Journal of Food Engineering 204 (2017) 8–17

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Energy efficiency and carbon footprint of home pasta cooking appliances

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ARTICLE INFO

Article history:
Received 11 August 2016
Received in revised form
7 January 2017
Accepted 12 January 2017
Available online 16 January 2017

Keywords:
Carbon footprint
Domestic gas and electric hobs
Pasta cooking energy efficiency
Energy consumption
Pasta cooking operating costs

ABSTRACT

The energy efficiency (η_C), carbon footprint (CF) and operating costs (C_C) of home dried pasta cooking were assessed. In particular, η_C for the electric hot-plate (46 ± 3%), induction (33 ± 5%), or LPG (30 ± 4%) hob was found to be definitively smaller than the minimum energy efficiency performance requirements for EU domestic hobs. Pans of different size, but with the same high thermal diffusivity, had a negligible effect on η_C at the probability level of 0.05. By covering the pan with its lid and setting the power rate of each cooking appliance initially to the maximum level to make the cooking water boil faster, and then to the minimum one to keep almost constant the cooking water temperature and allow starch granule gelatinization, GHG emissions reduced by 81, 73, or 86% with respect to those released with the LPG, electric, or induction hob adjusted at the maximum power setting, respectively. Such a cooking practice applied to the induction hob allowed CF and C_C to be minimized to 0.67 kg CO_{2e} and €0.47 per kg of pasta cooked. The resulting energy saving amounted to 31 or 18% of the energy consumed under the same procedure by the LPG or electric cooker, respectively. Such a cooking system in conjunction with the aforementioned practice might represent an eco-friendly solution to limit the environmental impact of dried pasta consumption.

1. Introduction

Food cooking is not only one of the most basic transformation processes of food industries, but additionally is a daily human activity. The energy consumed to cook a plate of pasta or brew a pot of coffee may represent the prevailing part of the energy consumed during the whole product life cycle (Carlsson-Kanyama and Boström-Carlsson, 2001; Xu et al., 2015), this making their use phase the most significant hotspot in terms of greenhouse gas (GHG) emissions.

As concerning the use phase of durum wheat semolina dried pasta, its cooking requires about 10 L of water per each kg (Barilla, 2009) with GHG emissions as high as 760 or 1600 g of carbon dioxide equivalent (CO_{2e}) depending on the use of a gas or electric hob (Barilla, 2009), whereas the overall GHGs emitted to produce one kg of durum wheat semolina dried pasta, packed in paperboard box in Italy, amounted to about 947 g CO_{2e} kg^{-1} (Barilla, 2009), this including the GHG emissions released during durum wheat cultivation (557 g CO_{2e} kg^{-1}). Thus, pasta cooking would have a significantly greater contribution than the field phase, representing as high as the 44.5 or 62.8% of the cradle-to grave carbon footprint of dried pasta, respectively (Barilla, 2009). Despite quite similar data were reported by other Environmental Product Declarations (EDP®) by Barilla (2013), De Cecco (2011), Lantmännen (2011), and Misko (2013), quite lower carbon footprint scores of about 105 or 480 g CO_{2e} kg^{-1} were reported by Notarnicola and Nicoletti (2001) or Cerere (2014), respectively. Thus, the GHGs emitted during pasta cooking need to be more accurately assessed. In fact, by referring to the overall Italian consumption of dry pasta (1.5 million Mg/yr), just a 10% reduction in the GHGs emitted during pasta cooking only would results in savings of about 114 or 240 Gg of CO_{2e}/yr by far greater than the GHG emissions (8 Gg CO_{2e}/yr) associated to the disposal of fruit and vegetable wastes in the selling points, as estimated by the Italian Ministry of Agriculture.

Food cooking methods have been established by several factors, such as cooking system prices, consumer nutritional needs and preferences in terms of cooked food taste, smell and texture, as well as its culture and ethics. Consumer behavior may even double (DeMerchant, 1997) or triple (Oliveira et al., 2012) the food cooking energy consumption, especially if the most basic energy saving

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http://dx.doi.org/10.1016/j.jfoodeng.2017.01.012
0260-8774/

practices are ignored. The use of a lid on a pot filled with water at the boiling point might cut energy requirements by one-eighth by limiting water evaporation (Newborough and Probert, 1987). Also, the cooking efficiency tends to increase with the volume of water in the pan or pan size (Hager and Morawicki, 2013; Newborough and Probert, 1987; Oberascher et al., 2011). Finally, the so-called passive cooking (i.e., the cooking of a product to a certain extent so as to complete its cooking by resorting to the residual heat only) lowers energy requirements, even if this procedure generally lengthens the product cooking time (Amann et al., 2007), and sometimes the quality of cooked foods.

The promotion of more energy-efficient stoves and cookware sets might usefully contribute to mitigate GHG emissions (Bhattacharya and Salam, 2002; Karunanithy and Shafer, 2016). Also, the energy carrier affects the amount of GHGs released. In fact, solid fuels (i.e., firewood, charcoal, coal) give rise to by far greater total GHG emissions per unit energy supplied than liquid (e.g., kerosene, heating oil) or gaseous (liquefied petroleum gas, LPG, natural gas, biogas) fuels (Hager and Morawicki, 2013).

In the USA and Europe, the great majority of cooking appliances are of the electric type, followed by natural gas appliances (Hager and Morawicki, 2013; Karunanithy and Shafer, 2016). On the contrary, in Italy the most common kitchen stove consists of four hobs, mainly powered by natural gas or LPG (Anon., 2016a). The electric or induction hobs are currently less used mainly because their simultaneous run with other home electric appliances results in a greater electricity demand, this shifting the configuration of the power purchasing contract from a normal 1.5- to 3.0-, 4.5- or 6.0-kW power supply.

Since the GHG emissions associated to the cooking phase of durum wheat semolina dried pasta appear to be not only very high, but also largely variable, the main aim of this work was to adapt the basic *water boiling test* (Global Alliance for Clean Cookstoves, 2014) to measure experimentally the energy requirements to cook dried pasta using three typical home hobs and three pans of different diameters so as to estimate the corresponding GHG emissions and operating costs, as well as to identify an optimal cooking procedure to minimize the carbon footprint of dried pasta cooking.

2. Materials and methods

2.1. Raw materials

A commercial slightly ribbed short-cut extruded pasta, labeled “Elicoidali” no. 47 and manufactured by Coop Italy (Casalecchio di Reno, BO, Italy) in 1 kg-packs, was used, as specified in the electronic supplement (Fig. S1a). It was made of durum wheat semolina, had the composition reported in parentheses (moisture: <12.5% w/w; raw protein: 12.5% w/w; total carbohydrates: 70.9% w/w; fat: 1.5% w/w; total fiber: 3% w/w), a specific energy content of 14.97 MJ kg^{-1}, and a set time of 11 min. The AACC Method 66–50.01 (AACC International, 1999) was used to assess the optimal pasta cooking time, this corresponding to the time at which the central white annular portion (i.e., non-gelatinized starch) of any ribbed tube disappeared. During the pasta cooking process, some pieces of pasta were collected at different cooking times and immediately halved to detect the presence of the central white annular portion. When such a circular segment was just barely visible, the cooking process was regarded as completed, and the resulting pasta was defined as cooked “al dente”, that is tender, but still firm to the bite.

2.2. Equipment and experimental procedure

Pasta cooking was carried out using three pans of different diameter and capacity (model Oumbärlig, Inter IKEA Systems B.V. 1999–2014, Sweden), made of magnetic stainless steel with a thick base consisting of one layer of aluminum between two layers of magnetic stainless steel. Their main characteristics are given in Table 1. Each lid was drilled to lodge a thermocouple so as to measure the cooking water temperature (T_{WM}) along the pan axis at mid-height of water level throughout each cooking test. Any test was started by setting a pan, pre-thermo-stated at (20 ± 1) °C, over the cooking system of choice. The latter was placed on a digital scale of the series PCE-BSH 10000 (CE Italy srl, Capannori, LU, Italy) with a load range of 0.6 g–10 kg, and a reading accuracy of 0.2 g, this resulting in a percentage error of 0.2% on a 100-g mass reading.

Firstly, the pan was filled with (1.50 ± 0.01) kg of de-ionized water at (20 ± 1) °C and closed with its lid. As the heating process was started, the cooking time and water temperature were automatically recorded. At the water temperature of about 98.5 °C, the lid was removed, and (14.0 ± 0.1) g of kitchen salt, and (125.0 ± 0.5) g of dried pasta, both at (20 ± 1) °C, were added to the cooking water.

Throughout all tests, the pasta cooking phase was carried out without a lid till the optimal cooking time, except for the final tests.

In this work, the following stoves were used:

1) A 2.2-kW camping stove (Campingaz Camp Bistrò, Camping Gaz Italia srl, Lonato del Garda, BS, Italy), fed with a 220-g LPG cylinder.
2) Two 1.5-kW electric 180-mm (Severin KP 1091, Elektrogeräte GmbH, Sundern, Germany) and 0.625-kW electric 145-mm (Heidolph MR 3001, Schwabach, Germany) hot-plate stoves, both equipped with a maximum plate temperature control. They were labeled electric hob A and B, respectively.
3) A 2-kW 190-mm induction-plate stove (Melchioni INDU, Melchioni Spa, Milan, Italy), equipped with a plate temperature control in the range of 60–240 °C.

During each pasta cooking test using either the electric or induction hob, the electric energy consumption, expressed in kWh, was monitored via a multifunction digital multimeter R571 (Colemeter, Sheung Wan, Hong Kong). By comparing its measurements when using the electric hob B or induction hob to those obtained with a more accurate power meter type RCE MP600 (RCE Srl, Salerno, Italy), characterized by an accuracy of ±1.0% when measuring power in the range of 0.4–3999 W, it was possible to detect an average percentage error and standard deviation of 7 and 2%, respectively.

Finally, the mass of water evaporated during each pasta cooking trial was determined as the difference between the initial and final masses of the pan filled with water, kitchen salt and dried pasta using the same technical balance mentioned above.

Temperatures were acquired with a custom made data logger based on an Arduino Nano 3.0 (ATmega328) board, equipped with the following hardware:

- Two temperature sensors type DS18B20 (Maxim Integrated Products, San Jose, California, USA) were used to acquire the instantaneous temperatures of cooking water and ambient air. Both sensors had a measured resolution of 0.1 ± 0.7 °C in the range of 17–100 °C, as detected using a digital K-type thermocouple probe connected to a professional temperature data logger Testo type 175 T3 (Testo SpA, Settimo Milanese, MI, Italy) having an accuracy of ±0.5 or ±0.7 °C in the range of −50 to +70 °C or 70–1000 °C, respectively.
- A piezo-buzzer to signal when the water temperature had reached 98.5 °C.
- An infrared thermometer designed for non-contact temperature sensing (MELEXIS MLX90614ESF-BAA-000-TU-ND, Melexis NV,

Table 1
Main geometry and characteristics of the cooking pans used in this work.

Cooking pan type	 A	 B	 C	Unit
Article no	502.864.20	902.864.23	002.864.13	
Mid-height diameter	200	230	300	[mm]
Height	130	150	190	[mm]
Bottom diameter (d_{PB})	145	180	220	[mm]
Pan mass (m_P)	783.5	1026	1486	[g]
Pan capacity	3	5	10	[L]
Lid mass	158.2	203	226	[g]

Sint Krispijnstraat z/n, B-8900 Ieper, Belgium) with a standard accuracy of 0.5 °C to determine the pan wall and hot-plate temperatures. Owing to the low emissivity of the polished steel pan wall, a small section of the pan wall surface facing the IR sensor was covered with an electrical, insulating black tape strip (having an emissivity of 0.97: http://www.infrared-thermography.com/material-1.htm). The IR thermometer was shielded using a stainless steel funnel-like truncated conical portion to prevent heat damage, and then mounted on a rigid support at about 1-cm distance from the pan wall and three different pan heights. Its accuracy was checked using the aforementioned data logger Testo type 175. More specifically, the K-type thermocouple probe was submerged in the water filling the pan and located as near as possible to the internal side of the black-taped pan-wall section under measurement. The water temperature was step-wisely increased to allow the pan temperature to reach a practically stable value. The average difference between the temperatures measured using such probes was −0.2 ± 0.9 °C in the range of 17–100 °C.
- a 4 × 20 characters LCD Display to show on-screen real-time information.

All data were acquired by the Arduino program, transmitted to a personal computer via a USB connection, and then transferred to an Excel spreadsheet using a freeware software Parallax Software Data Acquisition tool (PLX-DAQ, https://www.parallax.com/downloads/plx-daq).

A photo of one of the cooking systems used in this work is reported in the electronic supplement (Fig. S2). It shows the induction hob with lidded pan A positioned over the digital scale, the multimeter, and Arduino board connected to a PC via a USB cable to monitor the process parameters.

To minimize the pasta cooking energy consumption, three final tests were carried out using the pan A and each of the aforementioned hobs. Firstly, the pan was closed with the lid to limit water evaporation; then, the control knob of each hob was regulated to the maximum setting to bring as quickly as possible the cooking water to the boiling point. Secondly, once the kitchen salt and dried pasta were added to the boiling water and the latter restarted to boil, the lid was newly closed to minimize water vapor loss, and the control knob of each stove was adjusted to the minimum setting to keep the cooking temperature around 98 °C.

2.3. Energy efficiency evaluation method

Fig. 1 shows the block diagram used to represent the entire input and output energy flow in each cooking system. In particular, it visualizes the energy effectively consumed (E_{cons}) in the cooking conditions selected, the energy theoretically consumed to cook pasta (E_{th}), as well as all the energy losses to the outside environment, such as the energy dissipated by radiation (E_{rad}), convection and conduction from the pan and heating source (E_{cc}), and heat of water evaporation (E_{vap}). Instead of modeling all energy losses, the only percentage energy efficiency (η_C) of each pasta cooking system examined was estimated as the ratio between the instantaneous values of E_{th} and E_{cons}:

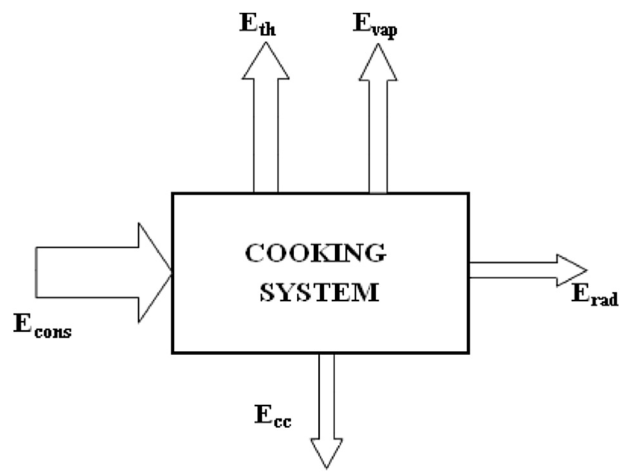

Fig. 1. Block diagram of the cooking system examined in this work. All symbols were listed in the Nomenclature section.

$$\eta_C = E_{th}(t)/E_{cons}(t) \times 100 \quad (1)$$

with

$$E_{th}(t) = q_{sW}(t) + q_{sP}(t) + q_{ss}(t) + q_{sPA}(t) + q_{gel} \quad (2)$$

$$q_{sW}(t) = c_{pW}\, m_{W0}\, [T_{WM}(t) - T_{W0}] \quad (3)$$

$$q_{sP}(t) = c_{pP}\, m_P\, [T_{WM}(t) - T_{P0}] \quad (4)$$

$$q_{ss}(t) = c_{ps}\, m_s\, [T_{WM}(t) - T_{s0}] \quad (5)$$

$$q_{sPA}(t) = c_{pPA}\, m_{PA}\, [T_{WM}(t) - T_{PA0}] \quad (6)$$

$$q_{gel} = m_{PA} x_S \Delta H_{gel} \quad (7)$$

where $q_{sW}(t)$, $q_{sP}(t)$, $q_{ss}(t)$, and $q_{sPA}(t)$ are the instantaneous energies required to raise the cooking water, pan, kitchen salt and dried pasta, respectively, from the initial temperature (T_{i0}) to the instantaneous water temperature at mid-height [$T_{WM}(t)$], this ranging from T_{W0} to the boiling point; whereas q_{gel} is the heat of wheat starch gelatinization, the enthalpy of starch gelatinization (ΔH_{gel}) being extracted from Ratnayake et al. (2009). All other symbols are listed in the *Nomenclature* section, while all the parameters used to calculate the cooking energy efficiency for the cooking systems under study were listed in Table 2.

To estimate E_{th}, it was assumed that the temperature of the pan at its mid-height practically coincided with that of the cooking water (T_{WM}) throughout the cooking process independently of the heat source (i.e., LPG flame, electric hob or induction plate) used. This was corroborated by monitoring the time course of the temperatures of the pan wall at 0.5 cm above its bottom (T_{PWB}), mid-height (T_{PWM}), and 0.5-cm below its top (T_{PWT}), and those of cooking water along the pan axis at 0.5 cm above the pan bottom (T_{WB}) and below the water top level (T_{WT}), and at the pan mid-height (T_{WM}). These data are presented in the electronic supplement (Fig. S3).

When using the gas burner, the instantaneous energy consumed $E_{cons}(t)$ was assumed as coinciding with the heat released by the complete combustion of LPG with oxygen under standard conditions:

$$E_{cons}(t) = m_{LPG}(t)\ LHV \tag{8}$$

where $m_{LPG}(t)$ is the instantaneous mass of LPG fuel consumed, as indirectly determined by measuring the instantaneous mass of the LPG cylinder using the technical scale mentioned above, while LHV is the lower heating value for LPG fuel. In accordance with ADEME (2007), LHV was assumed as 46 kJ g^{-1} (Table 2). Any test was performed using fresh LPG cylinders to prevent the effluent gas flow from varying with the remaining LPG level in the cylinder itself. To this end, several blank tests were carried by setting the gas control knob at the maximum, 1/3 or minimum level so as to measure the mass of the LPG cylinder as a function of time, and thus estimate $m_{LPG}(t)$ and $E_{cons}(t)$. During any pasta cooking test, the mass of LPG fuel consumed was assessed as the difference between the initial and final masses of the LPG cylinder used, and $E_{cons}(t)$ predicted as follows:

$$E_{comb}(t) = \left(\frac{m_{LPG} LHV_{LPG}}{t_C}\right) t \tag{9}$$

where t_C is the overall cooking time.

When using the electric hot-plate hobs, $E_{cons}(t)$ was monitored using the aforementioned multimeter and assumed to vary linearly with time (t) in accordance with Joule's first law:

$$E_{cons}(t) = R\, I^2\, t \tag{10}$$

where R is the electric resistance of the plate, and I the electric current. Such a linear relationship was also assumed to reconstruct the time course of E_{cons} when using the induction hob.

2.4. Statistical analysis of data

All pasta cooking tests were replicated from 1 to 3 times to assess the average values and standard deviations of a series of dependent variables, such as the masses of LPG consumed and water evaporated; temperatures of the cooking water and pan wall at different positions, and hot-plate; and electric energy consumption. Data were analyzed by Tukey test at a significance level of 0.05.

3. Results and discussion

3.1. Assessment of the optimal pasta cooking time

During pasta cooking some pieces of pasta were collected and promptly halved to detect the presence of the central white annular portion. Its progressive disappearance after a cooking time of 8, 10, 11, 12 and min is shown in the electronic supplement (Fig. S1c–f). At the nominal set time of 11 min, the white central segment was only just noticeable (Fig. S1e), and the pasta was retained as cooked “al dente”. After a cooking time of 12 min, the pasta sample became overcooked (Fig. S1f). Thereafter, the pasta cooking phase in all the following tests was set to 11 min.

3.2. LPG hob

A series of water heating tests, performed by setting the gas control knob (CK) to the maximum, (1/3), and minimum levels, allowed the heat generated by LPG combustion (E_{comb}) to be linearly related to time (t), as shown by the data presented in the electronic supplement (Fig. S4). By using the least squares method, it was possible to fit E_{cons}-vs.t via the least squares regressions listed in Table 3 – see Eqs. (11)–(13). In this way, it was possible to resort to Eq. (9) to estimate the overall energy consumed during the pasta cooking tests.

Fig. 2 shows the time course of the cooking water temperature at mid-height (T_{WM}), energy theoretically (E_{th}) and effectively (E_{cons}) consumed, and cooking energy efficiency (η_C) when using pan A and adjusting the gas control knob to the maximum or (1/3) setting throughout all testing. These operations resulted in a specific power supply of 15 ± 1 or 11 ± 1 kW per kg of dried pasta, respectively. More specifically, since the cooking water was generally heated from 20 to about 100 °C, E_{th} amounted to about 577 kJ. This resulted in quite a low cooking energy efficiency of (24 ± 3) % or (32 ± 1) %, respectively (Table 4). The lower efficiency of the cooking system operating at the maximum setting undoubtedly derived from the fact that the energy supplied was by far greater than that needed for the pasta cooking process. Throughout the water heating phase, the energy efficiency ($\eta_{C,H}$) was plausibly high in the range of 54–65%. Independently of the power supplied, there was no statistically significant difference in both the overall mass of water evaporated and t_C at the probability level of 0.05 (Table 4). This founding also corroborated our assumption of performing the cooking water heating phase with the pan unlidded.

Table 2
Parameters used to estimate the energy efficiency, carbon footprint and operating costs of dried pasta cooking.

Parameters	Value	Unit
c_{pW}	4.186	kJ kg^{-1} K^{-1}
c_{pP}	0.837	kJ kg^{-1} K^{-1}
c_{pPA}	1.840	kJ kg^{-1} K^{-1}
c_{ps}	1.160	kJ kg^{-1} K^{-1}
λ_{ev}	2.260	kJ g^{-1}
ΔH_{gel}	11.9	J g^{-1}
m_W	~1.50	kg
m_{PA}	125	g
m_s	14	g
x_S	0.71	g g^{-1}
FE_{EE}	323.6	g CO_{2e} kWh^{-1}
c_{EE}	0.245	€ kWh^{-1}
LHV	46	kJ g^{-1}
FE_{LPG}	3.498	kg CO_{2e} kg^{-1}
	76.04	g CO_{2e} MJ^{-1}
c_{LPG}	0.06	€ MJ^{-1}

Table 3
Main least squares regressions fitting the energy consumed (E_{cons}, in kJ) against time (t, in s) when using different cooktops with their control knob (CK) set at different levels during water heating (blank) or pasta cooking tests together with their corresponding coefficient of determination (r^2).

Cooktop Type	Test Type	CK setting	Regression [kJ]	(Eq.)	r^2 [−]
LPG Hob	Water Heating	max	$E_{cons} = (1.972 \pm 0.005)\ t$	(11)	0.998
		1/3	$E_{cons} = (1.467 \pm 0.001)\ t$	(12)	0.999
		min	$E_{cons} = (0.522 \pm 0.001)\ t$	(13)	0.998
		max-min	$E_{cons} = (2.030 \pm 0.002)\ t$ for $t \le 511$ s	(14)	0.999
			$E_{cons} = (878 \pm 1) + (0.313 \pm 0.001)\ t$ for $t \le 511$ s	(15)	0.998
Electric Hob A	Pasta Cooking	max	$E_{cons} = (1.47 \pm 0.03)\ t$ for $t \le 241$ s	(16)	0.999
			$E_{cons} = (224 \pm 9) + (0.54 \pm 0.01)\ t$ for $t \le 241$ s	(17)	0.999
Electric Hob B	Pasta Cooking	max	$E_{cons} = (0.607 \pm 0.001)\ t$	(18)	0.999
Induction Hob	Pasta Cooking	max	$E_{cons} = (1.919 \pm 0.007)\ t$	(19)	0.999
		medium	$E_{cons} = (1.628 \pm 0.003)\ t$	(20)	0.999
		min	$E_{cons} = (1.279 \pm 0.001)\ t$	(21)	0.999

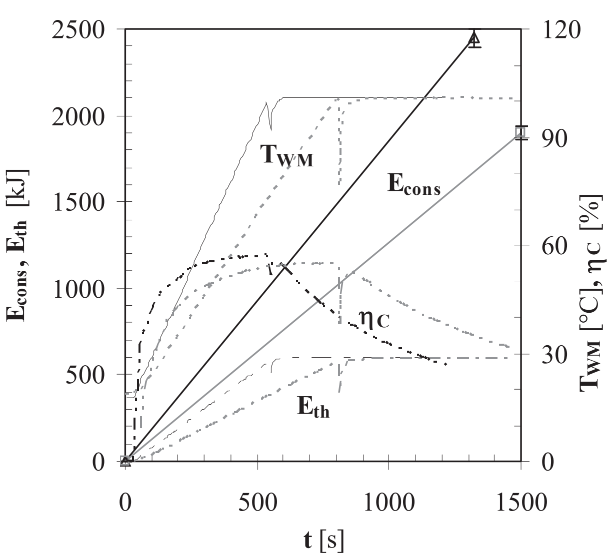

Fig. 2. Pasta cooking test using the pan A and LPG hob with the gas control knob set to the maximum (black lines) or minimum (grey lines) level: cooking water temperature at mid-height (T_{WM}: - - -, - - -), cooking energy theoretically (E_{th}: — • — •, — • — •) and effectively (E_{cons}: ——, ——) consumed, and energy efficiency (η_C: — • • —, — • • —) against time (t). The triangle and square symbols refer to the E_{cons} values estimated on the basis of the amounts of LPG consumed at the end of the corresponding cooking tests (average coefficient of variation of ±2%).

3.3. Electric hot plate

Fig. 3a shows the typical trend of the energy supplied by the electric hot-plate hob set at the maximum power of 1.5 kW during the pasta cooking process using pan A. As the plate temperature reached the maximum allowable temperature of ca. 242 °C (see Fig. S3b2 in the electronic supplement), the energy supplied was automatically limited. The instantaneous $E_{cons}(t)$ values were then correlated to t by using the least squares method, as shown by Eqs. (16) and (17) in Table 3.

Fig. 3a also shows the theoretical energy (E_{th}) necessary for the entire pasta cooking process, as calculated via Eq. (2), this tending to the aforementioned limiting value. Nevertheless, the hot-plate stove kept on absorbing energy and this resulted in further water evaporation and consequently in a decreasing energy efficiency of the cooking system. Actually, at the beginning of the cooking process, η_C resulted to be very low, probably because the electric energy was mainly consumed to heat the plate from the ambient temperature to the maximum allowable one. Just before the addition of the salt and dried pasta, η_C reached a maximum value of (60 ± 3) %. At the end of the cooking process, η_C reduced to (42 ± 5) % in consequence of an overall cooking water loss of about (119 ± 7) g, that is an evaporation ratio of (7.9 ± 0.5) % (Table 4).

When using the electric hot-plate stove B at its maximum setting (4.85 ± 0.09 kW kg^{-1} dried pasta), $E_{cons}(t)$ kept varying linearly with time throughout all the cooking test (Fig. 3b), and was reconstructed using the least squares regression listed in Table 3 – Eq. (18). All the other parameters mentioned above exhibited the same trend shown in Fig. 3a for the electric hob A. Moreover, as the cooking water started boiling, $\eta_{C,H}$ reached a greater maximum value $(74 \pm 3\%)$. Thereafter, the overall energy efficiency reduced to (49 ± 1) % (Table 4).

The electric hob A run at its maximum rated power of 1.47 ± 0.03 kW for just 240 s [see Eq. (16) in Table 3]. Then, to avoid T_{HP} exceeding the maximum allowable one, the electric power required by the appliance automatically reduced to (0.54 ± 0.01)

Table 4
Summary of the data collected during several pasta cooking tests performed with different home hobs and pans: hob diameter (d_H), pan bottom diameter (d_{PB}), pan bottom-to-hob diameter ratio (d_{PB}/d_H), number of trials (n), power setting, effectively (E_{cons}) and theoretically (E_{th}) energy consumed, mass of water evaporated at the end of the heating ($m_{WE,H}$) and cooking ($m_{WE,C}$) phases, overall water evaporation ratio (η_{WE}), energy efficiency at the end of the water heating phase ($\eta_{C,H}$) and pasta cooking (η_C), and overall cooking time (t_C).

Cooktop Type	d_H [mm]	d_{PB} [mm]	(d_{PB}/d_H) [−]	n	Power Setting [kW]	E_{cons} [kJ]	E_{th} [kJ]	$m_{WE,H}$ [g]	$m_{WE,C}$ [g]	η_{WE} [%]	$\eta_{C,H}$ [%]	η_C [%]	t_C [min]
LPG Hob	75	145	1.93	4	Max	2420 ± 196^a	577 ± 21^a	48 ± 7^a	357 ± 52^a	24 ± 3^a	54 ± 5^a	24 ± 3^a	21 ± 1^a
				4	(1/3)	1813 ± 109^b	575 ± 19^a	50 ± 23^a	$300 \pm 36^{a,b}$	20 ± 2^a	65 ± 15^a	32 ± 1^b	23 ± 1^a
		180	2.40	2	Max	2165 ± 22^a	605 ± 25^a	28 ± 2^b	336 ± 12^a	22 ± 1^a	55.2 ± 0.7^a	28.0 ± 0.9^a	18.2 ± 0.2^b
				2	(1/3)	1754 ± 142^b	591 ± 13^a	24 ± 4^b	227 ± 33^b	15 ± 2^b	59 ± 5^a	34 ± 3^b	22 ± 1^a
		220	2.93	2	Max	2151 ± 215^a	616 ± 25^a	34 ± 6^a	$317 \pm 48^{a,b}$	21 ± 3^a	60 ± 5^a	29 ± 3^a	18 ± 1^b
				2	(1/3)	1754 ± 142^b	593 ± 14^a	36 ± 6^a	242 ± 35^b	16 ± 2^b	61 ± 5^a	34 ± 3^b	23 ± 1^a
						Environmentally sustainable cooking practice							
		145	1.93	2	Max-Min	1261 ± 1^c	581 ± 1^a	28 ± 3^b	72 ± 5^c	4.8 ± 0.3^c	54 ± 1^a	46.0 ± 0.1^c	20.4 ± 0.1^a
EH A	180	145	0.81	3	Max	1236 ± 17^a	514 ± 65^a	5 ± 3^a	119 ± 7^a	7.9 ± 0.5^a	60 ± 3^a	42 ± 5^a	31.0 ± 0.5^a
EH B	145		1.00	4	Max	1135 ± 20^b	554 ± 15^a	3 ± 1^a	127 ± 14^a	8.4 ± 0.9^a	74 ± 3^b	49 ± 1^a	31.2 ± 0.5^a
EH A	180	180	1.00	3	Max	1274 ± 39^a	575 ± 21^a	4 ± 3^a	153 ± 8^b	10.2 ± 0.5^b	63 ± 2^a	45 ± 3^a	24 ± 1^b
EH B	145		1.24	3	Max	1154 ± 21^b	576 ± 13^a	3 ± 2^a	$121 \pm 19^{a,c}$	8 ± 1^a	72.1 ± 0.5^b	50 ± 1^a	31.4 ± 0.6^a
EH A	180	220	1.22	3	Max	1270 ± 18^a	531 ± 7^a	9 ± 3^a	168 ± 8^c	11.0 ± 0.6^c	61.0 ± 0.4^a	42.0 ± 0.1^a	32 ± 3^a
EH B	145		1.52	2	Max	1193 ± 120^b	570 ± 9^a	8 ± 4^a	127 ± 32^c	8.5 ± 0.5^a	65 ± 2^a	48 ± 6^a	33 ± 3^a
						Environmentally sustainable cooking practice							
EH A	180	145	0.81	2	Max-Min: CP	1028 ± 8^c	586 ± 4^a	3.7 ± 0.4^a	34 ± 5^b	2.3 ± 0.4^b	57.6 ± 0.1^a	57 ± 1^b	32 ± 1^a
				2	Max-Min: HP	760 ± 31^d	547 ± 10^a	3 ± 1^a	29 ± 7^b	1.9 ± 0.5^b	70 ± 5^b	72 ± 2^c	29.5 ± 0.1^c
IH	190	145	0.76	4	Max	2117 ± 137^a	580 ± 10^a	14 ± 11^a	504 ± 95^a	33 ± 6^a	75 ± 2^a	27 ± 1^a	17.7 ± 0.5^a
				4	Medium	1702 ± 208^b	550 ± 29^a	20 ± 17^a	287 ± 88^b	19 ± 6^b	78 ± 7^a	$33 \pm 5^{a,b}$	18.5 ± 0.9^a
				3	Min	1623 ± 59^b	569 ± 7^a	22 ± 13^a	296 ± 23^b	20 ± 1^b	69 ± 6^a	35 ± 1^b	21.1 ± 0.8^b
		180	0.95	2	Max	1990 ± 14^a	578 ± 6^a	6 ± 2^a	409 ± 15^a	27 ± 1^a	75 ± 4^a	$29 \pm 1^{a,b}$	17.2 ± 0.3^a
				2	Min	1526 ± 16^b	562 ± 30^a	5.6 ± 0.6^a	257 ± 22^a	17 ± 1^b	74 ± 4^a	37 ± 2^b	20.2 ± 0.2^b
		220	1.16	2	Max	1961 ± 7^a	614 ± 4^b	14 ± 8^a	398 ± 11^a	$27 \pm 1^{a,b}$	77 ± 3^a	31 ± 1^b	17 ± 1^a
				3	Min	1535 ± 15^b	$605 \pm 12^{a,b}$	12 ± 5^a	273 ± 7^b	18.2 ± 0.4^b	78 ± 3^a	39.4 ± 0.7^b	20.1 ± 0.2^b
						Environmentally sustainable cooking practice							
		145	0.76	2	Max-Min	868 ± 54^c	567 ± 10^a	3.1 ± 0.8^a	25 ± 12^c	1.7 ± 0.8^c	75 ± 6^a	65 ± 3^c	18 ± 1^a

EH Electric Hob.
IH Induction Hob.
CP cold plate.
HP hot plate.
- Different lowercase letters indicate statistically significant difference among the column means of each hob used at the probability level of 0.05.
- Different uppercase letters indicate statistically significant difference among the CF and C_C means referred to each hob operating at the low energy consumption procedure at the probability level of 0.05.

kW [see Eq. (17) in Table 3]. The energy delivered by such a hob, having a diameter of 180 mm, was greater than that capable of being absorbed by the pan itself, its bottom diameter being equal to 145 mm. Consequently, the overall cooking time (t_C) for the electric hob A practically coincided with that detected with the electric one B at $\alpha = 0.05$ (Table 4). In particular, the latter, having the same diameter of the pan bottom, was continuously and constantly powered during the whole cooking test (607 ± 1 W) [see Eq. (18) in Table 3]. Since E_{th} is independent of the cooking system, the lower energy consumed by the electric hob B, as well as the more effective heat transfer due to a unitary ratio between the plate and pan bottom diameters, yielded a greater η_C value than that of the electric hob A, even if such an increase in η_C was not statistically significant at $\alpha = 0.05$ (Table 4).

3.4. Induction-plate stove

Fig. 4 shows the time course of the cooking water temperature at mid-height (T_{WM}), energy theoretically (E_{th}) and effectively (E_{cons}) consumed, and cooking energy efficiency (η_C) when using the pan A and setting the control knob (CK) of the induction plate hob at the maximum or minimum level. Even with this stove, the energy delivered when the control knob was set to the maximum, medium or minimum level was found to increase linearly with time and was reconstructed using the least squares regressions listed in Table 3 – Eqs. (19)–(21). In the circumstances, the specific power supply reduced from 16 ± 1 to 13 ± 1 or 10.3 ± 0.4 kW kg^{-1} dried pasta, respectively.

At the maximum power setting, η_C reduced to (27 ± 1)% owing to the intense evaporation of water, this being about one-third of the initial amount (Table 4). By contrast, at the medium and minimum power settings, the water evaporation ratio lessened to (19 ± 6) and (20 ± 1) %, respectively. Consequently, η_C increased to (33 ± 1) and (35 ± 1) %. Such differences were however statistically insignificant at $\alpha = 0.05$ (Table 3). Of course, the lower the energy consumed the longer the overall cooking time became.

During the water-heating phase, η_C was quite high (69–78) %, and practically in line with the energy efficiency of typical home induction hobs, as measured with the carbon-steel block test by Acero et al. (2010) and Hager and Morawicki (2013). Moreover, at the maximum setting the cooking water started to boil in as shortly as 7 min (Fig. 4).

3.5. Effect of pan-to-hob diameter ratio

By using the other two pans B and C (Table 1), it was possible to vary the ratio between the pan bottom and hob diameters (d_{PB}/d_H) from 0.76 to 2.93 (Table 4), in order to assess the effect of such a parameter on the pasta cooking energy efficiency. Table 4 lists how the control knob of each hob was regulated, as well as the main parameters measured and estimated in these cooking tests.

As concerning the LPG stove, the only statistically significant difference at $\alpha = 0.05$ regarded η_C, that increased from 24-29% to 32–34%, when setting the gas control knob at the (1/3) level

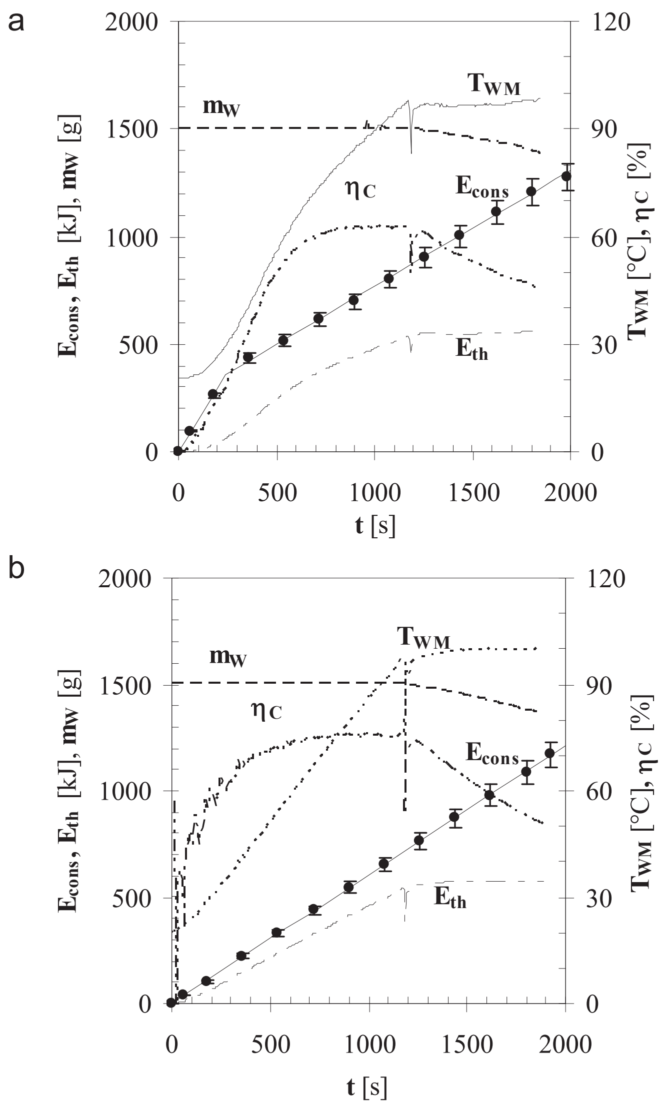

Fig. 3. Pasta cooking tests using the pan A and electric hot plat hobs A (**a**) and B (**b**) with the control knob to the maximum setting: time course of the amount (m_W: — —) and temperature at mid-height (T_{WM}: - - -) of the cooking water, energy theoretically (E_{th}: — • — •) and effectively (E_{cons}: ——) consumed, and energy efficiency (η_C: — • • —). The standard deviation for each dependent variable is listed in Table 4.

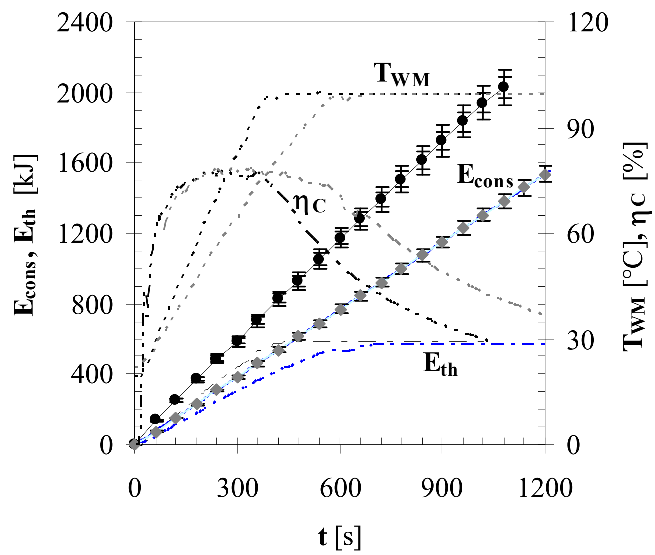

Fig. 4. Pasta cooking tests using the pan A and induction stove with the control knob set to the maximum (black lines and closed symbols) or minimum (grey lines and open symbols) level. Time course of the cooking water temperature at mid-height (T_{WM}: - - -, - - -), energy theoretically (E_{th}: — • — •, — • — •) and effectively (E_{cons}: ——, ——) consumed, and energy efficiency (η_C: — • • —, — • • —). The standard deviation for each dependent variable is listed in Table 4.

whatever the (d_{PB}/d_H) value (Table 4).

When using the electric hobs A and B, the only statistically significant difference regarded the pasta cooking time, which reduced from 31–33 min–24 min when setting the control knob at the maximum level and the pan bottom had the same diameter of the hot plate (Table 4).

Finally, when using the induction stove and varying (d_{PB}/d_H) from 0.76 to 1.16, no statistically significant difference among the parameters shown in Table 4 was detected, except for E_{cons}, $m_{WE,C}$, and η_C. As E_{cons} increased, the pasta cooking time (t_C) reduced from 20–21 min to 17–18 min.

3.6. Pasta cooking testing with minimum energy consumption

To improve the pasta cooking energy efficiency, a series of duplicated tests was carried using the pan A and setting each hob control knob to the maximum level to bring quite rapidly the cooking water up to the boiling point. As soon as the kitchen salt and dried pasta were added to the cooking water, and the mixture started to boil again, each hob control knob was adjusted to the minimum setting to keep the cooking temperature around 98 °C and the lid closed to limit water vapor loss. The time course of the main cooking process parameters (i.e., m_W, T_{WM}, E_{th}, E_{cons}, η_C) assessed here was reported in the electronic supplement (Fig. S5).

As concerning the LPG hob, duplicated water heating tests in the absence of pan were carried to measure the instantaneous amount of LPG consumed and thus estimate the energy released by LPG combustion. These data are reported in the electronic supplement (see closed symbols in Fig. S4) and were correlated as listed in Table 3 – Eqs. (14) and (15).

The above procedure resulted in an overall energy consumption of (1261 ± 1) kJ, and a cooking efficiency of (46.0 ± 0.1) %, while pasta cooking ended in practically the same cooking time previously assessed (Table 4).

When using the electric hob A, two tests were performed according to the aforementioned procedure starting with the electric plate at ~20 °C (cold plate) or 180 °C (hot plate). As shown in Table 4, despite the energy consumed (E_{cons}) during both tests was definitively smaller than that previously registered with both hobs, in the test carried out with the hot plate E_{cons} was about the 76% of that consumed with the electric plate initially at room temperature (Table 4). This resulted in an overall energy efficiency of 72% instead of 57%. In both tests, the water evaporation ratio (η_{WE}) leveled off at about 2% at $\alpha = 0.05$ (Table 4). Correspondingly, the t_C reduced to 29.5 min against 32 min, such a difference being statistically significant at $\alpha = 0.05$ (Table 4). The most remarkable result of such tests was that pasta cooking was ended using just the residual heat of the electric hot-plate. In fact, E_{cons} remained constant for $t \geq 1140$ s (Fig. S5bc). Only the performance detected with the cold electric plate was further compared to that observed with the other cooking appliances under study.

Finally, when using the induction stove with the control knob at the maximum setting, the high power was supplied for just 373 s (Fig. S5d). Then, to cook the added dried pasta the rate of the energy supplied was reduced to as little as (0.11 ± 0.02) kW so as to keep water boiling. At the end of the water heating phase, $\eta_{C,H}$ was as expected quite high (75 ± 6) %. Once the control knob had been switched to the minimum setting, η_C tended to drop to not less than (65 ± 3) %, the water evaporation ratio being limited to no more than 2% (Table 4). The overall energy consumption amounted to (868 ± 54) kJ, this being about 16% less or 14% greater than that consumed with the electric stove A starting with the cold- or hot-plate, respectively. Altogether, the overall cooking time (18 ± 1 min) did not statistically differ from that associated to the operation at the maximum setting (Table 4).

3.7. *Carbon footprint and operating costs of pasta cooking*

The assessment of the energy efficiency of different cooking appliances should not be limited to that of the specific appliance used to bring about a given duty (i.e. pasta cooking), but it should account for the extraction, conversion and transport efficiencies of the fuel source employed (Hager and Morawicki, 2013). Thus, to compare the overall effectiveness of the different hobs used here, the specific energy used to cook one kg of dried pasta allowed the estimation of the corresponding carbon footprint (CF), which is the total amount of GHGs produced directly and indirectly by an activity over the life stages of a product (BSI, 2008; Wiedmann and Minx, 2008), and energy costs.

The emission factors (referred to a time horizon of 100 years) for the energy sources used (i.e., electric energy and LPG) were extracted from ISPRA (2015) and ADEME (2007) reports, respectively. By relating the electric energy mix to the average Italian thermo-electric production from non-renewable and renewable sources, in 2014 the average emission factor for purchased electricity was of the order of 323.6 g CO_{2e} per kWh (SINAnet, 2015), as listed in Table 2. Then, the total electric energy needed to cook dried pasta was corrected to estimate the effective absorption of electric energy from the Italian grid, its average electric energy loss being about 6.7% of the electricity supplied in 2013 (ISPRA, 2015). As concerning the emission factor for LPG fuel, the GHG emissions resulting from LPG combustion only (803 g C_e kg^{-1}) were corrected to account for the so-called upstream emissions (ADEME, 2007), that is those that occurred during extraction, transportation (61 C_e kg^{-1}), and refining (90 C_e kg^{-1}). Thus, the total emission factor for LPG was set to 954 g C_e kg^{-1}, equivalent to 3.498 kg CO_{2e} kg^{-1}, as shown in Table 2.

Finally, the pasta cooking costs (C_C) were estimated by referring to the Italian residential utility charges for electric energy (€0.245/kWh: Eurostat, 2016) and LPG fuel (€ 0.051–0.065/MJ in the case of 15-kg LPG cylinders: Anon., 2016b) in the second semester of 2015. Since in Italy just the 5% of households makes use of LPG for heating, water heating and cooking, whereas the 80% of all households are connected to the natural gas network, the utility charges for natural gas (i.e., €0.0213/MJ: Eurostat, 2016) were also pointed out.

Thus, the values of the GHG emissions (CF) and energy costs (C_C) associated with pasta cooking for each cooking mode examined here were compared in Figs. 5 and 6, respectively.

Independently of the pan size, by using the electric hob B at its maximum power setting (i.e., ~4.9 kW kg^{-1}), it would be possible to cook pasta in about half an hour with minimum GHG emissions (0.88 ± 0.02 kg CO_{2e} kg^{-1}) and operating costs (0.62 ± 0.01 € kg^{-1}). With the induction hob at its maximum setting (i.e., 16 ± 1 kW kg^{-1}), pasta cooking would end in as short as about 18 min, but CF and C_C would approximately increase by 87%. Despite its smaller η_C value, the LPG cooker at its maximum setting would emit by far less GHGs than the induction stove (Fig. 5).

By applying the minimum cooking energy procedure mentioned above, thanks to its greater cooking energy efficiency (65 ± 3%), the induction stove resulted in the lowest CF and operating cost (i.e., 0.67 ± 0.04 kg CO_{2e} and €0.47 ± 0.03 per kg of dried pasta), followed by the electric plate (0.79 ± 0.01 kg CO_{2e} and €0.56 ± 0.01 per kg) and LPG (0.77 ± 0.01 kg CO_{2e} and €0.61 ± 0.01 per kg) hobs (Figs. 5 and 6), at the confidence level of 95%. If the LPG fuel price coincided with that of natural gas, the pasta cooking cost using the gas stove would reduce to €0.21/kg, that is to less than one-half or one-third of that related to the induction or electric hobs, respectively. Such a finding agreed with previous estimates by Karunanithy and Shafer (2016), the difference in utility charges depending on the technology used to deliver extract, convert, transmit, and end-use the energy source (i.e., LPG or electricity) of choice (Hager and Morawicki, 2013).

In Fig. 5 the CF of pasta cooking using different pans and hobs is also compared to the carbon footprint related to the field-to-retail life cycle of durum wheat semolina dried pasta (0.947 kg CO_{2e} kg^{-1}), as extracted from Barilla's EPD® (2009). The use of the

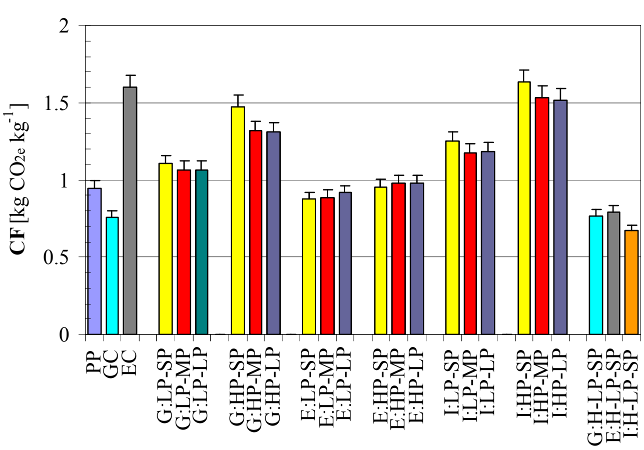

Fig. 5. Comparison among the *Carbon Footprint* (CF) values associated with the field-to-retail life cycle of durum wheat semolina dried pasta production (PP) and its gas- (GC) or electric- (EC) cooking, as extracted from Barilla (2009), and those referred to the pasta cooking phase using the GPL (G), electric (E) or induction (I) stove regulated at the maximum (HP) and/or minimum (LP) power setting, and a small- (SP), medium- (MP) or large- (LP) size pan. The error bars are used to represent an interval of one standard deviation from the mean CF values.

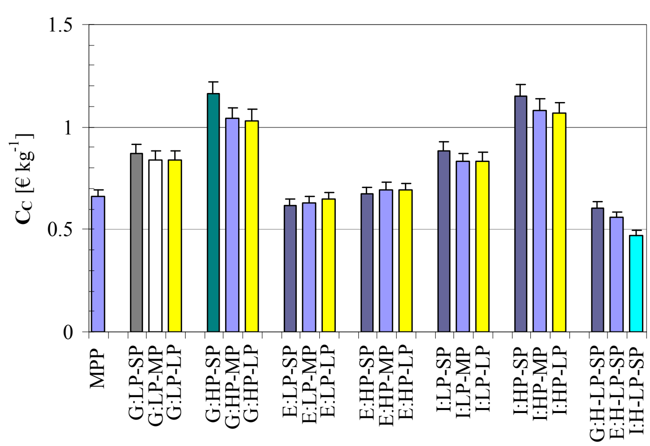

Fig. 6. Comparison among the minimum dried pasta prices (MPP) in Italian grocery stores and markets and operating costs (C_C) associated with the pasta cooking phase when using the GPL (G), electric (E) or induction (I) stove regulated at the maximum (HP) and/or minimum (LP) power setting, and a small- (SP), medium- (MP) or large- (LP) size pan. The error bars are used to represent an interval of one standard deviation from the mean C_C values.

electric hob B at the maximum setting would result in GHG emissions of almost the same order of magnitude (0.88 ± 0.02 kg CO_{2e} kg^{-1}).

In the circumstances, the agricultural activities and associated farming practices can no more be regarded as the hotspot of the cradle-to-grave environmental impact of dried pasta, since the contribution of cooking accounted for as much as 48% of the overall carbon footprint of pasta production and was in line with the range of values (46–59%) registered in the literature (Bevilacqua et al., 2007; Fusi et al., 2016; Röös et al., 2011; Barilla, 2013). Thus, all the current efforts directed to identify the good agricultural practices to comply with the principles of sustainability (Alhajj Ali et al., 2015; Gan et al., 2011; Silvestri, 2015) are to be re-considered, since the first priority to deal with is definitively the mitigation of the GHG emissions associated with food cooking.

The pasta cooking procedure recommended here would reduce GHG emissions by 81, 73, or 86% with respect to those released with the LPG, electric, or induction stove, respectively, each one operating at the maximum power setting. Moreover, such environmentally sustainable cooking practice, as applied to the induction stove, yielded quite significant energy savings of the order of 31 or 18% of the energy needs registered in conjunction with the LPG or electric cooker, respectively (Fig. 5).

In Fig. 6 the pasta cooking costs using different pans and hobs were compared to the minimum (€0.66/kg) price of durum wheat semolina dried pasta, as recently collected in Italian grocery stores and markets, its maximum price being €2.56/kg (Anon., 2016c). In general, the cooking costs were greater than the minimum market price of dried pasta, except for the eco-friendly cooking practice tested in this work, especially when it was coupled to the induction hob.

4. Conclusions

The overall energy efficiency (η_C) of dried pasta cooking using typical domestic appliances and cookware sets was definitively smaller than the minimum energy efficiency performance requirements for EU domestic hobs. It was found to range from 30 ± 4 to 33 ± 5 or 46 ± 3% for the LPG, induction or electric hot-plate hobs, respectively, these figures being also independent of the pan bottom-to-hob diameter ratio at the probability level of 0.05.

An environmentally sustainable pasta cooking practice was suggested to minimize cooking water evaporation, this being the most significant loss of energy, and applied to all the cooking appliances examined. The associated GHG emissions reduced by 81, 73, or 86% with respect to those released with the LPG, electric, or induction hob, respectively, each one adjusted at the maximum power setting. The induction hob appeared to be the cooking system best suited for the above good cooking practice. In fact, the associated carbon footprint and operating costs lowered to 0.67 ± 0.04 kg CO_{2e} and €0.47 ± 0.03 per kg of dried pasta, while the energy savings amounted to 31 or 18% of the energy consumed under the same procedure by the LPG or electric cooker, respectively.

By using the information technologies available on the market today, such a cooking practice might be easily converted in a built-in procedure to manage automatically the operation of novel induction cooking hobs so as to cut significantly the environmental impact of dried pasta consumption.

Acknowledgements

This research was supported by the Italian Ministry of Instruction, University and Research, special grant PRIN 2015 - prot. 2015MFP4RC_002.

Nomenclature

C_C	Operating cost of pasta cooking [€ kg^{-1}]
c_{EE}	electricity price [€ kWh^{-1}]
CF	Carbon Footprint related to the only energy consumed for pasta cooking [kg CO_{2e} kg^{-1}]
CK	Control knob setting
c_{LPG}	LPG fuel price [€ MJ^{-1}]
CP	Cold plate
c_{pi}	Specific heat of the i-th component [kJ kg^{-1} K^{-1}]
d_H	Hob diameter [mm]
d_{PB}	Pan bottom diameter [mm]
d_{PB}/d_H	pan bottom-to-hob diameter ratio [dimensionless]
E_{cc}	Energy dissipated by convection and conduction from the pan and heating source [kJ]
E_{comb}	Heat of combustion [kJ]
E_{cons}	Energy effectively consumed to cook pasta in the operating conditions selected [kJ]
EPD	Environmental Product Declaration
E_{rad}	Energy dissipated by radiation from the pan and heating source [kJ]
E_{th}	Energy theoretically consumed to cook pasta [kJ], as defined by Eq. (2)
E_{vap}	Heat of water evaporation [kJ]
FE_{EE}	Emission factor for the electric energy distributed at the Italian grid, inclusive of non-renewable and renewable sources [g CO_{2e} kWh^{-1}]
FE_{LPG}	Emission Factor for LPG combustion, including the GHG upstream emissions [g CO_{2e} kg^{-1}]
GHG	Greenhouse gas
HP	Hot plate
I	Electric current [A]
LHV	Lower heating value for LPG fuel [MJ kg^{-1}]
LPG	Liquefied petroleum gas
m_i	Amount of the i-th component used to cook pasta [kg]
m_{LPG}	Mass of LPG fuel burnt [g]
n	Number of cooking tests performed
q_{gel}	Heat of starch gelatinization [kJ]
q_{si}	Sensible heat for the generic i-th component changing its temperature from T_{i0} to T_W [kJ]
R	Electric resistance of the hot-plate hob [Ω]
r^2	coefficient of determination
t	Cooking time [s]
t_C	pasta cooking time [s]
T_{HP}	Temperature of the hot plate surface [°C]
T_{i0}	Initial temperature of the generic i-th component [°C]
T_{PWi}	Temperature of the pan wall at the generic ith position [°C]
T_{Wi}	Instantaneous temperature of the cooking water at the generic ith position [°C]
x_S	mass fraction of starch in dried pasta [g g^{-1}]

Greek symbols

α	Probability level
ΔH_{gel}	Gelatinization enthalpy of wheat starch [kJ kg^{-1}]
η_C	Energy efficiency of the cooking system [%]
η_{WE}	Percentage fraction of water evaporated at the end of the cooking process [%]
λ_{ev}	Latent heat of water evaporation at 100 °C [kJ kg^{-1}]

Subscripts

B	referred to the position at 0.5 cm above the pan bottom
C	referred to the pasta cooking phase
E	referred to water evaporated
P	referred to the pan

PA referred to the dried pasta
PW referred to the pan wall
H referred to the heating phase of the cooking water
M referred to the position at pan or water mid-height
s referred to the kitchen salt
S referred to the starch contained in the dried pasta
T referred to the position at 0.5 cm below the pan or water top level
W referred to water
0 initial

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jfoodeng.2017.01.012.

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