the transient heat flux transferred
55 from a hot metallic surface to a product placed in contact with it (figure 1).
56 A heat flux sensor is embedded in the metallic plate and designed to be as
57 non-intrusive as possible. The heat flux sensor consists of a metallic cylinder
58 previously instrumented with thermocouples. The method is based on the
59 resolution of an Inverse Heat Conduction Problem (IHCP) for the estimation
60 of heat flux from temperature measurements. The procedure is tested and

61 validated for two configurations where either an elastomer plate or a cereal
 62 batter at room temperature, is placed on or spread over the hot surface.

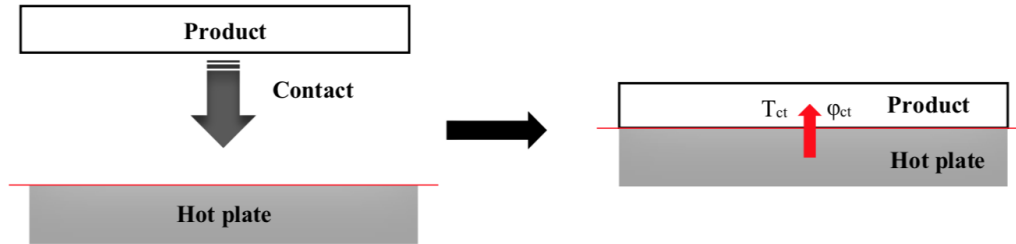


Figure 1: Schematic description of the study

63 Numerical and experimental studies are first conducted with an elastomer
 64 plate to design the heat flux sensor. An axisymmetric 2D Finite Element
 65 Model is developed to simulate the heat flux at the elastomer/cast iron inter-
 66 face. Simulations are performed, taking into consideration that the thermal
 67 contact is not perfect and the contact time not instantaneous [17]. The me-
 68 dia are supposed homogeneous. The comparison is made between the heat
 69 flux deduced from 2D model and the heat flux obtained by the resolution of
 70 an IHCP based on the temperature variations of the 2D model to validate
 71 the 1D assumption of the direct problem. Then, the objective is to study
 72 the ability of the method to estimate a known 1D heat flux and to test its
 73 sensitivity.

74 *2.1. 2D numerical model applied to elastomer plate*

75 The description of the study with the elastomer is given in figure 2. A
 76 metallic mass stuck on the elastomer permits creating a heat sink and main-
 77 taining constant pressure after contact with the hot plate during the exper-
 78 imental tests. A perfect thermal contact is assumed between the metallic

79 mass and the elastomer ($z = 8 \text{ mm}$). The upper and lateral surfaces of these
 80 two materials and the thermal insulation are subjected to thermal exchanges
 81 by natural convection and thermal radiation.

82 A time varying contact resistance R_c is introduced ($z = 0$) to take into
 83 account the roughness and the non-instantaneous contact between the elas-
 84 tomer and cast iron. More details about the variation of the contact re-
 85 sistance are given in the subsection 3.3. The temperature of the bottom
 86 surface of the cast iron ($z = -15 \text{ mm}$) is assumed to be constant throughout
 87 the simulation. The air and wall temperatures are also constant.

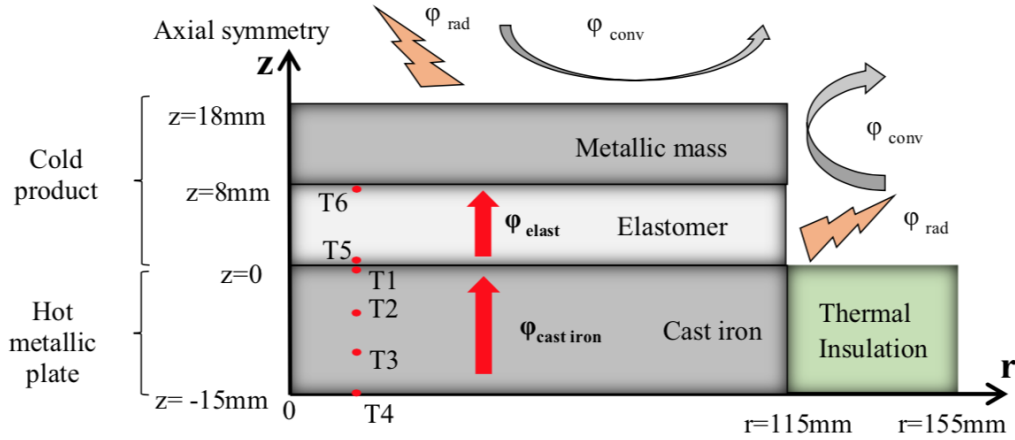


Figure 2: Schematic description of the 2D axisymmetric model

In the cast iron, the elastomer and the metallic mass, the governing equation is:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = 0 \quad (1)$$

88 The conductivities and thermal capacities of the cast iron and the elas-
 89 tomer are functions of the temperature (figure 3). The boundary conditions

90 are the following:

- Interface between the air and the metallic mass, the elastomer and the thermal insulation:

$$-k_{e,m} \frac{\partial T_{e,m}}{\partial z} = \varphi_{rad} + \varphi_{conv} \quad (2)$$

φ_{rad} is the radiative heat flux between the materials surfaces and surrounding walls considered as a black surface at ambient air temperature:

$$\varphi_{rad} = \epsilon_{e,m} \sigma (T_{e,m}^4 - T_{wall}^4) \quad (3)$$

φ_{conv} is the convective heat flux. Free convection correlations for the horizontal plate ($z=18$ mm) and for the vertical surface ($r=115$ mm) are used.

$$\varphi_{conv} = h_{conv} (T_{e,m} - T_{wall}) \quad (4)$$

- Interface between the metallic mass and the elastomer ($z=8$ mm):

$$-k_e \frac{\partial T_e}{\partial z} = -k_m \frac{\partial T_m}{\partial z} \quad (5)$$

- Interface between the elastomer and the cast iron ($z=0+$):

$$-k_e \frac{\partial T_e}{\partial z} = \frac{T_{ci} - T_e}{R_c} \quad (6)$$

- Interface between the cast iron and the elastomer ($z=0-$):

$$-k_{ci} \frac{\partial T_{ci}}{\partial z} = \frac{T_{ci} - T_e}{R_c} \quad (7)$$

- Bottom of the cast iron ($z=-15\text{mm}$):

$$T_{ci} = T_{imp} \quad (8)$$

91 Where ci , e and m correspond to cast iron, elastomer and metallic
 92 mass, respectively. R_c is the thermal contact resistance and T_{imp} is the
 93 imposed temperature.

94 This model permits calculating the heat flux exchanged at the interface
 95 between the cast iron and the elastomer ($\varphi_{2D_{model}}$) based on equations 6
 96 and 7. This heat flux will be used as a point of comparison in the following
 97 numerical study of IHCP.

98 2.2. IHCP one dimension

99 The problem consists in estimating the heat flux at the interface between
 100 cast iron and elastomer ($z = 0$) using the temperature recorded in different
 101 positions in the two materials.

Two IHCP are solved separately: one in the cast iron and the second in the elastomer. Considering a one-dimensional problem in the central part of the plates, the heat equation therefore takes the following form:

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \quad (9)$$

The thermophysical properties are a function of the temperature (1) and the boundary conditions are the following:

$$z = 0 \quad -k_{ci,e} \frac{\partial T_{ci,e}}{\partial z} = \varphi \quad (10)$$

$$z = -15\text{mm} \quad T_{ci} = T_{imp1} \quad (11)$$

$$z = 8\text{mm} \quad T_e = T_{imp2} \quad (12)$$

The equations are solved by a pure implicit method. In order to obtain an acceptable sensitivity, the location of the sensors $T2$ and $T5$ must be determined precisely and conform to the criteria described in the literature [23, 24]. The noise measurement must be mastered in order to limit its amplification. A deep implantation was chosen using the following criteria [23]:

$$1 > \Delta t_i > 10^{-2} \quad (13)$$

102 with Δt_i the characteristic time step: $\Delta t_i = \frac{\alpha \Delta t}{E^2}$

Δt being the time discretization of the numerical model (s), α the thermal diffusivity ($\text{m}^2 \cdot \text{s}^{-1}$) and E the distance between the temperature sensor and the contact surface. The value of Δt must be chosen such that the temperature variation during the step time is greater than the measurement noise δT :

$$\frac{T(z_j, t + \Delta t) - T(z_j, t)}{\delta T} \gg 1 \quad (14)$$

Thermocouples must be accurately positioned to meet the following condition:

$$\frac{\delta z}{d} < 0.05 \quad (15)$$

103 Where δz is the error on the thermocouple position and d the distance be-
 104 tween the contact surface and the closest sensor.

The heat flux is then determined using a procedure which minimizes a quadratic criterion [17] equal to the sum of squares of differences between the measured and computed temperatures at the selected spatial point. For each case, only one thermocouple located at d is used to estimate the heat flux:

$$S(\varphi(t)) = \frac{1}{2} \sum_{t=1}^N (T(d, t) - T_{exp}(d, t))^2 \quad (16)$$

105 With N being the number of measurements and the subscript d refers to the
 106 location of the selected thermocouple.

107 This goal function is minimized using an iterative regularization method.
 108 A stopping criterion is imposed for the minimization procedure:

$$S(\varphi(t)^{fk}) = N\sigma^2 \quad (17)$$

109 With σ^2 is the noise variance due to temperature measurements and fk is
 110 the last iteration index.

111 The three criteria (13), (14) and (15) are taken into account to design
 112 the experimental device. In literature, the numerical tests are often carried
 113 out with academics signals like triangular, square or sin wave heat flux [25].
 114 In this study, the contact heat flux varies considerably and quickly. An
 115 exponential decay of heat flux is expected. IHCPs are solved in the elastomer
 116 and the cast iron from the temperatures given by the 2D model to estimate
 117 the heat flux at the interface cast iron / elastomer. The two estimated heat
 118 fluxes, one by IHCP in the elastomer and the other by IHCP in the cast iron,
 119 are compared to validate the procedure and experimental design.

120 3. Experimental study

121 3.1. Thermo-physical properties

122 The thermal properties of the cast iron and the silicone elastomer were
123 measured with various equipments indicated in table 1. Measurements of
124 diffusivity and specific heat were performed on both materials, see figure 3.
125 The expansion coefficient of the cast iron was also determined. The thermal
126 conductivity was deduced from the thermal diffusivity, density and specific
127 heat. The properties measured are in good agreement with those of the
literature [26, 27].

Table 1: Thermal properties

Property	Method	Apparatus	Accuracy
$\rho(\text{kg}\cdot\text{m}^{-3})$	Pycnometer	Mettler Toledo XS205	$\pm 4\%$
	Dilatometer	Linseis L75H	
$c_p(\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})$	Calorimeter	Netzsch 204 F1 Phoenix	$\pm 3\%$
$\alpha(\text{m}^2\cdot\text{s}^{-1})$	LFA	Netzsch LFA 457	$\pm 5\%$

128

129 3.2. Description of experimental set-up and instrumentation

130 A 23 cm diameter and 15 mm thick cast iron plate was used as hot surface.
131 A hole was bored in the center of the plate so that an instrumented flux
132 meter also made of cast iron could be inserted into the plate, see figure 4. Its
133 diameter was 30 mm and it was held in position by a mechanical adjustment.
134 It is considered here that the elevation of the plate's temperature would
135 result in the expansion of the material and therefore tighten the contact flux
136 meter/plate. Therefore, no contact resistance between these two materials
137 was considered.

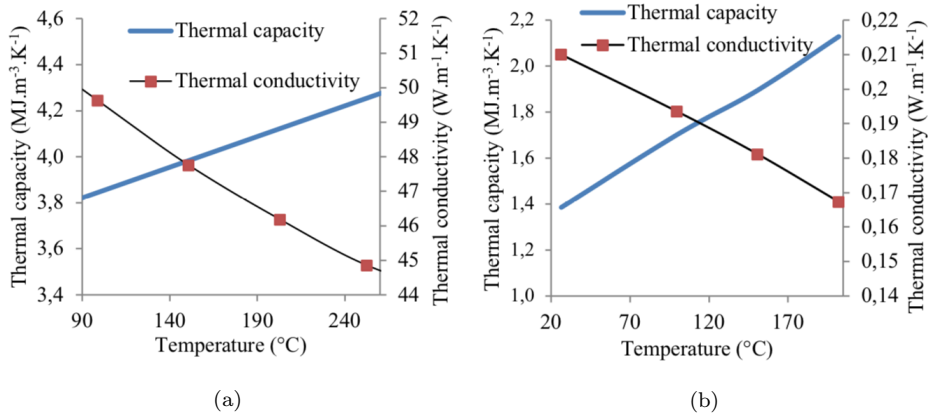
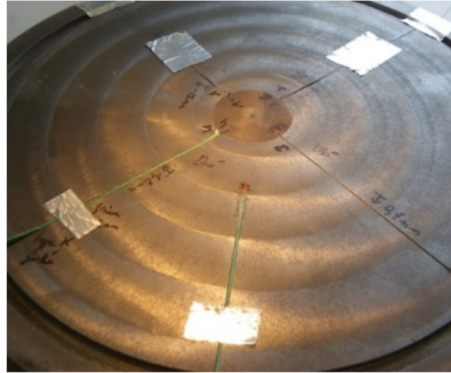


Figure 3: Thermal capacity and thermal conductivity for cast iron (a) and elastomer (b)

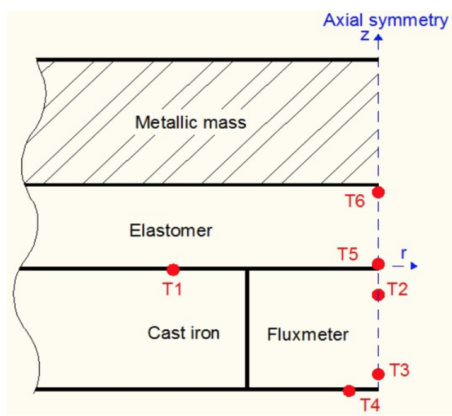
138 In order to meet the criteria given in (13), the first thermocouple was
 139 located 3 mm from the surface ($z = 0$), assuming a time step $\Delta t = 0.1$ s for
 140 the IHCP.

141 At this position, the characteristic time was 0.14 s, which corresponds
 142 to the criteria (13) $1 > \Delta t_i > 10^{-2}$. Three K-type stainless steel jacketed
 143 thermocouples of 500 μm diameter were embedded at different depths: T2,
 144 T3 and T4 (figure 4). The thermocouple T2 was used as output to estimate
 145 the heat flux while the thermocouple T3, was taken into account as boundary
 146 conditions. These thermocouples were placed along the isotherms. In the 30
 147 mm pellet, the bores were drilled at 90° from each other and are parallel to
 148 the expected isotherms. They had a length of 13 mm and a 4 mm space in
 149 radius direction between each bore is present in order to cause no interference.

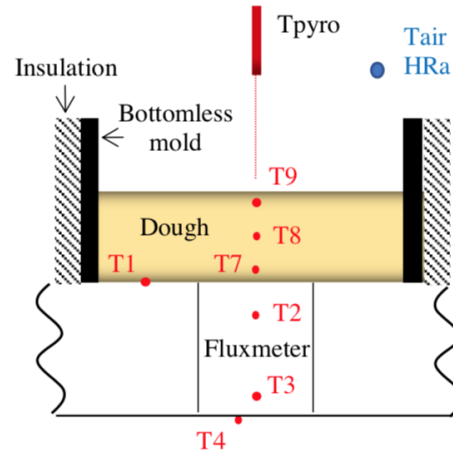
150 A 250 μm diameter thermocouple T1 was located next to the flux meter.
 151 Due to its location, its measurement was not reliable but could quickly detect
 152 contact with a product. The time constant of the sensors and the contact
 153 resistance between the probes and the material were assumed negligible.



(a)



(b)



(c)

Figure 4: Instrumented fluxmeter (a) placed under an elastomer (b) or under dough (c)

154 A 23 cm diameter radiant hob was placed under the cast iron plate. The
155 power supplied to this device is regulated by a solid-state relay (Eurotherm
156 Epack) controlled by an analogical signal (Eurotherm 3216). The solid-state
157 relay communicated via Ethernet with a desktop computer. The radiant hob
158 / hot plate system was thermally insulated on the lateral sides and at the
159 bottom by a high temperature insulating material made of calcium silicate.

160 The surface facing the heater was blackened by applying a uniform layer
161 of graphite to obtain an emissivity of the plate close to black body emissivity.
162 The contact surface was treated with a thin layer of burnt sunflower oil to
163 enhance the contact.

164 *Elastomer*: In order to simulate the heating of a cold product, an 8 mm
165 thick silicone elastomer was used. 80 μm diameter K-type thermocouples
166 (weld of 160 μm) were located along the isotherms at a depth of 0.25 mm and
167 7.75 mm from the contact surface (table 2). The thermocouple T5 was used
168 to estimate the heat flux while the thermocouple T6 was used as boundary
169 conditions. The characteristic time was 0.21 s which also met the criteria
170 (13). To ensure the contact elastomer/hot plate, a metallic mass was bonded
171 to the elastomer and the assembly was placed on the heating surface for
172 the tests. The metallic mass permitted maintaining contact pressure during
173 testing.

174 *Cereal batter*: A PTFE bottomless mold of internal dimensions 14 x 11.5 x
175 2 cm, surrounded by thermal insulation, was placed on the surface of the cast
176 iron plate. About 150 g of batter at room temperature was poured into the
177 bottomless mold, which represents 8 mm thick (figure 4). Three temperatures
178 were recorded by K-type thermocouples in the dough (T7, T8, T9). The

179 diameter of the thermocouples was 125 μm and a pyrometer measured the
 180 surface temperature. The mass loss was measured using a Radwag PS6000
 181 R2 (accuracy 0.01 g). In addition, air temperature and relative humidity
 182 were also recorded. The batter used consisted of a mixture of an industrial
 183 preparation (Francine[®] mix) and sterilized semi-skimmed milk. The weight
 184 percentage used was 37 % mix and 63 % milk. The thermal properties were
 185 calculated with the correlations of Baik & al.[28] presented in appendix A.
 186 These correlations were used to consider the properties as functions of the
 187 temperature and the water content.

188 The z coordinates of the different thermocouples are indicated in table 2.
 189 The temperature measurements were performed by a QuantumX MX1609KB
 190 data acquisition system communicating with the desktop computer by Eth-
 191 ernet. The acquisition period was set at 20 ms.

Table 2: Implantation of thermocouples (mm)

Cast iron		Elastomer		Dough	
T1	0	T5	0.25	T7	1.0
T2	-3	T6	7.75	T8	4.0
T3	-12.5			T9	7.0
T4	-15				

192 3.3. Contact thermal resistance

193 When the product (elastomer or cereal batter) is placed or spread on
 194 the hot surface (cast iron disc), the contact cannot be considered instanta-
 195 neous. Others authors like Beck [17] suppose a gradual contact which leads

196 to consider a decrease of contact resistance with time. A similar procedure
197 was conducted here. Based on pictures obtained with a scanning electron
198 microscope (figure 5), the surface roughness of the cast iron was observed
199 to estimate the final air gap at the interface (between $50\ \mu\text{m}$ and $100\ \mu\text{m}$).
200 Thus, the final contact resistance is equivalent to thermal resistance caused
201 by an air gap of this thickness or more. As Beck [17] a gradual contact in
202 $0.3\ \text{s}$ is assumed and a mathematical relation (polynomial form) with time
203 was used to take into account this decrease with time (figure 6).

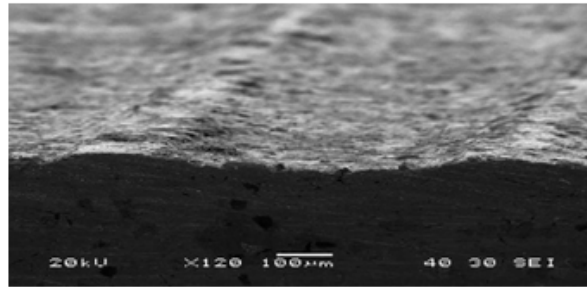


Figure 5: SEM view of the cast iron surface

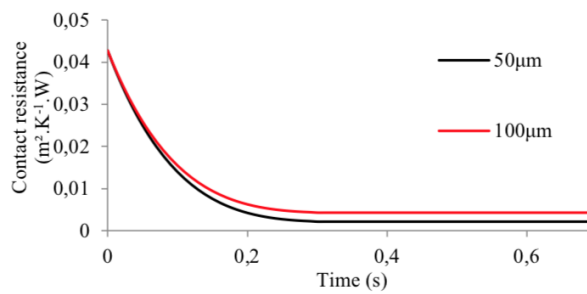


Figure 6: Contact resistances for air gaps of $50\ \mu\text{m}$ and $100\ \mu\text{m}$

204 4. Results and discussion

205 In this section, the flux meter designed is tested. Firstly, the numerical
206 results demonstrate the feasibility of the method and validate the IHCP. The
207 experimental tests are then presented with an elastomer plate and a cereal
208 dough.

209 4.1. Numerical studies

210 Two tests were conducted, the initial bottom surface temperature of the
211 cast iron was imposed at 100 °C and 200 °C. The initial temperature of the
212 elastomer was 20 °C. The gradual contact lasted 0.3 s as previously indicated
213 and it was initialized at $t = 1$ s. The direct problem was solved with a step
214 time of 20 ms corresponding to the maximum acquisition frequency.

215 4.1.1. 2D model simulation

216 The temperature variations in the cast iron and the elastomer are respec-
217 tively presented in figure 7 a and b for the test performed at 100 °C. The
218 thermal resistance in this instance is equivalent to an air gap of 100 μm . The
219 heat flux at the contact surface calculated by the direct model is also plotted.

220 The temperatures near the contact surface varied significantly. The max-
221 imum temperature difference was higher than 60 °C in the elastomer, because
222 of the low thermal conductivity. In contrast, in the cast iron, the tempera-
223 ture difference was rather weak, about 2 °C but the variations were still higher
224 than the noise measurement obtained at 100 °C. For the tests at 200 °C, the
225 temperature difference in the cast iron was 5.5 °C in the case of an air gap
226 of 50 μm and 4.5 °C in the case of an air gap of 100 μm .

227 The impact of the mesh on the temperature evolutions was also studied
 228 and a satisfactory relationship between computation time and accuracy of the
 229 results was found. The Finite Element Model composed of 12 330 triangular
 230 elements.

231 Moreover, heat fluxes distributions with radius were investigated to check
 232 the uniformity of the interface heat flux. The figure 8 shows the heat flux
 233 distribution with radius r for selected times (before the contact, at the contact
 234 instant and after the contact instant). This plot is relating to the 2D heat
 235 transfer model as presented in figure 2. We note that the heat flux is globally
 236 constant with the radius in this configuration.

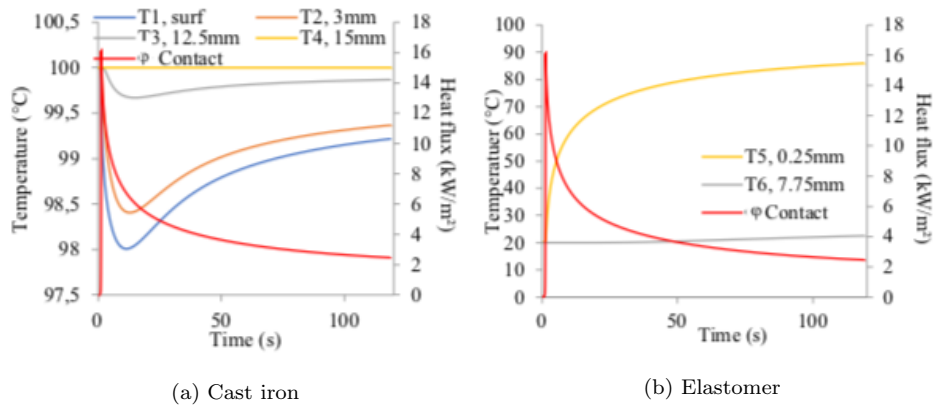


Figure 7: Numerical temperature evolutions and heat flux at the contact surface

237 4.1.2. IHCP estimation from the evolution of 2D temperature

238 In this part the 2D simulated temperatures were used to estimate the heat
 239 fluxes at the interface elastomer/cast iron by the inverse method. Before that,
 240 a sensitivity analysis was carried to check the feasibility of the estimation by
 241 an inverse procedure. Each value of heat flux estimated at a given time is

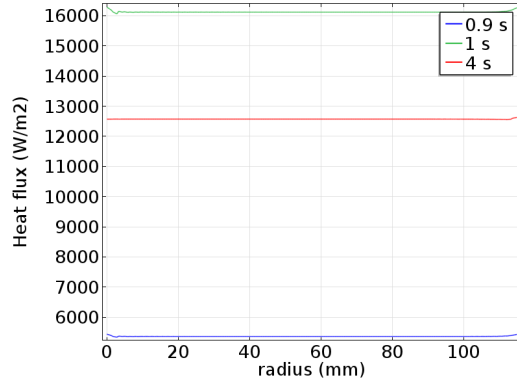


Figure 8: Heat flux distribution as function of radius

242 an independent parameter. No dependence between the parameters appears
 243 here as it's shown in the figure 9 which concerns the sensitivity analysis for
 244 the cast iron. This figure presents the sensitivity coefficients $\frac{\partial T}{\partial \varphi}$ vs time for
 245 the selected position (3 mm from the interface). The sensitivity coefficients
 246 plotted are those before the contact (φ_{bc}), at the instant of contact (φ_c) and
 247 after the contact (φ_{ac}). All sensitivity coefficients are the same trend ,i.e,
 248 sudden peak immediately after the heat flux variation followed by a rapid
 249 decrease. Globally, no dependence between the signals appears.

250 Figure 10a shows the heat fluxes estimated by inverse techniques and
 251 calculated by the 2D model for the test at 100 °C, and for a final contact
 252 resistance equivalent to 100 μm . We observed good agreement between the
 253 three curves, except for the beginning of the estimation. Indeed, a "delay"
 254 on the estimation at the beginning of the flux was observed ($t = 1$ s). This
 255 phenomenon was visible in the first 0.3 seconds of the onset of flux ($t = 1.3$
 256 s). However, for the rest of the estimation, the relative error was less than
 257 2%. The resolution of the IHCP provide better accuracy if the calculation

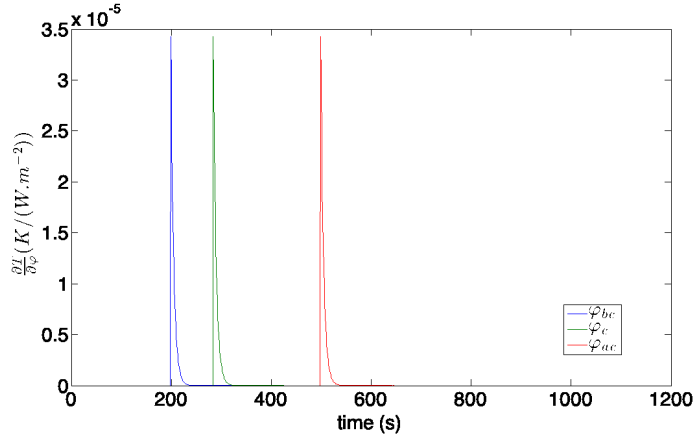


Figure 9: Sensitivity coefficients variations for a selected position (3 mm) in the cast iron.

258 time of IHCP is 0.1 s. From these results, the 1D assumption of the problem
 259 was validated.

260 The time step of the calculation used for the direct problem also affected
 261 the estimated heat flux. Indeed, an excessively long time step would result
 262 in a poor estimation in the first seconds of contact. Conversely, an exces-
 263 sively short time step would result in rebound phenomena due to the small
 264 temperature variations during the step time. After the first few seconds the
 265 influence of this step time was more negligible although disturbances could
 266 appear for a short step time (figure 10b).

267 The numerical analysis showed that the inverse method was able to re-
 268 estimate an imposed heat flux with satisfactory accuracy. Thereafter, a time
 269 step of 0.1 s was used.

270 A study of the impact of uncertainties on the thermo-physical properties
 271 and position of the thermocouples was conducted: 5% for thermal conduc-
 272 tivity and heat capacity and 0.25 mm for the location of thermocouple. For

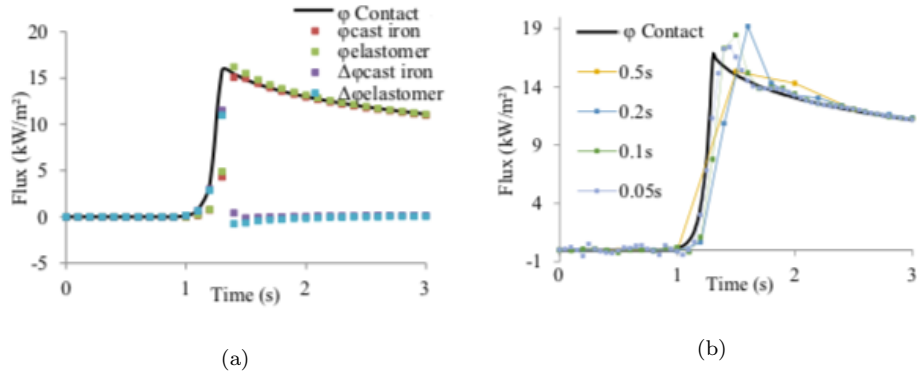


Figure 10: (a) Comparison between heat fluxes computed by the 2D model and estimated by IHCP; (b) Influence of the step time on the estimation

273 this last point, the heat fluxes estimation were done with nodes located at
 274 3.25 mm (instead of 3 mm) in the cast iron and at 0.5 mm (instead of 0.25
 275 mm) in the elastomer. Figure 11 shows the differences between the heat flux
 276 imposed and estimated at the interface during the first eight seconds. The
 277 error on the estimation could be considerable at the beginning of contact
 278 (between $t = 1$ s and $t = 2$ s), mainly for the heat flux based on the cast iron
 279 temperatures and this, whatever the error source: properties uncertainties
 280 or sensors location. After 3 seconds, the errors tend to zero.

281 4.2. Experimental studies with elastomer

282 The cast iron plate was heated using a constant supply voltage of the
 283 infrared heating element. When the steady state was established, the elas-
 284 tomer was suddenly placed in contact on the cast iron plate. A metallic
 285 mass bonded to the upper face of the elastomer ensured constant pressure
 286 throughout the duration of the experiment in order to favour the repeatabil-
 287 ity of measurements. Temperatures were recorded every 20 ms. An average

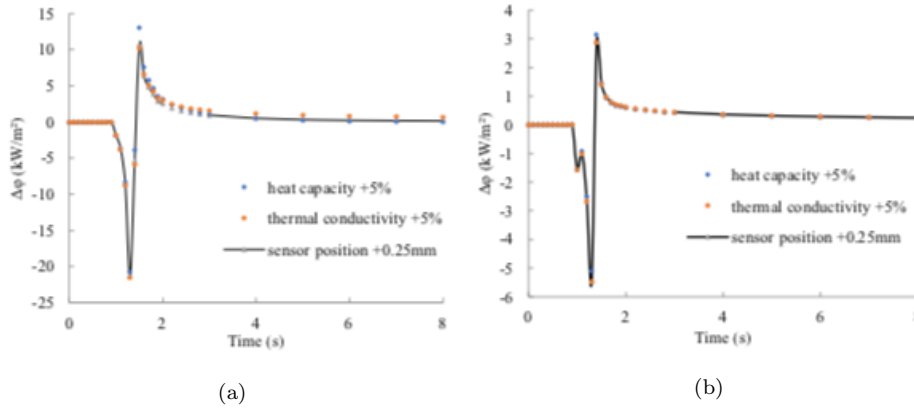


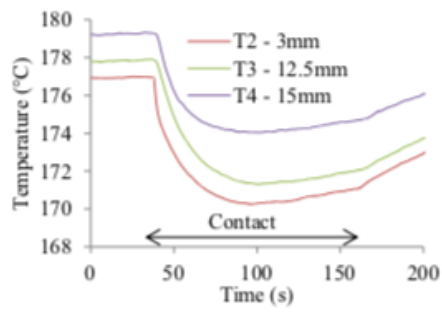
Figure 11: Difference between fixed and estimated heat flux for thermal properties and sensor position errors: (a) cast iron, (b) elastomer

288 of 5 measurements were performed and stored every 0.1 s. This time step
 289 allowed a temperature variation greater than the measurement noise (14).

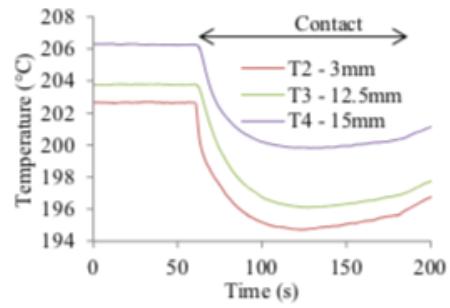
290 Firstly, the experiments performed with a fixed power of 140 W are de-
 291 scribed. In this case the lower surface of cast iron plate was initially at a
 292 temperature above 170 °C. The contact between the elastomer and the cast
 293 iron lasted 120 seconds. The temperatures recorded at 3 mm, 12,5 mm and
 294 15 mm in cast iron are reported in figure 12a. A rapid drop in temperatures
 295 was visible as soon as the materials came into contact, with a temperature
 296 difference of about 4 °C between the sensors T2 and T4. In the elastomer,
 297 the temperature difference rapidly became greater than 100 °C (figure 12c).

298 Figure 12b and 12d shows another test performed for a power of 200 W,
 299 i.e. an initial cast iron temperature above 200 °C. In this case the tempera-
 300 ture difference between the sensors T2 and T4 was about 6 °C.

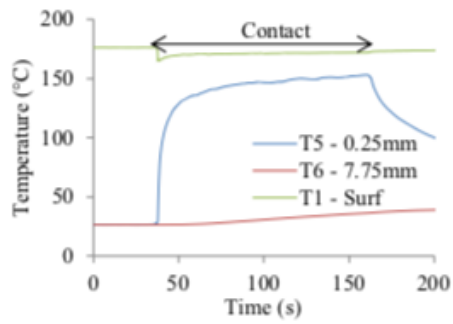
301 Figure 13 shows that the heat fluxes estimated based on elastomer tem-
 302 peratures and cast iron temperatures are very similar in the temperature



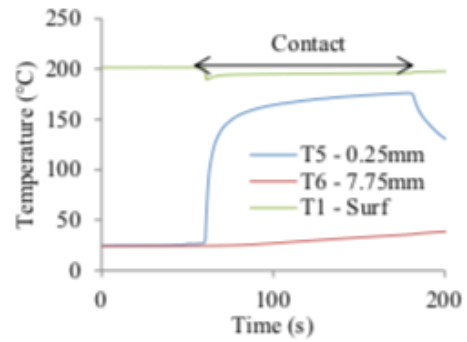
(a)



(b)



(c)



(d)

Figure 12: Temperatures of the cast iron (a, b) and elastomer (c, d) for initial cast iron temperatures of 170 °C and 200 °C

303 range studied. Based on the heat flux profiles, the contact duration was es-
304 timated at about 0.3 s. The estimation of the maximum peak was difficult
305 during the first instant due to the weak thermal gradient in the cast iron.
306 Logically, the higher the temperature of plate was, the higher the peak with a
307 maximum at $42 \text{ kW}\cdot\text{m}^{-2}$ for the test at $200 \text{ }^\circ\text{C}$ against $35 \text{ kW}\cdot\text{m}^{-2}$ for the test
308 at $170 \text{ }^\circ\text{C}$. Before the contact and after the elastomer withdrawal ($t > 130$
309 s), the heat flux estimated with cast iron temperatures corresponded to heat
310 losses with the ambiance ($\approx 5 \text{ kW}\cdot\text{m}^{-2}$). The procedure was repeated 4
311 times and error bars were added to the plots to underline the repeatability
312 of the method. These results demonstrate the ability of the IHCP method to
313 accurately estimate a heat flux transferred at the interface of two contacted
314 materials. In fact, when the elastomer was suddenly brought into contact
315 with the cast iron, the temperatures into the cast iron decreased although
316 the temperature into the elastomer increased. The thermal responses were
317 only due to the heat flux transferred and the own thermal properties of each
318 material. It is possible to estimate by inverse method the trend and the val-
319 ues of this heat flux based on the temperature variation at a selected point
320 and knowing with accuracy the thermal properties. Here, the heat flux was
321 estimated by two means: one ICHP is solved in the cast iron and a second
322 one is solved in the elastomer.

To estimate the contact thermal resistance, an additional test was per-
formed for a time long enough to reach steady state (figure 14). The tempera-
tures at the interface were calculated by the one-dimensional heat conduction
model for the two materials at the end of the heat flux estimation. In steady
state, the surface temperatures obtained numerically by the direct model

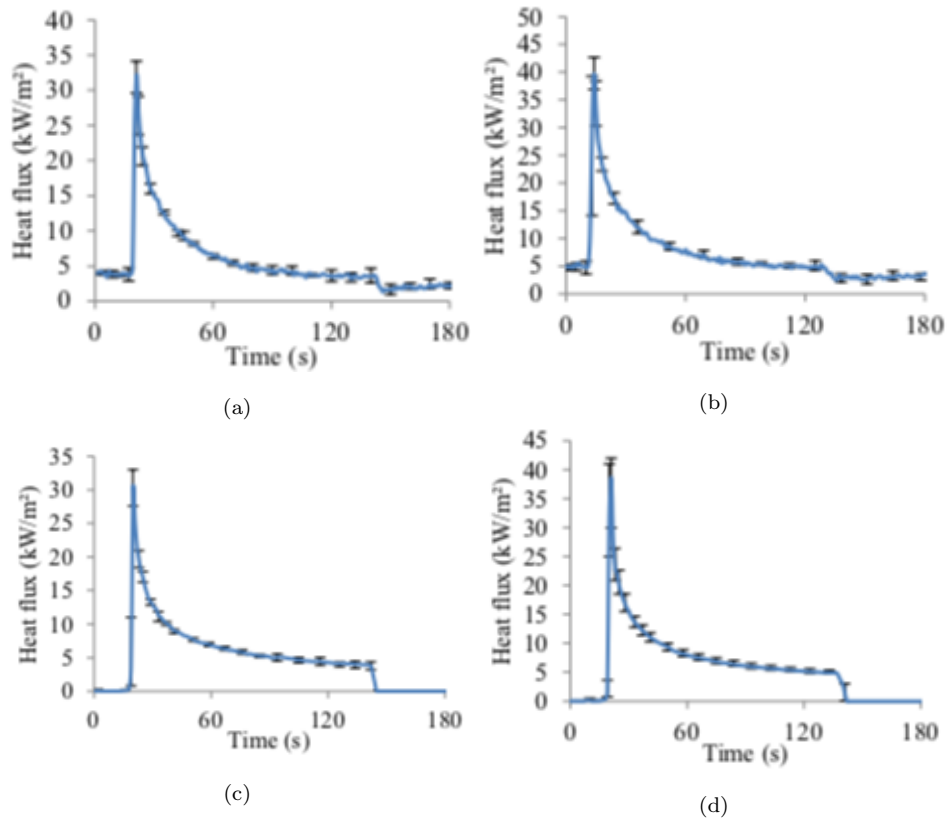


Figure 13: Comparison of estimated heat fluxes in cast iron (a-b) and elastomer (c-d) at 170 °C and 200 °C

were 198.2 °C and 187.1 °C for respectively the cast iron and the elastomer. Based on the heat flux estimated at 4.9 kW·m⁻² and the interface temperatures, the contact resistance was calculated by the equation (18) after 220 s:

$$R_c = \frac{T_{\text{surf cast iron (z=0-)}} - T_{\text{surf elastomer (z=0+)}}}{\varphi} \quad (18)$$

323 A value of $2.3 \times 10^{-3} \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ was calculated. In this case, this thermal
 324 resistance value corresponded to an equivalent thermal resistance caused by
 325 a 53 μm air gap.

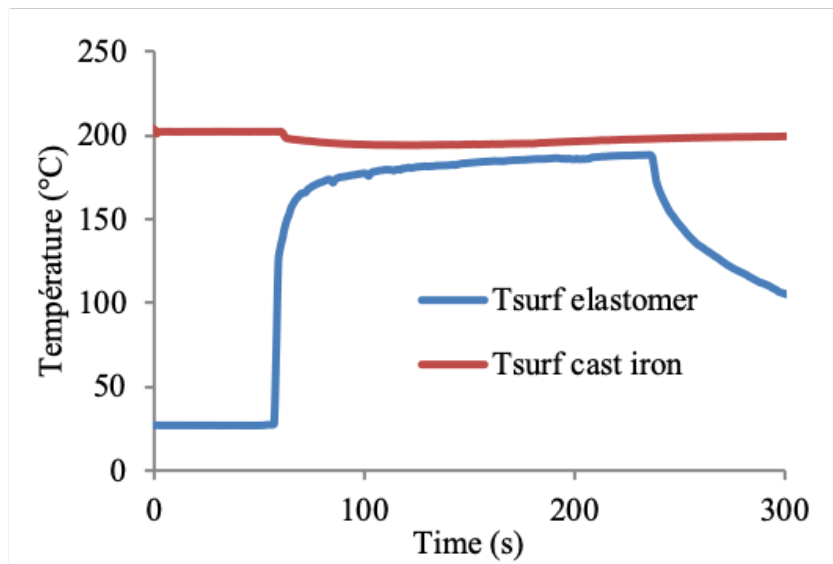


Figure 14: Temperature evolutions for the contact resistance estimation at 200 °C

326 4.3. Experimental tests with cereal dough

327 For this study, the temperature of the cast iron plate was regulated, and
 328 a set point of 200 °C was imposed for temperature T2. A bottomless PTFE
 329 mold surrounded by thermal insulation, was placed on the surface of the cast

330 iron plate. When steady state was reached, 150 ± 3 g of dough, initially at
331 room temperature, was poured in the crucible, corresponding to a thickness
332 of about 8 mm. The mass variation was continuously recorded by a precision
333 balance, three temperature sensors were embedded into the dough (table 2)
334 and air conditions were tracked.

335 In order to verify the repeatability of the measurements, this test was
336 performed 3 times in the same experimental conditions. Figure 15 shows the
337 temperatures measured within the dough during 20 minutes and the dimensionless mass obtained by mass monitoring. For the temperatures curves, the
338 errorbars representing the maximum/minimum values are also plotted. The
339 dough temperatures quickly increase and reach steady state after about 15
340 minutes. During this same duration, the mass losses represent approximately
341 15 % of the initial mass. A good repeatability is observed for the temperature measurements inside the dough and for the mass losses. The heat
342 flux estimated by IHCP presents an initial peak of $35 \text{ kW}\cdot\text{m}^{-2}$ and quickly
343 decrease to stabilize around $3.5 \text{ kW}\cdot\text{m}^{-2}$ with a weak dispersion (minimum
344 and maximum heat fluxes are also shown). Moreover, Figure 15d shows the
345 estimated temperatures at the interface cast iron/dough. The weak dispersion of temperature shows a good repeatability of these three tests. The
346 time integration of the estimated heat flux provides the energy per unit area
347 transmitted by the cast iron. This energy (J) is compared with that deduced
348 from an energy balance performed on the batter measurements, taking into
349 account the sensible heat, the mass losses and the heat flux exchanged by
350 radiation and convection with ambience (equation (19)).
351
352
353

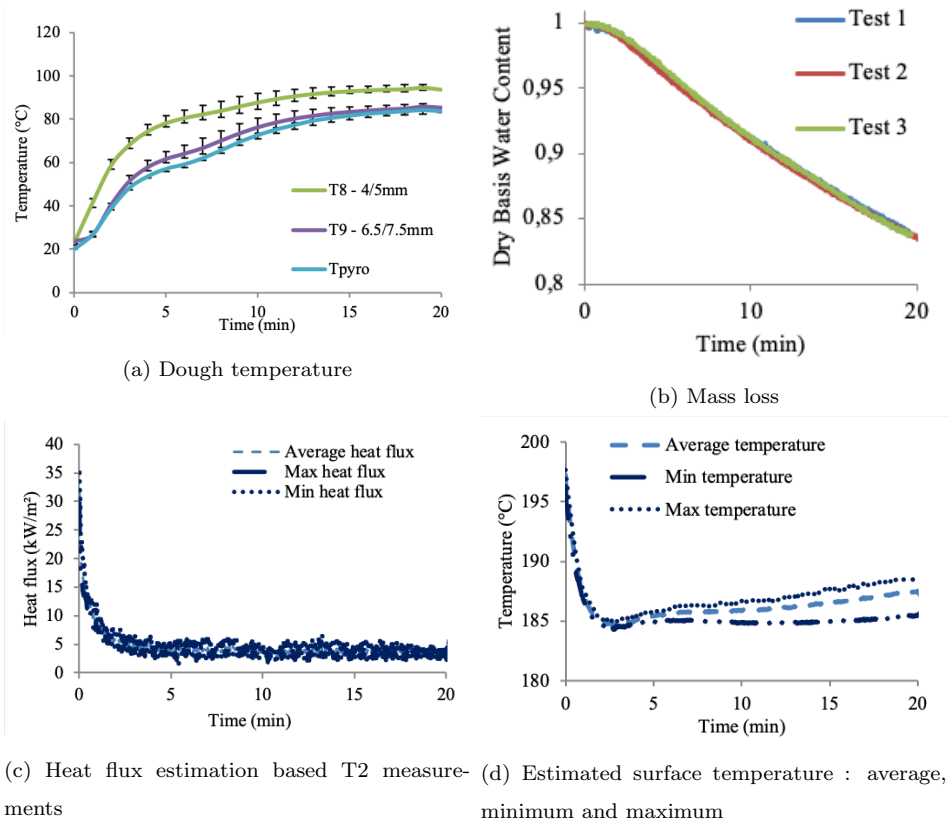


Figure 15: Measurements and estimated results for three tests at 200 °C

$$\int \varphi(t) dt S_{surf} = -\Delta m L_v - h_{conv} S_{surf} (T_{pyrometer} - T_{amb}) - \epsilon \sigma S_{surf} (T_{pyrometer}^4 - T_{amb}^4) + m c_p (T_{7,8,9} - T_0) \quad (19)$$

354 In this equation 19, the natural convection coefficient has been set at
 355 $6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$. This value was deduced from relationships referenced in liter-
 356 ature [29]. The emissivity of the cereal dough was measured using a Shimadzu
 357 UV-3600 spectrophotometer ($\epsilon = 0.9$). The specific heat was calculated using
 358 the Baik & al. correlations [28] (see appendix A). The sensible heat was
 359 determined by decomposing the dough as 3 layers of 2 mm, 4 mm and 2 mm
 360 whose the temperatures were respectively T7, T8 and T9. The results are
 361 given in table 3.

362 In the case of a baking carried out at 170°C , the total energy deduced
 363 from the fluxmeter measurements was equal to 70 kJ whereas the total energy
 364 calculated based on the equation 19 was 70 kJ (error inferior to 3 %). It can
 365 be assumed that there was a small heat loss between the energy calculated by
 366 the IHCP method and the incoming energy into the dough which demonstrate
 367 the reliability of the inverse method. This total energy was distributed as
 368 follows: 32 kJ related to the sensible heat, 27 kJ related to water vaporization
 369 and 9 kJ related to the heat exchanges with the ambiance (convection and
 370 radiation). Logically, the higher the heater temperature is, the greater the
 371 total energy transmitted to the dough is, for a similar baking duration. Thus,
 372 the total energy was 83 kJ at 200°C and 105 kJ at 230°C . The final dough
 373 temperatures being higher, the sensible heats were also greater. As mass
 374 losses increased with temperature, latent heat followed the same trend, as

375 did convection and radiation heat losses.

Table 3: Fluxmeter energy and total energy balance

Temperature (°C)	Fluxmeter energy (kJ)	Sensible heat (kJ)	Latent heat (kJ)	Convection/Radiation (kJ)	Total energy balance (kJ)
170	70	32	27	9	68
200	83	34	36	11	81
230	105	36	53	12	101

376 5. Conclusion

377 A method based on solving IHCPs was developed to estimate the heat
378 flux transferred from a hot plate to a cold product during direct contact
379 heating. This method was first developed and tested by numerical studies.
380 A bi-dimensional numerical model was built to predict thermal phenomena
381 during contact between a cold elastomer and a hot cast iron plate in the
382 case of imperfect contact. The heat flux transmitted from the hot plate
383 to the elastomer was directly deduced from this model. Two Inverse Heat
384 Conduction Problems were developed and tested based on some temperatures
385 of the hot plate and the elastomer. The two estimated heat flux obtained
386 were compared with the direct model heat flux to validate the prescribed
387 procedure. A sensitivity analysis was performed to quantify the impact of
388 uncertainties (thermal properties and sensor locations) on the estimation and
389 verify the robustness of the method.

390 Based on this numerical study, an experimental set-up was designed with
391 adequate instrumentations. Experimental studies were first carried out for
392 a contact hot plate / elastomer as numerically tested. The two heat flux
393 estimated from elastomer temperatures on the one hand and from hot plate

394 temperatures on the other hand demonstrated the ability of the method to es-
 395 timate an unknown heat flux. The procedure was next tested for the baking
 396 of a cereal dough. An energy balance conducted from temperatures mea-
 397 surements and mass losses measurements confirmed the value of total energy
 398 supplied to the dough deduced from the time integration of the estimated
 399 heat flux. Moreover, this energy balance provided a detailed distribution
 400 (sensible heat, water vaporization, convection and radiation heat losses) and
 401 participated to the total validation of the proposed method.

402 Appendix A

403 The thermal properties of the bakery product are estimated using the
 404 Baik & al. correlations [28]. These correlations depend on the mass fraction
 405 of each component (water, protein, carbohydrate, fat, fiber and ash): $c_p =$
 406 $\sum Y_i^W c_{p_i}$, $k = \sum Y_i^W k_i$, $\rho = \frac{1}{\sum \frac{Y_i^W}{\rho_i}}$. The composition of the dough are given
 407 in table 4.

Table 4: Dough composition

	Industrial preparation (%)	Milk (%)	Bakery product (%)
Protein	14.00	3.11	7.09
Carbohydrate	65.60	4.66	26.93
Fat	3.20	1.55	2.16
Fiber	3.70	0.00	1.35
Ash	1.20	0.24	0.59
Water	12.30	90.44	61.89

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