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Evaluation of heating performances and associated variability of domestic cooking appliances (oven-baking and pan-frying)

Jérémie Cernela [a,b], Bertrand Heyd [a,b], Bertrand Broyart [a,b,*]

[a] AgroParisTech, UMR 1145 Génie Industriel Alimentaire, 1 avenue des Olympiades, F-91300 Massy, France
[b] INRA, UMR 1145 Génie Industriel Alimentaire, 1 avenue des Olympiades, F-91300 Massy, France

HIGHLIGHTS

- Domestic oven baking and pan-frying are thermally chracterised.
- Quantitative data on the variability of domestic heating conditions are given.
- Variability due to domestic appliances and cooking practices is very large.

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ABSTRACT

By comparison with those in industry, domestic cooking processes are rarely studied with respect to heat transfer although they can drastically modify the quality of heated products. In order to compensate for this lack of information in the literature, the aim of this work was to propose test procedures to evaluate the variability of domestic appliance heating performances in the case of oven-baking and pan-frying. The measurements included the continuous recording of pan temperature during pan-frying using different types of hobs (electric, halogen, gas, induction) and pans; the continuous recording of air temperature and measurement of the convective heat transfer coefficient and equivalent radiative temperature during oven-baking using different types of ovens. The results revealed broad variations in heating conditions depending on the type of appliance used and on consumer behaviour. For pan-frying, it was shown that pan temperature varied constantly during heating. From an initial value of 200 °C and a given product load, it could fall to 150 °C or rise to 330 °C at medium or high heat, respectively. For oven-baking, heating was sometimes performed at an actual air temperature that differed considerably from the air temperature set on the oven. These measurements also showed relatively low convective heat transfer coefficient values, ranging from 6 W/m^2 K under free convection to 16 W/m^2 K under forced convection.

1. Introduction

During their shelf-life (from industrial production to final preparation by the consumer), processed food products (served as whole meals or parts of a meal) are subjected to different heat treatments, either at an industrial level or in the consumer's kitchen. While there is much literature devoted to the heat transfer phenomena which occur during industrial treatments, domestic heating has been more rarely studied. This may seem paradoxical because the domestic heating of foodstuffs is the final step before the consumer's dinner table and is known to affect both the nutritional and sensory characteristics of food products [1,2]. Moreover, if account is taken of the variability associated with domestic operations, the consequence is that consumers may obtain very different levels of quality (nutrient composition, possible presence of neoformed compounds, colour, flavour, texture) from one standardised industrial food product. This observation also explains why food product manufacturers are increasingly concerned about how their products are prepared at a domestic scale. These concerns are reflected by the detailed preparation instructions shown on food product packaging and are the subject of the French research programme ANR-09-ALIA-002 DOMINOVE, funded by the French National Research Agency (ANR), involving industrial partners and dealing with domestic heating of pre-fried food products.

* Corresponding author. AgroParisTech, UMR 1145 Génie Industriel Alimentaire, 1 avenue des Olympiades, F-91300 Massy, France. Tel.: +33 (0) 1 69 93 51 24; fax: +33 (0) 1 69 93 51 85.
E-mail address: bertrand.broyart@agroparistech.fr (B. Broyart).

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Based on this assessment, the objective of this study was to propose test procedures that could evaluate the heating performance of domestic heating appliances. Oven-baking and pan-frying were the techniques selected for this study. These operations were chosen because they are the most widely used in the home and also because they can be used for a broad range of food products.

In the case of domestic oven-baking, some studies were found to have included measurements of heat transfer coefficients using a metal heat sink equipped with heat flux sensors or thermocouples. For example, Sparrow and Abraham [3] measured total heat transfer coefficients which ranged from 18 W/m^2 K to 26 W/m^2 K for domestic ovens. As for convective heat transfer coefficients, values of 15 W/m^2 K were reported by Carson et al. [4]. However, Sakin et al. [5] and Sato et al. [6] reported respectively very different values of 25 and 10 W/m^2 K for air velocities of 0.6 m/s, suggesting a high variability of operating conditions in domestic appliances. In terms of the ratio between the different modes of heat transfer involved in domestic oven-baking, Baik et al. [7] reported that the share of radiative flux was in most cases higher than 50% at a typical air-temperature set point. Some authors also provided information on air temperature during heating [4,8–10], highlighting variations concerning its evolution profile (compliance with the set point or not, oscillations). But no reference was made to the relationship between evolutions in air temperature and the air-temperature control systems installed in the baking ovens tested.

In the case of domestic pan-frying, studies were found to have investigated the evolution of particular quality criteria for heated food products [11–13]. However, apart from the fact that these experiments were performed with an initial pan temperature ranging from 150 °C to 250 °C, little information is available on the method used to measure pan temperature and how it evolves during heating. By broadening the search to studies dealing with heat and mass transfer during cooking on domestic or out-of-home catering devices (single or double-sided grills), more information could be found on evolutions of heating surface temperatures and their measurement [14–20]. Unfortunately, these data were not representative of the thermal conditions encountered at a domestic scale because the appliances used during these studies were often equipped with an additional heating temperature control system and thus operated at constant temperature, whereas domestic appliances usually operate at a constant heating power (and a variable heating surface temperature).

In view of this lack of data in the literature, the objective of the present study was therefore to propose test procedures to evaluate the heating performances of domestic heating appliances (used for oven-baking and pan-frying). These performances were determined by measuring several heat transfer parameters: effective air temperature (just above the product) during heating and the level of radiation and convection for oven-baking; changes to pan temperature under the product during heating for pan-frying. To investigate the potential of these test procedures, a series of domestic baking ovens, and different combinations of pans and hob types, where characterised in thermal terms. For pan-frying, the influence of consumer behaviour on heating performance was also evaluated because the heating tests were performed at either high or low heat, and oil was or was not placed in the bottom of the pan before the product.

Considering the number of experiments presented and discussed here, the results of this study can also be considered as an attempt to evaluate the variability inherent in domestic oven-baking and pan-frying operations. These results may therefore help food manufacturers to take account of the broad range of operating conditions that might be experienced by solid foodstuffs during domestic heating.

Table 1
Domestic heating hobs selected for pan-frying tests.

Hob[a]	Electrical power at max. knob position (W)	Power knob position (actual/maximum)		
		Pre-heating	Heating (medium heat)	Heating (high heat)
Electric (Evolutive, Seb)	2000	6/6	3/6	5/6
Halogen (Brandt)	1750	6/6	3/6	5/6
Induction (TI302, Brandt)	2500	8/9	4/9	7/9
Gas (DCM240VE1, De Dietrich)	2200	max (medium burner)	min (large burner)	max (medium burner)

[a] All the heating hobs tested had a diameter of 19 cm.

2. Materials and methods

2.1. Domestic appliances selected for pan-frying tests

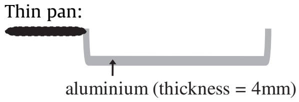
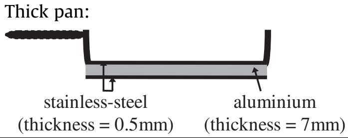
Two different PTFE-coated pans with a 25 cm internal diameter were selected for this study: a thin, pure aluminium pan (thickness 4 mm) and a thicker pan (8 mm) made of aluminium sandwiched between two thin layers of stainless steel. These pans were used in combination with four typical domestic heating hobs: electric, gas, halogen and induction (see Table 1 for specifications). The thin pan was not used on the induction hob, as aluminium is not a ferrous metal.

2.2. Test procedure to evaluate the heating performance of domestic pan-frying appliances

In order to characterise the intensity of heat treatment independently of the type of hob used, pan-temperature measurements were required. A T-type thermocouple was therefore inserted in the bottom of the pans selected for the experiments in a very small hole about 2 mm below the pan surface (precise slotting of the bottom of the pan having been performed previously). Pan temperature was thus recorded every 5 s using a data logger (34970A with 34901A module, Agilent, Loveland, Colorado, USA).

After choosing a combination of heating hob and pan, a precise protocol was followed for each test. This started with a pre-heating step at maximum heating power (using the appropriate knob position as discussed in Table 1) until a pan temperature of 200 °C was reached. At this precise time, a thermal load consisting of three breaded poultry products with a total approximate mass of 300 g (obtained from a local market, Massy, France) was placed on the pan with one product being centred above the thermocouple used to measure pan temperature. The heating power was then adjusted immediately to medium or high level (by changing the knob position, Table 1) in order to reproduce the behaviour of consumers heating at either medium or high heat. The total heating time was then fixed at 10 min, the products being turned over after 5 min on one side. The influence of consumer behaviour on heating performance was also taken into account by performing each test with or without the addition of 35 g sunflower oil (local market, Massy, France) in order to obtain an oil layer of ca. 1 mm thick in the pan. This layer could be expected to modify the intensity of heat exchange between product and pan during heating and hence the kinetics of pan-temperature variations. When no oil was added, the spatial heterogeneity of the pan surface temperature was also evaluated at the end of the pre-heating step (before the products are placed in the pan) using an infra-red thermography camera

Table 2
Heating tests in order to evaluate the heating performance of domestic pan-frying appliances.

Influence of material		Influence of consumer behaviour	
Nature of hob	Nature of pan	Oil in the pan	Power during heating
Electric	Thin pan: 	No/Yes	Medium/High (Table 1)
Halogen			
Induction[a]	Thick pan: 		
Gas			

[a] The thin pan was not used with induction hob, the aluminium not being a ferrous metal.

(Ti9, Fluke, Everett, Washington, USA) assuming a PTFE thermal emissivity of 0.95. To measure the heating power effectively delivered, and to compare the thermal efficiency of each heating mode, the instantaneous electrical power delivered by the heating device was also recorded during the heating test with a Watt-meter (adapted from AAD1D5E, Saia-Burgess, Murten, Switzerland) except for the gas hob where a constant volumetric flow rate of gas was converted into electrical power using the heating value given by the French gas distribution company (1 m^3 consumed being equal to 11.09 kWh).

Twenty-eight heating tests were thus performed according to the operating conditions specified in Table 2. For each combination of hob and pan, the test at high heat with the addition of oil was performed in triplicate and an average value of 5 °C was calculated as the standard error of pan-temperature measurements.

2.3. Domestic appliances selected for oven-baking tests

Three commercial electrical ovens were selected for this study, all operating under free or forced convection: oven #1 (AKZ 216, Whirlpool), oven #2 (F-4016, Scholtes) and a mini-oven (FC-400 MB, Brandt). The technical specifications of these appliances are shown in Table 3. These choices were based on three differentiation criteria: the size of baking chamber, the sophistication of the air-temperature control system (mode of control and position of sensor used for this control) and also the heating mode at the top and bottom of the oven (direct heating with electrical resistances within the baking chamber or indirect heating via electrical resistances separated from the baking chamber by a metal wall).

2.4. Test procedure to evaluate the heating performance of domestic baking ovens

In order to measure the effective air temperature (above the product), all ovens selected for the study were instrumented with an additional stainless steel-coated T-type thermocouple of 1 mm diameter (TC, Dardilly, France) fixed 12 cm above the centre of the cooking zone. This stainless steel coating of low thermal emissivity was able to limit errors of measurement in air temperature due to a thermal radiation effect.

Two air-temperature set points were selected for the heating tests (180 °C and 240 °C), each heating test being performed under forced or free convection. After selecting the air-temperature set point, each heating test started with a normalised pre-heating step. The end of pre-heating was defined as the time at which the air temperature displayed a periodic oscillation around a constant value close to the air-temperature set point. A 30-cm diameter aluminium baking dish containing the same products as those used for the pan-frying tests was then placed at the centre of the baking chamber and heated for 15 min. The effective air temperature was measured every 5 s using the same data logger. To compare the thermal efficiency of the different ovens tested, the instantaneous electrical power delivered by the baking oven during the heating experiments was recorded using the same Watt-meter as that used for pan-frying experiments.

To complete the thermal characterisation of baking ovens, additional measurements of the convective heat transfer coefficient h_c and the equivalent radiative temperature T_r were performed during heating. This radiative temperature was defined as the theoretical uniform oven wall temperature leading to the same level of thermal radiation flux as that received by the product during heating. It was then supposed to vary at each position in the baking chamber because oven wall temperature cannot be considered as uniform under real-life conditions [21]. To evaluate these two parameters, a copper block acting as a heat sink (width: 6 cm, length: 7 cm, height: 3 cm) was instrumented with two 4 cm^2 surface heat flux sensors (Captec, Lille, France) of low and high thermal emissivity (respectively 0.05 and 0.94). The sensors also provided measurements of their own temperature which was also that of the T_b block. That could be assumed to be

Table 3
Electric domestic ovens used for oven-baking tests.

Oven	Maximum power (W)	Baking chamber size (L)	Air-temperature control system	Mode of heating
Oven #1 (AKZ216, Whirlpool)	3500	50	Electronic control (power card) with temperature sensor in baking chamber	Direct (top) Indirect (bottom)
Oven #2 (F-4016, Scholtes)	3000	50	Electronic control (on/off thermostat) with temperature sensor in baking chamber	Direct (top) Indirect (bottom)
Mini-oven (FC-400 MB, Brandt)	1500	30	Mechanical control (bimetallic thermostat in a cavity adjacent to baking chamber)	Direct (top and bottom)

Table 4
Heating tests to evaluate the heating performance of domestic oven-baking appliances.

Type of oven[a]	Air-temperature set point	Convection
Oven #1 Oven #2 Mini-oven	180/240 °C	On/Off

[a] For each oven, tests under forced convection with an air-temperature set point of 240 °C were repeated three times.

uniform because of the high thermal conductivity of copper, the dimensions of the block (half thickness 1.5 cm) and the relatively low convective heat transfer coefficient values anticipated (Biot number always lower than 0.1). The instrumented heat sink was placed in the empty preheated oven. Heat flux and temperature measurements were then recorded every 5 s. To identify h_r and T_r from flux and temperature measurements, linear combinations of the following equations were used:

$$q_{le} = h_c(T_\infty - T_b) + \varepsilon_{le}\sigma\left(T_r^4 - T_b^4\right) \quad (1)$$

$$q_{he} = h_c(T_\infty - T_b) + \varepsilon_{he}\sigma\left(T_r^4 - T_b^4\right) \quad (2)$$

where T_∞ is the air temperature above the heat sink, q_{le} and q_{he} the heat flux densities (W/m^2) recorded by the low emissivity ε_{le} and high emissivity ε_{he} heat flux sensors, respectively, T_b the temperature of the block and σ the Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4). In order to prevent perturbations induced by opening the oven door and to ensure a sufficient temperature difference between the heat sink and air for calculation, the linear regression was only performed using data corresponding to reduced block temperatures U ranging from 0.6 to 0.3, with U calculated according to

$$U = (T_\infty - T_b)/(T_\infty - T_{b0}) \quad (3)$$

where T_{b0} is the block temperature at the beginning of the test.

Twelve heating tests were thus performed according to the operating conditions specified in Table 4. To assess the repeatability of measurements, heating tests under forced convection with an air-temperature set point of 240 °C were repeated three times for each oven.

Table 5
Pan heating rate during pre-heating at maximum power and pan-temperature gradient across the pan diameter at the end of pre-heating.

Hob	Pan	Pan pre-heating rate (°C/min) *(pan-temperature gradient after pre-heating[a])*	
		No oil	Oil
Electric	Thin	40 ± 1 *(100 °C)*	37 ± 2
	Thick	52 ± 1 *(25 °C)*	49 ± 3
Gas	Thin	97 ± 9 *(130 °C)*	79 ± 2
	Thick	58 ± 2 *(100 °C)*	54 ± 3
Halogen	Thin	67 ± 6 *(100 °C)*	62 ± 11
	Thick	64 ± 9 *(50 °C)*	59 ± 4
Induction	Thick	127 ± 6 *(70 °C)*	103 ± 3

[a] Only measured during the heating test with no oil.

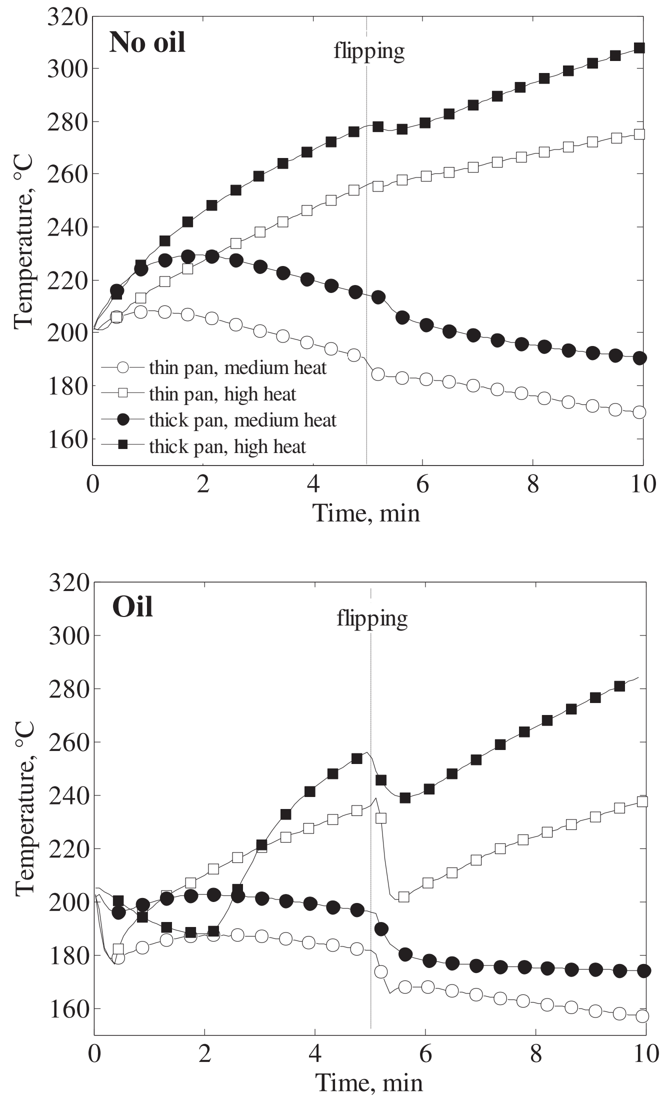


Fig. 1. Evolution of pan temperatures under a centrally-placed product during the pan-frying of three breaded poultry products on an electric hob without or with a thin layer of oil.

3. Results and discussion

3.1. Evaluation of the heating performance of domestic pan-frying appliances

The analysis of pan-temperature recordings during the pre-heating step at maximum power showed that whichever pan/hob combination was tested, the evolution of pan temperatures followed a quasi-linear profile between 20 °C and 200 °C. The pan pre-heating rate was calculated for each test and the values are presented in Table 5, which shows a very broad range from 37 °C/min to 127 °C/min. The most rapid pre-heating rates were observed with gas and induction hobs, which was logical as these two hobs delivered the highest power (the case of induction being particular since it enables the very efficient generation of energy in the pan by means of the Joule effect [22]). Pan type only had an effect on the pre-heating rate with electric and gas hobs. In the former case, the thin pan (being lighter and slightly warped) caused a poorer physical (and hence thermal) contact and hence a slower rate. This phenomenon was of no importance with gas the hob because the

Table 6
Variations in pan temperature during heating tests of domestic pan-frying appliances.

Hob	Pan	Final T (°C) (oil/no oil)	
		Medium heat	High heat
Electric	Thin	155/170	235/274
	Thick	172/188	279/307
Gas	Thin	179/198	280/301
	Thick	188/235	305/332
Halogen	Thin	181/196	286/315
	Thick	205/227	265/306
Induction	Thick	152/173	260/268

pan surface was heated directly by the gas flame. In this case, the thick pan heated at a slower rate. The presence of oil in the pan tended to lower pre-heating rates, particularly with fast-heating modes: induction and gas hobs. At the end of the pre-heating step, temperature gradients across the pan diameter surface could easily reach 100 °C or even 130 °C (thin pan on a gas hob). It could also be seen that the higher the heating rate, the higher was this temperature gradient at the end of pre-heating. Indeed, a lower heating rate and a thick pan favoured radial thermal conduction within the pan, thus leading to a more uniform pan surface temperature.

Once the food products had been placed in the pan at 200 °C, very marked differences in pan temperature were observed, depending on the test performed. For reasons of brevity and clarity, the patterns of pan-temperature variations during heating have only been shown for heating tests on the electric hob (Fig. 1), as tests performed using the other hobs displayed the same trends. A synthetic analysis of all heating tests is shown in Table 6 which gives the final pan temperature, in the knowledge that each test started with a pan temperature of 200 °C.

Whatever the experimental conditions tested, pan temperature always varied during the heating test. At a high heat, pan temperature always rose during the test, to reach a final value of between 235 °C and 330 °C (Fig. 1 and Table 6). When heating at medium heat, it always decreased and never exceeded the initial pan temperature of 200 °C (except using the gas and halogen hobs with the thick pan and no oil). It is also interesting to note that whatever the hob, the final temperature reached with the thick pan was nearly always higher than that of the thin pan under the same heating conditions. To explain this, and as presented in Table 2, it is important to note that the thick pan was heavier but its edge was made of thin (1 mm) stainless steel (low thermal conductivity), while the edge of the thin pan was made of thick (2.5 mm) aluminium (high thermal conductivity). Because the surface at the edge represented 40% of the total surface in both pans, the role of a cooling fin played by the edge of the pan was thus less efficient with the thick pan, leading to a higher and more uniform pan temperature.

The addition of oil between the pan and the product tended to lower pan temperature (Fig. 1 and Table 6), thus confirming the fact that the oil layer significantly enhanced the quality of heat transfer between the pan and product. Indeed, as oil has a higher thermal conductivity, it replaced air as interstitial fluid between the product and the pan. This also explains why, when the products were flipped after 5 min, the drop in pan temperature was more pronounced with oil than without oil (Fig. 1).

Continuous recordings of instantaneous electrical power measurements are not presented here. Their analysis showed that the power delivered during heating was always constant with the electric, induction and gas hobs. For electric and induction hobs, a test at medium heat (knob position: 3 out of 6) corresponded to a delivered power of 300/400 W whereas for the gas hob, a test under the same conditions corresponded to a power of 1000 W. At high heat, these three hob types delivered a power of around 2000 W.

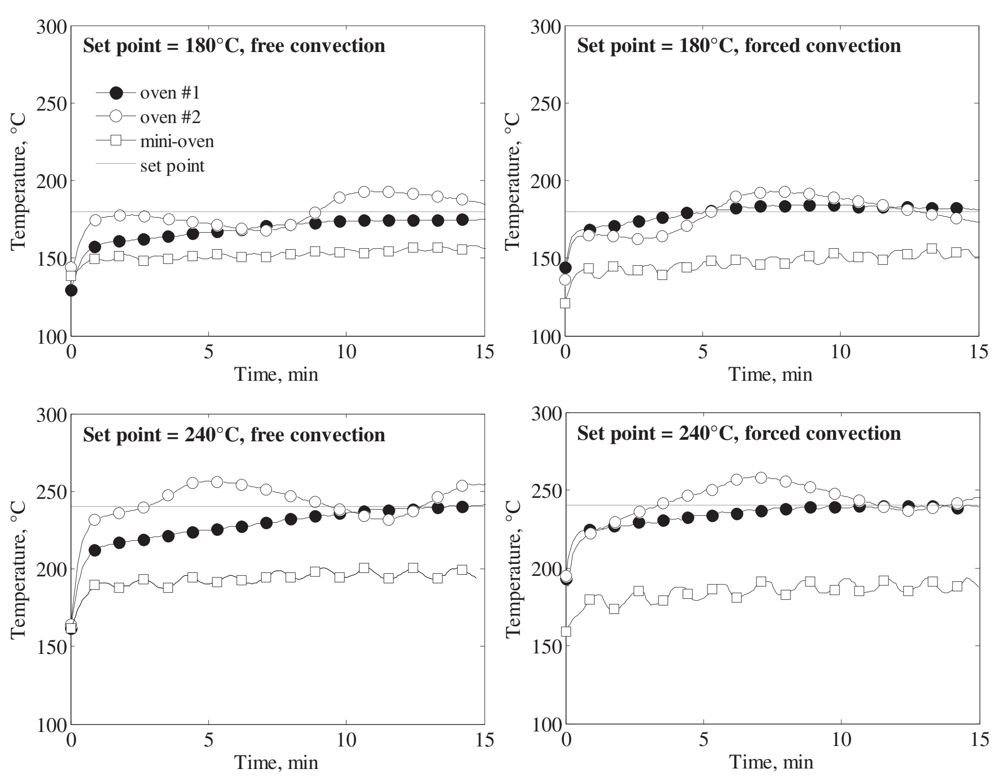


Fig. 2. Evolution of air temperatures during the oven-baking of three breaded poultry products under free or forced convection at a set point of 180 °C or 240 °C.

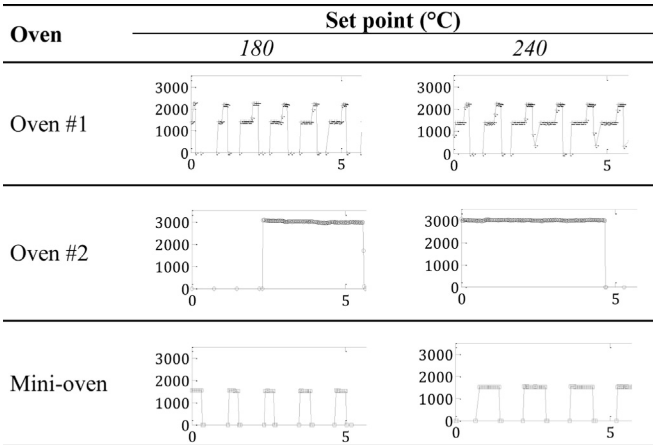


Fig. 3. Current power profile under forced convection during the first minutes of heating products in an oven. Time (min) on the *x*-axis and current power (W) on the *y*-axis.

Table 7
Values for the convective heat transfer coefficient h_c, equivalent radiative temperature T_r and radiative heat transfer coefficient h_r measured during oven-baking tests.

Oven	Convection	Set point (°C)	h_c (W/m^2 K)[a]	T_r (°C)[a]	h_r (W/m^2 K)[a,b]
Oven #1	Free	180	6.8	174	15.9
		240	8.0	229	19.4
	Forced	180	14.7	186	16.6
		240	15.0 ± 0.2	241 ± 3	20.3 ± 0.2
Oven #2	Free	180	6.6	166	15.4
		240	7.9	223	19.0
	Forced	180	16.3	168	15.4
		240	15.7 ± 0.7	235 ± 5	19.8 ± 0.4
Mini-oven	Free	180	7.2	179	16.2
		240	8.7	224	19.1
	Forced	180	9.1	175	15.9
		240	11.2 ± 0.2	218 ± 2	18.7 ± 0.1

[a] Standard deviations given in this table for tests at 240 °C under forced convection are the result of three independent measurements.
[b] Values calculated with a copper block (heat sink) temperature of 120 °C and high emissivity heat flux sensor (0.94).

For the halogen hob, the power delivered was not constant during a heating test. It ranged from 0 W to 1750 W according to a rectangular function (typical for duty cycle control), the time spent at zero power depending on the knob position.

3.2. Evaluation of the heating performance of oven-baking appliances

For ovens #1 and #2, whatever the convection mode and the air-temperature set point, a pre-heating time of around 10–15 min was required to reach the air-temperature set point. Once this had been reached, the air temperature in these two ovens continued rising for about 5 min to a maximum value that was 35 °C higher than the set point. Finally, the time necessary to reach a stable air temperature close to the set point was more than 30 min, which is twice longer than the 15 min pre-heating time often specified by oven manufacturers. In the mini-oven, the pre-heating time was significantly shorter (up to 10 min at 240 °C) although power consumption was lower (Table 3), probably because of the small size of the baking chamber. Unlike the other two ovens, the overshoot of the air-temperature set point was limited (around 10 °C), and the stabilised air temperature was 10–30 °C lower than the set point.

At the end of the pre-heating step, an aluminium baking dish containing three breaded products (thermal load) was placed in the baking oven and product heating then started.

Variations in air temperature during product heating are presented in Fig. 2 for all the conditions investigated. These temperature measurements started just after oven door opening, when the products were placed in the baking chamber. This explains why the initial air temperature was always below the air-temperature set point (ca. 130 °C at 180 °C and ca. 170 °C at 240 °C, whatever the oven considered).

Very different air-temperature variation patterns are thus observed for the three ovens. Whatever the convection mode or air-temperature set point, the air-temperature control systems in ovens #1 and #2 enabled the air-temperature set point to be reached again after ca. 5–10 min. This took 5 min with oven #2 but an overshoot of 10–30 °C above the set point was noted under forced convection conditions, together with oscillations of large amplitude and low frequency around the set point value. With oven #1, 10 min were necessary to reach the air-temperature set point again, but this time there was no overshoot. These differences in behaviour were related to the air-temperature control mode; Fig. 3 shows the recordings of the instantaneous electrical power consumed during the five first minutes of heating. With oven #1, air temperature was controlled by a power card, the electrical power delivered varying between three values (0, 1400 and 2200 W) according to a rectangular function which thus enabled the precise control of air temperature and limited any set point overshoot. The air temperature in oven #2 was controlled by a basic electronic on/off thermostat and displayed alternating long periods (of several minutes) at 0 (thermostat off) or 3000 W (thermostat on). This control mode explains the large amplitude and low frequency oscillations recorded with this type of oven.

Concerning the mini-oven, the average air temperature during product heating was surprisingly very low when compared to the air-temperature set point (ca. −30 °C at 180 °C and −50 °C at 240 °C). This unfavourable ratio between the mass of heated product and baking chamber size explains this observation. Moreover, and as discussed in Table 3, the bimetallic mechanical thermostat of the mini-oven measured the air temperature in a small cavity close to the baking chamber. For this reason, the perturbations of air temperature due to door opening and product heating did not change the frequency of heating/cooling of the two blades in the bimetallic mechanical thermostat. Electric energy to the heating elements was supplied at the same frequency as at the end of pre-heating and varied between 0 W and 1500 W, as shown in Fig. 3.

As for the convection and radiation levels in domestic baking ovens, the values for convective heat transfer coefficient h_c and equivalent radiative temperature T_r that were measured and calculated for each heating test are shown in Table 7. In all three ovens, the convective heat transfer coefficients measured under free convection were almost the same (6–8 W/m^2 K). By contrast, in a forced convection mode, there was a significant difference between ovens #1 and #2 (ca. 15 W/m^2 K) and the mini-oven (ca. 10 W/m^2 K). However, unlike the other ovens, the mini-oven fan did not always operate during heating. Its motor is directly coupled to the bimetallic mechanical thermostat. The h_c value in the mini-oven thus fluctuated between 7 W/m^2 K (fan off) and 15 W/m^2 K (fan on). Our experimental results thus showed that air temperature did not have a significant effect on the value of h_c whatever the selected oven, and these values were close to those reported in the bibliographic study referred to in the introduction. It is interesting to note that the measured h_c values in the forced convection mode were relatively low compared to the values measured in an industrial tunnel oven [7]. This was certainly due to the different constraints associated with the design of domestic oven (shape and

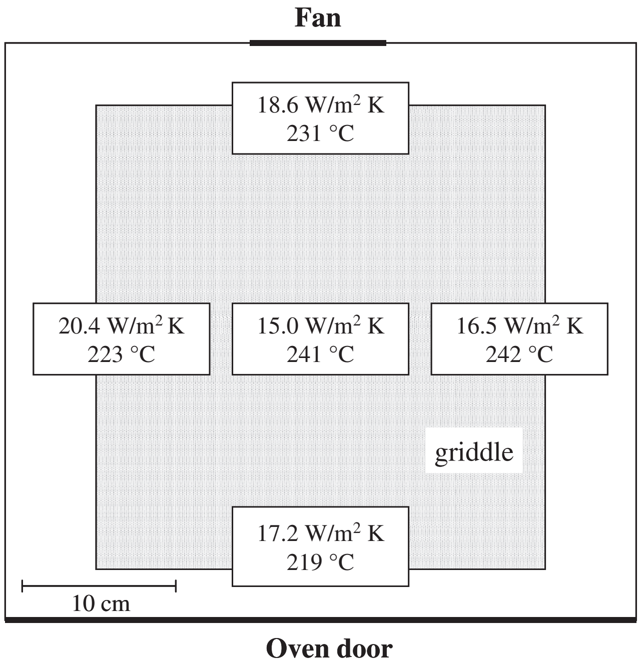


Fig. 4. Heat transfer coefficient (W/m^2 K) and equivalent radiative temperature (°C) measured at different locations within the baking chamber during heating tests with oven #1 operating at 240 °C under forced convection.

size of baking chamber, cost of materials). However, operation under a forced convection mode enabled the h_c values to roughly double, which would then significantly reduce cooking time, particularly in the case of relatively small products (where internal resistance to heat transfer is low). Moreover and even if not documented in this work, it must be kept in mind that increasing the level of convective heat transfer leads to an increase of product drying rate [23] which can result in product surface desiccation and overheating (not always desirable for some types of food products).

The results regarding the equivalent radiative temperature measured were more difficult to interpret because the unstable air temperature within the baking chamber (Fig. 2) probably caused fluctuating oven wall temperatures, even though these temperatures are supposed to be more stable than air temperatures. In oven #1, the equivalent radiative temperature was close to the air-temperature set point. In oven #2 and the mini-oven, this radiative temperature was 10–20 °C lower than the air-temperature set point. For the mini-oven, the radiative temperature was also higher than the actual air temperature (which was itself up to 50 °C lower than the air-temperature set point as shown in Fig. 2) probably due to the fact that the door opening for this mini-oven had a greater impact on the actual air temperature than on the wall temperature. Another explanation could be the fact that, in the mini-oven, the heat losses were lower than for the other ovens (lower level of convection heat transfer in forced convection as indicated in Table 7).

In order to compare the respective contributions of convective and radiative heat to the total heat flux, a radiative heat transfer coefficient h_r (in W/m^2 K) was calculated. It had the same dimension of convective heat transfer coefficient and was calculated according to [23]

$$h_r = \varepsilon_{\mathrm{he}}\sigma\left(T_r^2 - T_b^2\right)(T_r - T_b) \tag{4}$$

where T_b is the copper block (heat sink) temperature recorded during the test and $\varepsilon_{\mathrm{he}}$ the emissivity of the high emissivity heat flux sensor. The value of this coefficient depended on the copper block temperature and its value was calculated (see Table 7) for a block temperature equal to 120 °C. By dividing the convection heat transfer coefficient by the sum of the convection and radiative heat transfer coefficients, it was therefore possible to evaluate an order of magnitude of the ratio of convective over total heat flux received by the heat sink during heating. Under free convection, this ratio was ca. 30%, while under forced convection it was between 30% and 60%, which was comparable to the values reported by Baik et al. [7] and Sparrow and Abraham [3].

Finally, in order to highlight a possible heterogeneity of h_c and T_r depending on position in the oven, five positions were selected for heat flux measurements (centre, left, right, front, back, as shown in Fig. 4) for oven #1 operating under forced convection at 240 °C. A significant spatial heterogeneity of h_c and T_r was noted, and they differed by up to 6 W/m^2 K for the heat transfer coefficient and 20 °C for the equivalent radiative temperature.

4. Conclusion

This study describes a series of test procedures to evaluate the heating performances of domestic appliances in the case of pan-frying (continuous measurement of pan temperature) and oven-baking (heat flux measurements). To evaluate the performance of oven-baking appliances, characterisation in terms of radiative and convective heat flux appeared to be more informative than classic air-temperature measurements. As for pan-frying appliances, although pan-temperature measurements provided new insights into our understanding of the heat transfer phenomena which occur during heating, a measurement of the heat flux exchanged between product and pan would probably be a useful improvement to the test procedure proposed here.

In order to assess the efficiency of these test procedures, they were applied to a series of domestic appliances (different combinations of pans and hobs, different types of ovens). For heat treatments of comparable intensity, the results show considerable variability in effective operating conditions (as experienced directly by the product during heating) depending on both the types of materials used and the behaviour of the consumer when cooking at home. The operating conditions stipulated by food product manufacturers may lead to a great variability in heating conditions. Depending on the intensity of heat treatment (heating at medium or high heat), during domestic pan-frying, pan temperature declines continuously (medium heat) or rises (high heat) to values that may be higher than 330 °C. Likewise, the oven-baking tests showed that the effective air temperature could be very different for heat treatments at the same air-temperature set point. These differences were due to the type of oven used, the mode of convection selected and the level of convection reached (related to the power of the fan installed in the baking chamber) as well as the level of sophistication of air-temperature control systems. In these domestic appliances, the convective heat flux ratio was evaluated at ca. 30%, and between 30% and 60%, respectively, of the total heat flux under free convection and forced convection. Our study thus enabled the identification of some shortcomings in the domestic appliances tested. For pan-frying appliances, the role of cooling fin played by the edge of the pan was identified. In order to increase the energy efficiency of the operation and to lower temperature gradients over the heating surface, a pan edge of thin stainless steel (low thermal conductivity) would appear to be an appropriate choice. To prevent the overheating of food products, the addition of a temperature indicator (whose colour is modified at temperatures over 300 °C) seems to be an interesting option. Concerning domestic ovens, air-temperature control systems could be improved in some appliances (an increase in heating power would enable more rapid stabilisation of the air temperature after door opening and the placing of food products in the baking chamber). Moreover, in order to reduce the thermal heterogeneity detected in ovens (Fig. 4), efforts should be made to improve the air flow pattern in the baking chamber and reduce heat loss to the surroundings.

Apart from these calculations, these findings may help food product manufacturers and researchers to take account of the broad range of operating conditions that may be experienced by processed food products during domestic cooking. The results could also be used for modelling purposes if the variability inherent in operating conditions (difficult to ignore in domestic applications) were to be taken into account in the modelling procedure. Recent studies on temperature changes during thermal sterilisation or food freezing [24] or modifications to the properties of foods (including microbial load) throughout the cold chain [25] have confirmed growing interest in modelling and prediction in uncertain environments that takes account of variable operating conditions during processing. As for heat and mass transfer modelling in products during domestic heating, there is clearly a lack of information on the levels and variability of heating conditions. Our findings have thus contributed to making up for this deficiency.

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