Development of experimental devices in order to study the interactions between heat and mass transfer phenomena and thermal degradation reactions of lipids during domestic reheating of pre-fried food products

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ABSTRACT

The present paper deals with the development and thermal characterization of two original experimental laboratory devices developed in order to study thermal degradation of lipids during domestic reheating of industrial pre-fried products. These devices are hot-air cooking and contact heating devices (called pan-frying if oil is added between the product and the heating surface) since these two modes of reheating are commonly used by consumers for these types of products. When defining the specifications of these devices, it was decided to develop prototype devices allowing to work in perfectly controlled environmental conditions in terms of heat transfer phenomena. This specification is required for experiments leading to the production of food samples to be analyzed in order to study the nature and extent of chemical reactions involved in lipids thermal degradation reactions. It was also listed as a specification to be able to reproduce in the laboratory the variability inherent to domestic operations, this variability being mainly due to the nature and sophistication of apparatus used in domestic conditions and the goodwill of consumer to follow reheating conditions proposed by food product manufacturers. Results about this variability will be given in this paper concerning both hot-air cooking and contact heating in “classical” domestic operations. The technicalities (design factors, control mode) and performances (in terms of heat transfer phenomena) of the two experimental laboratory devices will also be detailed in this paper.

Keywords: hot-air cooking; pan-frying; heat flux

INTRODUCTION

Lipids are a key macronutrient since they constitute *circa* 40% of the total energy intake for women or men. When solid products containing lipids are submitted to high temperatures, thermal degradation reactions of lipids occur. The chemical reactions of concern are oxidation, isomerisation of polyunsaturated fatty acids and degradation reaction of sterols and liposoluble vitamins. Some reaction products showing recognized or suspected toxicity have also been identified in the reactions listed above: acrylamide, furan, *trans*-fatty acids, polycyclic aromatic hydrocarbons… While a lot of studies can be found about degradation reaction of lipids in oils and products heated during deep-frying [1], few studies concern thermal degradation reactions of lipids during contact heating or oven cooking of food products. Moreover, the results obtained in deep-frying can not be extrapolated to pan-frying or hot-air cooking since these processes differ radically in terms of nature and intensity of transfer phenomena occurring during heating. In parallel, a serious lack of data has been identified concerning thermal characterization of transfer phenomena during contact heating or pan-frying (especially between product and heating surface). This lack of data is probably due to difficulties in terms of metrology in order to assess reliable values of contact heat transfer coefficient (whose value can drastically change during heat treatment of a solid food product) and surface temperatures (for both product and heating surface). Consequent difficulties are hence encountered when trying to predict food product temperature rise during contact heating. Some experimental and theoretical studies can nevertheless be found concerning single- or double-sided pan frying of beef burgers: [2], [3], [4]. With regards to these stakes, a French national 3-years research project called DOMINOVE (“DOMestic heating of deep-fat fried products IN OVEn and pan”) has been supported by the French Research National Agency (ANR) since 2010. This project aims at studying the extent of lipid thermal degradation during domestic reheating of industrial pre-fried food products by hot-air cooking or pan-frying. The products retained for this project are potato products, a breaded poultry product containing cheese and an Asiatic product (garnish made of pork meat and vegetables wrapped within a rice paper). A more generic study will also be carried on a solid model gel product containing a dispersed lipidic phase in order to control the structure and composition of the reactive medium. From these data and developing mechanistic models for both transfer phenomena and chemical reactivity, one of the objectives of the project is to propose optimal domestic reheating conditions for pre-fried product increasing the nutritional characteristics of the product and maintaining satisfying sensorial quality. In this general context, this paper specifically deals with the development and thermal characterization of two original experimental laboratory hot-air cooking and pan-frying devices specifically instrumented to allow the study of heat and mass transfer phenomena occurring during reheating. These devices must satisfy to two complementary specifications: (1) to work in perfectly controlled environmental conditions in term of heat transfer phenomena in order to study lipids thermal degradation reactions within the food product (2) to reproduce in the laboratory the variability inherent to domestic operations, this variability being mainly due to the nature and sophistication of apparatus used in domestic conditions and the goodwill of consumer to follow reheating conditions proposed by food product manufacturers. This paper will first present original results taken from an experimental campaign aiming at evaluating the variability inherent to hot-air cooking and contact heating at domestic scale in "classical" operating conditions. The effect of both nature of apparatus used and behaviour of the consumer will be examined. In a second part, the experimental laboratory devices developed in our laboratory to reproduce the domestic operations of concern and their thermal characterization will be discussed.

MATERIALS & METHODS

For the study of the variability inherent to domestic hot-air cooking, three commercial electric ovens were used: two built-in ovens of normal size and a mini-oven capable, these three ovens operating in free or forced convection conditions (see Tab. 1 for selected settings). The pre-heating power is the power delivered during the preheating of the empty oven (during *circa* 15/20 minutes) and the heating power corresponds to the power delivered during heating of food products.

Table 1. Domestic hot-air cooking devices specifications and selected settings

Device	Model	Volume (L)	Pre-heating power (W)		Heating power (W)	
			free conv.	*forced conv.*	*free conv.*	*forced conv.*
Built-in oven #1	Whirlpool AKZ216	52	3500	3500	2300	2300
Built-in oven #2	Scholtes F-4016	*circa* 50	3000	3000	3000	3000
Mini-oven	Brandt FC-400MB	40	1500	1500	1500	1500

To reproduce practical consumer behavior, after a pre-heating step (until the oven has reached steady-state conditions), a thin aluminum cooking plate (30 cm diameter) containing 3 breaded poultry products (total mass *circa* 300g) was put at the centre of the oven cavity, at an height equal to the third of the cavity height. During these experiments, the product thermal environment was assessed by three variables: the air temperature above the thermal boundary layer developed at the immediate vicinity of the product, the convective heat transfer coefficient giving an indication of the quality of convective exchange between the product and the surrounding air and the equivalent radiative temperature which is the temperature reached by the oven walls if all these walls had the same temperature. Each of these variables is expected to be non uniform in the oven cavity and variable in time mainly due to oven design factors (effect of nature and position of fans for an oven cavity geometry on the air flow pattern) and level of sophistication of air temperature control system. During experimental trials, air temperature (T_∞) was measured using a T-type thermocouple (TC, Dardilly, France) fixed 12cm above the centre of the cooking plate. The convective heat transfer coefficient (h_{cv}) and the equivalent radiative temperature (T_{ray}) were measured at the center of the cooking plate using air temperature and heat fluxes measurements apparatus. This apparatus consisted in a copper heat sink (width: 6cm, length: 7cm, height: 3cm) instrumented with two 4 cm² surfacic heat flux sensors (Captec, Lille, France) of low and high known thermal emissivities, each of them receiving the sum of a convective and a radiative heat flux. The two variables of interest were identified by linear regression after a linear combination of the two expressions of total thermal fluxes allowing the separation of the two unknown variables. The period of rapid temperature rise of the copper load was used for this data treatment.

For contact heating, a similar methodology is used to characterize variability in domestic conditions. Two Teflon®-coated pans were selected: a thin and light aluminium pan (pan #1, internal diameter 25cm and thickness 4mm) and a heavier one made from an assembly of stainless steel and aluminium (pan #2, internal diameter 23cm, thickness 8mm). Pan temperature was measured using a T-type thermocouple inserted in a very thin hole at *circa* 2 to 3 mm below the pan surface after a precise slotting of the bottom part of the pan. To reproduce domestic conditions, after a pre-heating step at maximum power (in order to reach 200°C for pan temperature), a thermal load of 3 breaded poultry products were put in the pan, one of which centred above the position of pan temperature measurement. At this particular time, the selected heating power is adjusted to a medium or high level (see Tab. 2). Total cooking time is fixed to 10 minutes with a flipping of the products after 5 minutes of heating on one face. This operation is made with or without sunflower oil (35g of oil used representing a thin layer of *circa* 1 mm). The heterogeneity of the pan surface temperature was evaluated just before the disposal of the products using an infrared thermography camera (Ti9, Fluke, Roissy, France). The pans were heated using four commercial heating devices typically encountered in domestic conditions (see Tab. 2). The variable used for the characterization of the product thermal environment during contact heating is the pan temperature below the product during heating.

Table 2. Domestic heating devices specifications and selected settings for contact heating study

Device	**Burner diameter (cm)**	**Pre-heating power (W)**	**Heating power (W)**	
			medium	*high*
Electric hob	18,5	2000 (6/6)	300 (3/6)	1100 (5/6)
Gas hob	medium	2200 (maxi)	-	2200 (maxi)
	large	-	1000 (mini)	-
Vitroceramic hob (halogen)	19	1700 (6/6)	1700 (3/6)	1700 (5/6)
Induction hob	18	2000 (8/9)	400 (4/9)	1300 (7/9)

For hot-air cooking and contact-heating devices, the electrical power consumptions were recorded during all experiments with a Joule-meter, except for gas heating for which the constant volumetric flow rate of gas consumed is converted into electrical power by a correlation factor (1 m^3 consumed equals to 11 kWh).

RESULTS & DISCUSSION

Characterization of domestic heating devices: Tab. 3 gives the pre-heating rates of the domestic devices used for contact heating (assuming that the pan temperature rise is linear from ambient temperature to 200°C). The fastest pre-heating is achieved with the induction hob whereas the electric hob seems to be the less efficient device. The addition of an oil layer has no significant effect on pre-heating rate except for induction hob with a lowered pan temperature rise. By contrast, the nature of the pan has an effect on the pre-heating rate: the thin pan (pan #1) has a slower heating rate than the heavier one (pan #2) when used with electric hob while the reverse is observed on gas hob. For electric hob, the quality of physical contact between the pan and the heating surface seems to have a significant influence on preheating rate (pan #2 is obviously heavier and pan #1 leading to a better physical and hence thermal contact). For the gas hob, the pan thickness (pan# 1 is thinner) and the nature of the pan material (pan #2 contains stainless-steel which is about ten times less conductive than aluminium) seems to be prevalent on pre-heating rate (quality of physical contact has no longer importance when the bottom surface is heated by the flame of the burning gas). The heterogeneity of pan surface temperature at the end of pre-heating depends widely on the type of pan selected. On the same device, the heaviest pan with better physical contact shows a lower heterogeneity (about 40°C) than the lighter one (100°C). Two others explanations can be given: the higher thickness of pan #2 allows a better energy transport by conduction and its lower diameter leads to a lower cooling surface (upper surface of the pan). The heating device also has an impact. On the vitroceramic hob, pan #2 presents greater surface temperature heterogeneity (*circa* 60°C) than on the electric hob. A possible explanation could be the pre-heating rate which is significantly higher in the case of the vitroceramic hob (see Tab. 3). This hypothesis is reinforced by looking at pan #2 surface temperature mapping on the induction hob (with the highest pre-heating rate) for which the heterogeneity is even greater (*circa* 100°C).

Table 3. Pre-heating rates of the domestic contact-heating devices

Device	**Pan**	**Oil**	**Pre-heating rate (°C/s)**	**Std (°C/s)**
Electric hob	1	**no**/ yes	**0.64**/ 0.62	**0.04**/ 0.02
	2	**no**/ yes	**0.77**/ 0.75	**0.02**/ 0.08
Gas hob	1	**no**/ yes	**1.58**/ 1.30	**0.11**/ 0.03
	2	**no**/ yes	**0.96**/ 0.91	**0.02**/ 0.05
Vitroceramic hob	1	**no**/ yes	**1.14**/ 1.04	**0.07**/ 0.15
	2	**no**/ yes	**1.01**/ 0.94	**0.12**/ 0.08
Induction hob	2	**no**/ yes	**2.20**/ 1.66	**0.12**/ 0.04

Once food products have been put on the pan, the four contact-heating devices (operating at medium power) show very different behaviours (see Fig. 1). This can be explained by the power delivered but also by the device (with different thermal efficiency of induction or gas devices for example). Pan temperature is never constant during heating. For this trial, the most efficient devices are the gas and vitroceramic hobs but with a much higher power consumption (1000 and 1700W) than the others. It can be noticed that the vitroceramic hob is the only device to have a control system (see Fig. 1b) in comparison with other devices delivering constant power. Thermal inertia seems to be a pregnant phenomenon on the electric hob device since the pan temperature continues to rise despite the drop in power delivered just after the products deposal. This observation is also valid when using the pan #1 (not shown here). The small change of slope observed after five minutes of heating (especially seen on Fig. 1a for electric and induction hobs) corresponds to the flipping of products. This phenomenon is more pronounced when oil is present (not shown here) because of the better physical contact between pan and product which implies a better thermal contact. Trials at high power (not shown here) show a pan temperature always rising and reaching *circa* 300°C.

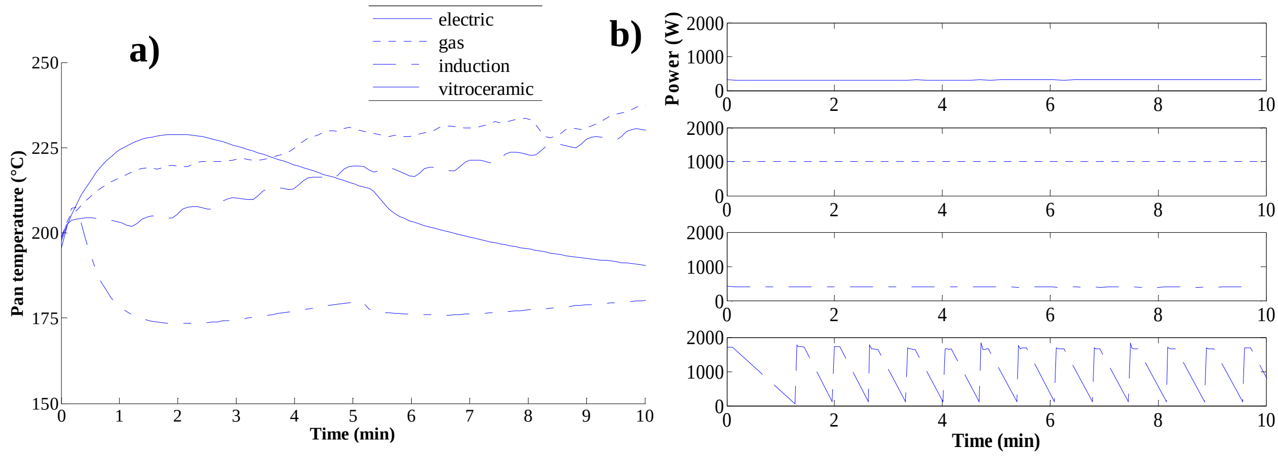

Figure 1. Cooking of three breaded poultry products for contact-heating devices (medium cooking power, pan #2) a) Evolution of pan temperature under the product b) Evolution of instantaneous power delivered by the devices

When looking at the pre-heating rate for the hot-air cooking devices (Tab. 4), it can be noted a good accordance for the two built-in ovens tested whatever the convection mode or the setpoint temperature. In the mini-oven the pre-heating rate is significantly higher although the power consumption is lower (due to the lower cavity volume) with a significant effect of the value of setpoint temperature.

Table 4. Pre-heating rates of the hot-air cooking devices

Device	Convection	Set point (°C)	Pre-heating speed (°C/s)	Std (°C/s)
Built-in oven 1	free	180/ **240**	0.20/ **0.26**	-
	forced	180/ **240**	0.21/ **0.20**	-/ **0.005**
Built-in oven 2	free	180/ **240**	0.27/ **0.26**	-/-
	forced	180/ **240**	0.24/ **0.25**	-/-
Mini-oven	free	180/ **240**	0.54/ **0.36**	-/-
	forced	180/ **240**	0.40/ **0.31**	-/ **0.03**

Very different air temperature evolutions during cooking are also observed for hot-air cooking devices in free convection (see Fig. 2). This is mainly due to the different modes of temperature control within the oven (and hence power delivered as seen in Fig. 2b). Whatever the oven, the set point is never successfully reached and kept constant during cooking: in built-in oven #1 and mini-oven, the set point is never reached again after the disturbance caused by the opening of the door whereas in built-in oven #2, it is quickly exceeded and starts oscillating with a large amplitude. In forced convection mode (not shown here), same patterns are observed. The air temperature in the mini-oven is very far from the set point. In that case the pre-heating step seems to play a key role in the temperature evolution during cooking because: the set point is reached at the end of the preheating step but temperature decreases immediately after door opening and beginning of cooking.

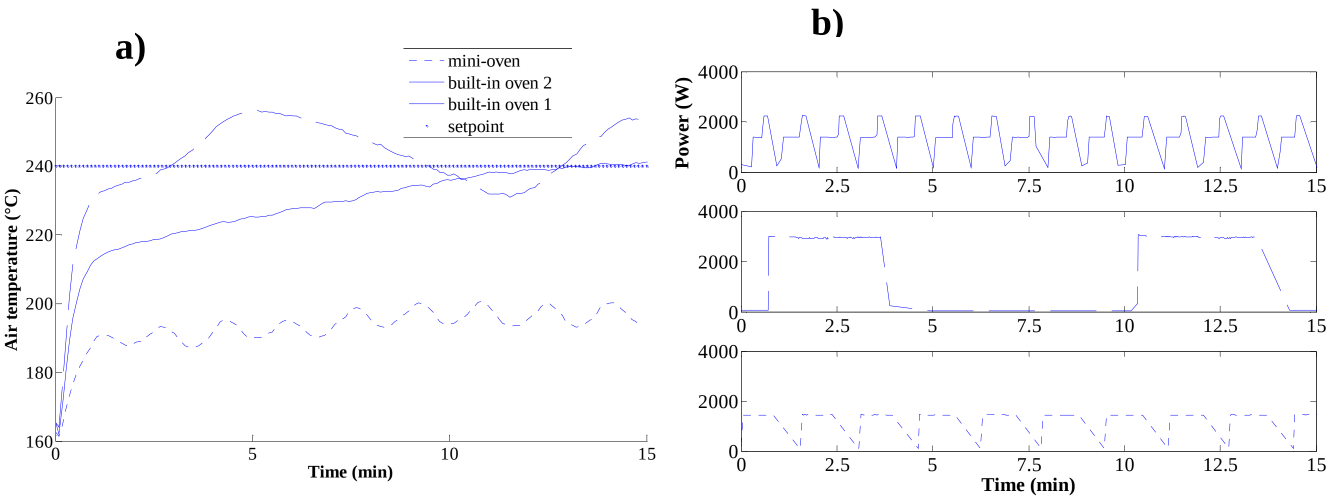

Figure 2. Cooking of three "cordons-bleu" in the three tested ovens (set point 240°C, free convection)
a) Evolution of air temperature above the cooking plate b) Evolution of instantaneous power consumed by the ovens

In the three ovens selected, the convective heat transfer coefficients measured at the centre of the cooking plate in free convection are nearly the same (6 to 8 W/m².K). In contrast for the forced convection mode, we note a significant difference between the two built-in ovens (*circa* 15 W/m².K) and the mini-oven (11 W/m².K) which can be explained by the position of the fan (centred in the back wall for built-in ovens and in the right wall for mini-oven) and maybe its rotation speed (no data available on the fan rotation speed). The results on equivalent radiative temperature measured at the centre of the cooking plate is more difficult to interpret because of the unstable air temperature (see Fig. 2a). However we can assume that wall temperature is more stable than air temperature. In the built-in ovens, for forced convection and a set point of 240°C, the radiative equivalent temperature is close to the set point (241,7°C +/- 3,6°C for built-in oven #1 and 234,7°C +/- 5,2°C for built-in oven #2) whereas the set point value is far to be reached in the mini-oven (218,1°C +/- 1,1°C). This lower value encountered in the mini-oven is consistent with the previous observations for air temperature evolution during cooking (Fig. 2a). For free convection, the radiative equivalent temperature is on average 10°C below the set point whatever the oven. It would certainly be interesting to make a spatial mapping of these variables on the surface of cooking plate to show a possible heterogeneity in the ovens.

Development of laboratory heating devices: The previous results reinforce the need for us to develop laboratory devices to study heat and mass transfer phenomena during cooking in constant and repeatable conditions. The experimental device for hot air cooking was developed from one of the three commercial ovens previously studied (Whirlpool AKZ216, Boulanger, Massy, France). The air temperature control was improved by adding a PID controller to the installed electronic control system. This one controls the air temperature 12cm above the centre of the cooking plan (height: third of the total height of the cavity). This device can reach and control set point air temperature until 250°C. After the disturbance caused by the opening of the door the set point is quickly reached again and maintained constant throughout cooking (+/- 1°C) in comparison with performances exhibited by commercial domestic devices. The air temperature gradient on the cooking plate (30 cm diameter) is about 5°C whatever the air temperature set point. The convection mode has an influence on the value and heterogeneity of the convective heat transfer coefficient over the cooking plate. In free convection, it is quite uniform on the cooking plate (7 W/m².K) whereas in forced convection, a greater dispersion is noted (from 14,5 to 23,5 W/m².K) explained especially by the location of the fan. Trends are the same for the equivalent radiative temperature. In free convection, it is close to the air temperature set point except near the front side of the oven where there is a lower value (about 10°C lower) which can be explained by the cooling phenomenon due to the oven door. In forced convection, the equivalent radiative temperature is on average 20°C lower than the set point and more dispersed (30°C lower near the fan and equal to the set point to the right).

Contrary to the hot air cooking device, the laboratory device for contact heating is an original prototype. A stainless-steel pan (MD2I, Boulogne-Billancourt, France), with a bottom made of a sandwich stainless steel/aluminium/stainless steel (internal diameter 34cm, thickness 8mm) is positioned on a double jacketed stainless-steel cylindrical basis filled with an insulating material (Superwoolblanket 607, Sored UPM, Messein, France) as shown on Fig. 3. The heating source is a heating resistance (3000W, Résistances

Services, Marseille, France) which is fixed inside the basis on a stainless-steel plate just under the pan. A T-type thermocouple is inserted in the centre of the pan 2 mm below the surface through a thin hole below the pan surface after a precise slotting of the bottom part of the pan. This measure is used for controlling the pan temperature at the centre of pan surface using a PID controller and cooking can be made up to 250°C. The two main advantages of this device are: (a) the good surface temperature uniformity of the pan compared to what is observed in domestic conditions (less than 5°C on the cooking area of diameter 30cm) which allows to cook a substantial amount of products in the same conditions (b) the high thermal inertia of the system coupled to the pan temperature control which allows to work in constant and very repeatable conditions contrary to what happen in domestic devices (as discussed above).

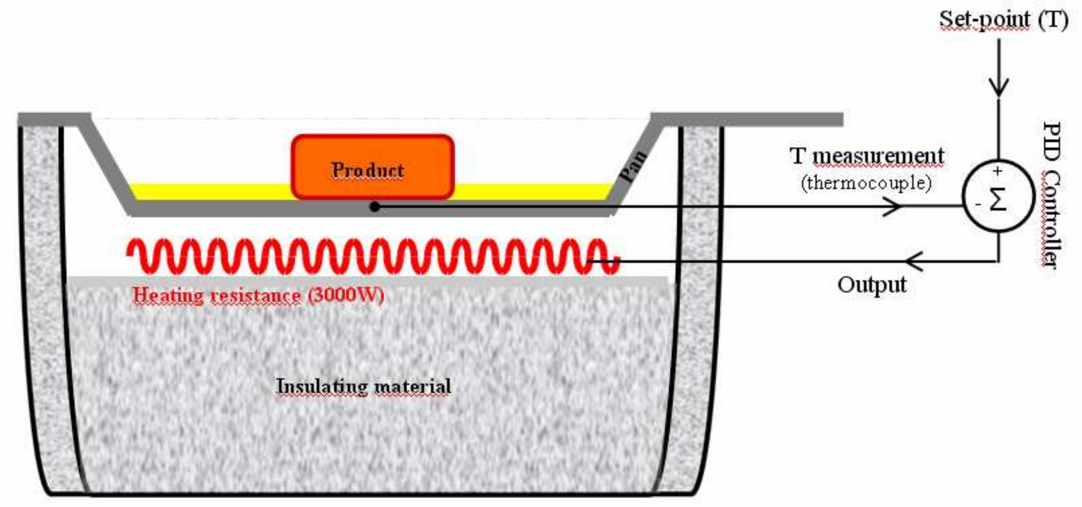

Figure 3. Schematic representation of original prototype developed for contact heating

These two laboratory devices are equipped with an acquisition chain to record the temperatures (air temperature for hot-air cooking device and pan temperature for contact-heating device) consisting of an acquisition central (Agilent 34970A, Massy, France) connected to a PC. A thermal heat flux sensor is currently developed and will soon be added to the pan in order to access to the pan surface temperature (below the heated product) and the thermal heat flux delivered by the pan to the product.

CONCLUSION

During domestic hot-air or contact cooking, the behaviour of the consumer and the equipment influence greatly the thermal environment of the heated product and hence certainly the magnitude of heat and mass transfers and reactivity of lipids within the product. These data about “variability of domestic operating conditions” will be used in further studies to study the propagation of uncertainties upon variables characterizing thermal environment of heated product on the predicted variables of mechanistic models of heat and mass transfer and chemical reactivity to be developed. These observations led us to develop two heating devices in order to study heat and mass transfers in repeatable and constant conditions: a hot-air heating device based on a commercial oven which was modified for a better air temperature control, and a original prototype for contact-heating with a better surface temperature control and homogeneity.

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