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Experimental investigation of steam pressure coffee extraction in a stove-top coffee maker

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ABSTRACT

The most common household coffee-brewing method in Italy makes use of a stove-top coffee maker known as *moka*. This device uses the steam pressure, produced by the water contained in an autoclave-type aluminum kettle heated by an external source, to force upwards water itself through a roasted and ground coffee bed contained in a funnel-shaped filter. Despite its well-established usage, the *moka* has never been the subject of detailed analysis, which led to a series of unclear descriptions or misinterpretations concerning its functioning, such as the consolidated misbelieve that standard atmosphere boiling point temperature is needed to drive the water out. The detailed measurement of the thermodynamics of the *moka*, described here, sheds light on its actual behaviour. It is shown that extraction commences at pretty low temperatures and depends on the initial amount of dry air in the kettle. Remarks on the time decreasing value of the coffee bed permeability are also drawn. A correct understanding of the extraction phenomenon, together with considerations on the coffee chemistry, serves the purpose of assessing possible ways to improve the quality of *moka* product.

1. Introduction

The most popular household coffee-brewing method in Italy is that performed by using an inexpensive stove-top coffee maker invented by the aluminum technologist Alfonso Bialetti in 1933 [1,2]. This coffee maker was industrially produced and commercialized, by the Inventors son Renato from 1946, with the trademark denomination of “Moka Express”, but, nowadays, it is simply known as *moka*. In its original version, *moka* consists of two octagonal conoids, which can be regarded as the very epitome of Italian household hardware, and in this version has racked up sales of more than 105 million units since market launch [1], with an actual production of 4 million pieces per year [3]. During the 1970s, the *moka* attracted the attention of several designers which reinvented the shape without remarkably affecting the overall proportion, and by the 1980s stainless steel started to parallel aluminum as *moka* construction material [4].

Due to its low cost and easy-to-handle characteristics, *moka* is used, albeit not extensively, also in others countries where is also known as stove-top *espresso* or often misnamed *mocha* or *moca*. An exception is represented by Spain where it is known as *napolitana*, *cafetera de rosca*, *cafetera de fuego* or *italiana* and its use is spread almost like in Italy [5–7], and Portugal where it is known as *cafeteira italiana*.

This ingenious device uses the steam pressure, produced by the water contained in an autoclave-type aluminum kettle heated by an external source (gas or electrical stove), to force upwards the same water through a roasted and ground coffee bed contained in a funnel-shaped filter. The beverage is conveyed through appropriate tubing into an upper vessel, screwed and sealed by a rubber gasket to the base kettle. The end of the brewing operation is usually announced by noisy mixture of boiling water and its vapour flowing from the upper tube, to indicate water depletion [8,9].

Undoubtedly, a relevant part of the success of the *moka* coffee maker has been played by the word “Express” in its trademark denomination. In facts this word evokes the worldwide well-known *espresso* coffee brew, which is prepared by very different coffee machine and it is also organoleptically very different from *moka* coffee brew.

Italian *espresso* is a beverage prepared on request from roasted and ground coffee beans by means of hot (90 ± 5 °C) water pressure (9 ± 2 bar) applied for a short time (30 ± 5 s) to a compact roast and ground coffee cake (6.5 ± 1.5 g) by a percolation machine, to obtain a small cup of a concentrated foamy elixir [8].

Unfortunately, the main factors controlling the coffee extraction in the *moka*, such as the thermodynamic relationship between water pressure and temperature, the Darcys law of linear filtration

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[9] as well as the physico-chemical nature of roasted and ground coffee, led to a beverage sometimes partially characterized by harsh bitter flavour often describe as "burnt", and by lack of the foam layer typical of true Italian *espresso* coffee brew [8]. Differently from espresso coffee machine, the thermal balance of *moka* is somewhat flimsy, being affected by several variables not easy to control [8]. It has been suggested that the main feature, shared by *moka* and *espresso*, is the fact that water wets the grounds once through, increasing the extraction yield by fresh solvent power [8].

It is clear that, in order to objectively interpret the differences between *moka* and *espresso* brewing methods, it is necessary to study in detail the *moka* functioning.

The *moka* coffee extraction physics, inspired from a primordial washing machine known as *lisciveuse* [1], in turn derived from the steam engine of a couple of centuries ago [4], have not been the subject of detailed studies.

It has to be stressed out that, a part of a plethora of surprisingly unconceivable, physically uncorrect or simply vague functioning descriptions published even on scientific literature [5,6,10,11], the only one paper dealing more correctly, although not thoroughly, with the *moka* physics has been published 74 years after the *moka* invention [9].

In this work, we attempt to fill this gap by performing detailed measurements on a standard commercial *moka*, in order to better understand its underlying physics and functioning characteristics. In addition, the availability of an experimental database, constitutes a necessary requirement for the development and validation of a mathematical model of the device. This, in turn, can be particularly useful for parametric analysis and/or optimization studies.

The present work, to the authors' best knowledge, is the first experimental attempt to investigate in detail the *moka* physics in order to put in evidence misinterpretations or myths, and to assess how this physics affects the beverage quality.

2. Experimental setup

Among the different types of stove-top coffee makers available on the market, *MOKA EXPRESS*®, produced by Bialetti Industrie S.p.A., Omegna(VB), Italy, is the most largely used household device. It is a stove-top aluminum coffee maker, made in different sizes, and its three cups version has been used in the experiments. The coffee maker is composed of a 220 cm^3 capacity lower tank, a 50 cm^3 capacity funnel-shaped filter, a washer, a downstream filter plate, and a topper pot, as shown in Fig. 1.

2.1. Operative conditions

The experiments have been conducted for a standard usage of the three cups *moka*, which is considered to be a 150 g of water filling of the tank, and a 15 g of coffee filling of the funnel. The coffee employed is a 100% *Coffea arabica* L. blend with a medium roasting degree (total weight loss 16%), coarsely ground powder for stove-top coffee makers. An electrical stove has been used to heat the coffee maker for two different values of heating power. Two series of 10 experiments at 400 W and 600 W have been made.

2.2. Data acquisition system

In order to collect the data from the test rig, a National Instruments (NI) SCXI-1300 General-purpose voltage module has been used; it is connected to a SCXI-1102B channel amplifier, and mounted on a SCXI-1000 chassis. The chassis is connected to a PC through a NI PCI-6221 data acquisition (DAQ) device. The software used is LabView version 7, which allow to directly process the input voltage data into desired physical quantities, by programming *virtual instruments* (VIs).

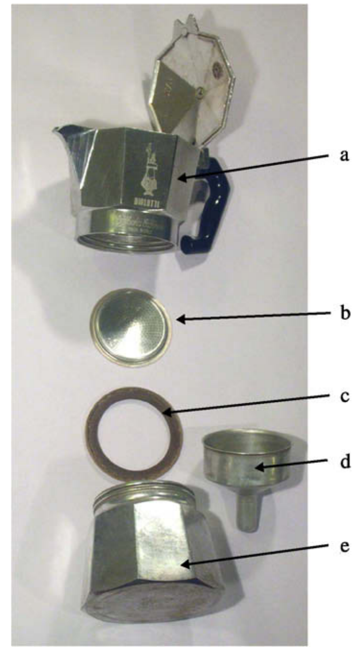

Fig. 1. Coffee maker parts: (a) topper pot; (b) downstream filter plate; (c) washer; (d) funnel-shaped filter; (e) lower tank.

2.3. Temperature measurements

In order to better understand the phenomenon of the steam pressure coffee extraction, a series of temperature sensors have been installed. Four probes have been used to infer temperature at different points within the lower tank, where part of the hot water turns into vapour, whose pressure supports the extraction. These probes, numbered TI [0–3], are Chromel/Alumel thermocouples with U (insulated) hot junction and 1.6 mm inconel sheath. They are mounted in pairs on 2 bolts with 8 M thread, and screwed on the lower tank. Six probes, numbered TE [4–9], have been used to measure the external temperature of the tank and the pot, in order to assess the heating behaviour, and collect the most available data. They have been realized with Chromel/Alumel cable type GG-30-KK, and they have been fixed to the device with an epossidic bicomponent resin. Two more Chromel/Alumel thermocouples with insulated hot junction have been used to measure the temperature of the aqueous extract (coffee) in the little column of the top pot.

A sketch of the coffee maker with a schematic view of probes positioning is presented in Fig. 2a.

2.4. Pressure probe

The vapour–air mixture pressure in the lower tank has been monitored by means of a Wheatstone bridge-based sensor, produced by Kulite. The model used, XTEL-190-100D, is a 0–7 bar (100 PSI) pressure range transducer, operating in differential mode, with temperature compensation between 80 °C and 275 °C.

2.5. Mass flow measure

For detecting the water level inside the tank at different height, eight resistive circuits have been used. Their electrical scheme is sketched in Fig. 2b. Each circuit is composed of a 9 V DC generator

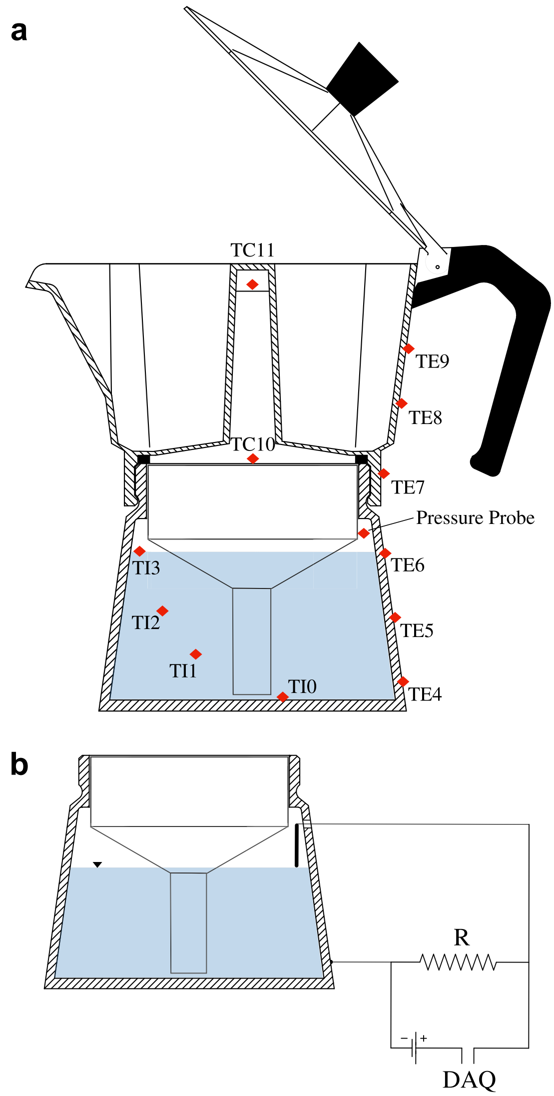

Fig. 2. Coffee maker sketch: (a) probes positioning; (b) water level detector scheme.

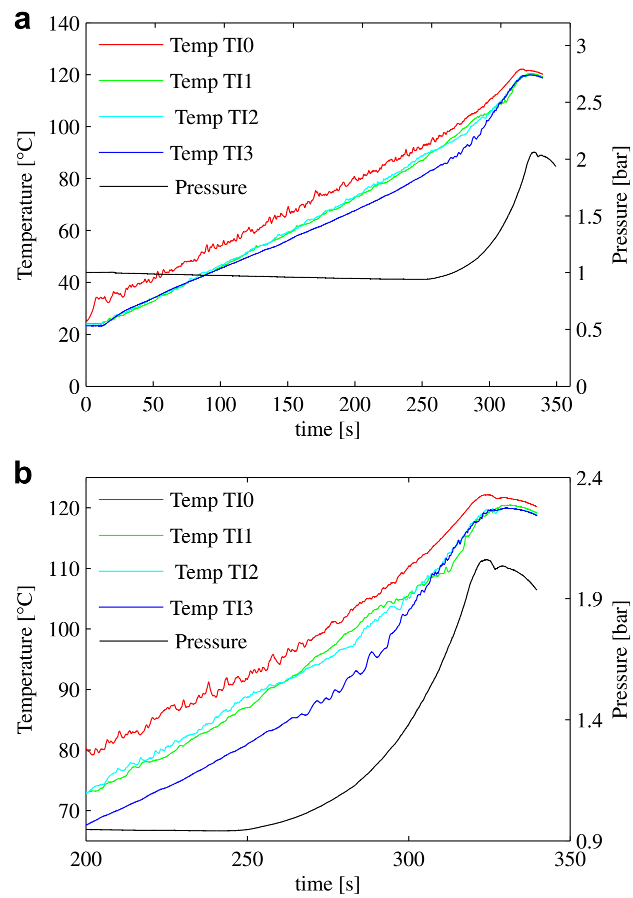

Fig. 3. In-tank temperature histories: (a) whole experiment; (b) detailed view of the late phase of extraction.

and a 7.5 MΩ resistance, and it is connected to the DAQ system. Inside the tank, the circuits are made of copper wires insulated with high temperature silicone. The system senses a discontinuous resistance variation as the tip of the wire gets out of the water.

2.6. Heater

The heating source used is a common 600 W electric cooker, whose temperature has been monitored and kept as steady as possible during the experiments.

3. Results and discussion

3.1. In-tank thermodynamic behaviour

Fig. 3 shows the pressure and temperature histories in the tank, for a representative experiment with a heating power of 400 W. The temperatures in this figure are those obtained from the four probles TI [0–3] that, as indicated in Fig. 2a, are positioned at different heights.

It is an article of faith, among stove-top coffee maker users, to think that standard atmosphere boiling point temperature is needed to drive the water out of the tank [6], and to think that the pressure rise is due to thermodynamic equilibrium between water and its vapor in saturation conditions [11]. While the first of these common believes might, at a first sight, be justified by Fig. 3, where a sensible pressure rise is perceived at about 90 °C of the water, the second is clearly disproved. TI0 probe is in contact with the bottom of the tank and senses the temperature of the water layer adjacent to the wall. TI1 and TI2 probes are immersed in water for most of the extraction time and give almost equivalent values for the water temperature, apart from slight oscillations due to convective plumes. On the other hand, TI3 probe, which is positioned at the top of the tank, measures the temperature of the air–vapour mixture. This temperature is considerably lower than the water temperature, which indicates lack of thermodynamic equilibrium during the extraction process.

Fig. 4 shows the temperature of the water TI2 inside the tank and the eight measurements of water flowed. It reveals that, despite the first impression, even the first convincement is wrong. In fact, extraction commences at lower temperatures.

It is interesting to observe that the *moka* behaviour can be split into two phases. Up to approximately 120 g of water flowed, the lower tank air–vapour mixture and the evaporating water can be considered a closed system, whose pressure, increased by sensible heat and water evaporation, drives the extraction of the coffee. We name this phase *regular extraction phase*. In this phase liquid–solid extraction occurs.

When the water level in the tank reaches the end of the funnel, there is a short-cut between external ambient and internal air–vapour mixture, which no more drives in-tank water out of the tank. At this point, the remaining water undergoes intense evaporation.

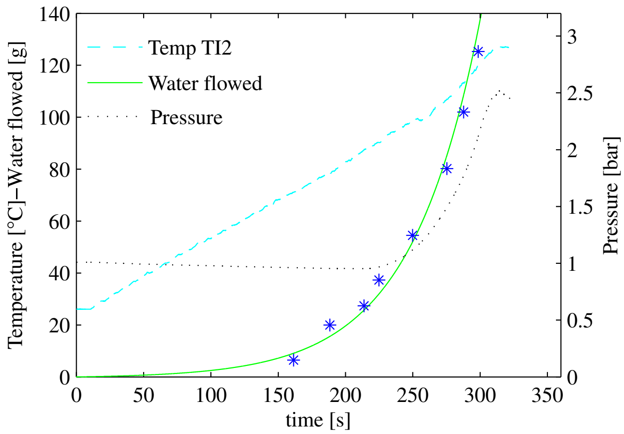

Fig. 4. In-tank temperature, pressure, and water flowed.

We name this phase, announced by a well-known rattling sound, *strombolian phase*, because of its typical volcano-like behaviour. Fig. 5 depicts the different phases during extraction.

High temperature extraction fluids (vapour, water and their mixture) transit in the coffee bed is noxious for the quality of the extract because, under these conditions, such fluids are more efficient in solubilizing less soluble compounds, generally conferring bitterness and astringency [12], and/or in stripping least volatile aroma compounds which are organoleptically unpleasant and described as clove-like, smoky, burnt, medicinal/chemical [13]. This is witnessed by an extraction yield (defined as the percentage of the brew total solids with respect to ground and roasted coffee dose) which is generally higher in comparison with the other brewing methods (e.g. filter, *espresso*, plunger or "French Press"). In particular extraction yield ranging from 18% to 22% have been proposed as the most acceptable, as far as brews quality is concerned. The coffee brews below 16% are considered to be under-extracted and those above 24% are considered to be over-extracted [13]. Independently on the coffee used (quality and quantity), values from 27.59 ± 0.28% [7] to 31.9% [8] have been reported. In a comparison between *moka* and *espresso* coffee extraction methods, the beverage concentration range suggested to be optimal for quality (> 2% for *moka* and > 3% for *espresso*) has been obtained by *moka* operating under conditions of coffee dose and powder particle size distribution leading to an extraction yield higher than 30% [14] and outside the optimal range suggested by the same authors (18–25%).

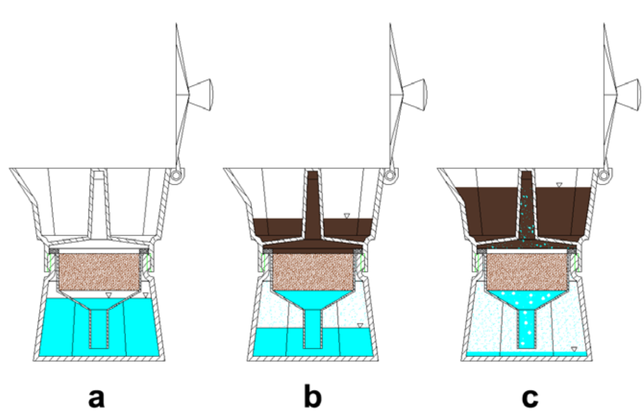

Fig. 5. extraction phases: (a) beginning; (b) regular extraction; (c) strombolian extraction.

Strombolian phase, corresponding to a vapour–liquid–solid extraction, is difficult to study because of its complex thermodynamics, while more detailed considerations can be drawn from the regular extraction phase.

Measured water level data have been fitted with an exponential regression for each experiment, as illustrated in Fig. 4. The function used is

$$m = -a + ae^{b\tau}, \tag{1}$$

where m is the water flowed in grams and τ is the time elapsed from the beginning of the experiment. The water flow, $\dot{m}$, is easily obtained by deriving (1). The mean correlation coefficient between measured data and regression model for all the experiments is 0.9963 and 0.9948, for 400 W and 600 W heating power, respectively.

The mean in-tank water temperature, $\overline{T}_w$, has been calculated:

$$\overline{T}_w = \frac{\int T\dot{m}\,d\tau}{\dot{m}\,d\tau} \tag{2}$$

and is reported in Table 1, together with the initial and final extraction temperatures. Table 1 shows that the initial in-tank extraction temperatures are clearly below the misbelieved value of 100 °C, with great part of the water flowing at quite low temperatures. In Table 1, the initial in-tank water temperature is considered at 10 g of water flowed, which is the first value sensed by the water level measurement apparatus. Whereas the final in-tank water temperature is taken at 120 g of water flowed, considered as the beginning of the *strombolian* phase.

At the beginning of the heating process, the tank has 20 cm^3 of space occupied by air, which we may consider, for simplicity, at saturated conditions. During the extraction, the pressure contribution due to air can be deduced by applying ideal gas law and the regression model for water flow. Pressure due to dry air is calculated as follows:

$$p_{air}(\tau) = \frac{TI3(\tau)}{V_{air}(\tau)} \frac{p_{(air,0)}V_0}{T_0}, \tag{3}$$

where $p_{(air,0)}$, V_0, and T_0 are the initial partial pressure, volume and temperature of dry air, respectively, TI3(τ) is the temperature measured by the higher in-tank temperature probe, and $V(\tau)$ is the volume occupied by air at a certain time τ, which depends on Eq. (1):

$$V_{air}(\tau) = \frac{m}{\rho_w} + V_0, \tag{4}$$

where ρ_w is the water density.

It has been already stressed out the absence of thermodynamic equilibrium between liquid and vapour phases of water, which results in a temperature difference sensed by probes whether immersed or not. Vapour conditions are driven by both evaporation from liquid–vapour separation surface and convective heat transfer with each surrounding surface. A question arise on whether vapour is at saturated or overheated conditions, which is not possible to answer precisely. Nevertheless, vapour formation and heating can be considered driven mainly by evaporation. So, in order to estimate the pressure due to water vapour, saturated vapour at air–vapour temperature, TI3, rather than in-tank water temperature, has been assumed. Values are obtained by means of IAPWS

Table 1
Temperatures of in-tank water during extraction

Heat flux	Initial		Final		Mean	
	Mean	Std.	Mean	Std.	Mean	Std.
400 W	68.7	2.7	117.2	1.2	94.3	1.6
600 W	70.2	2.9	120.6	3.0	97.6	1.2

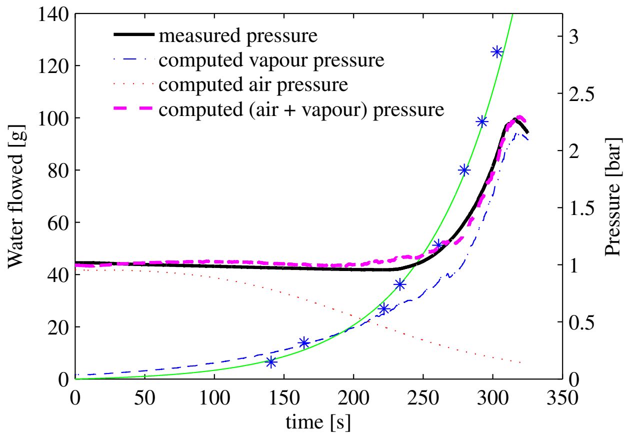

Fig. 6. Pressure contribution of dry air and saturated vapour.

IF-97 tables. Fig. 6 depicts a representative experiment, and it shows that very good agreement exists between our assumptions and measured pressure. This reveals the major contribution of dry air in leading the extraction, and it will be the subject of further detailed analysis.

3.2. Aqueous extract

The funnel-shaped filter has 50 cm^3 capacity and is filled with 15 g of coffee. Coffee true density is 1190 kg/m^3 [15], thus the coffee bed filling ratio is 0.244. The first drop of aqueous extract is sensed by TC10 probe after the funnel has been completely filled by water, completing the *imbibition phase*. This happens when an approximative amount of 40 g of water has flowed out of the lower tank. This can be noticed in Fig. 7, when TC10 probe experience a sudden temperature variation due to the contact with the aqueous extract. In the imbibition phase no pressure drop is sensed, partly because the water flow is low, and partly because in this phase the coffee matrix presents low resistance to water penetration. During imbibition and extraction phases the coffee undergoes chemical transformations due to the interaction with water, which substantially chance its properties [16,17]. The coffee bed water invasion, during the imbibition phase, induces the solubilization of more soluble and low molecular weight compounds, as well as more volatile aromatics (low temperature/pressure extraction). Simultaneously, there is the coffee bed particle swelling, due to the swelling of water-insoluble polysaccharides present in the roasted coffee [16], and with the geometrical rearrangement of the coffee particles due to upwards water flow [18]. As soon as the coffee bed swelling and spatial rearrangement provoke the progressive decrease of the coffee bed porosity, the extraction proceeds at increasing temperatures/pressures, thus making the decrease in coffee bed porosity and the solubilization of coffee compounds competitive phenomena. The process goes on up to the starting of the *strombolian* phase, which marks the passage from a closed thermodynamic system to an open one.

In its passage through the coffee bed, water transfers part of its heat to the bed itself. Aqueous extract temperatures are sensibly lower than that of the in-tank water. This is clearly visible in Fig. 7, where the extracted coffee has a much lower temperature, TC10, than that, TI2, of the water in the tank.

After 120 g of water flowed the *strombolian* phase begins, and no accurate measurements of the extraction phenomenon can be made. As highlighted in Fig. 7b, a limited zone in between 50 g and 120 g of water flowed has been considered. In Table 2 the initial, final, and mean extract temperatures for the restricted zone are presented.

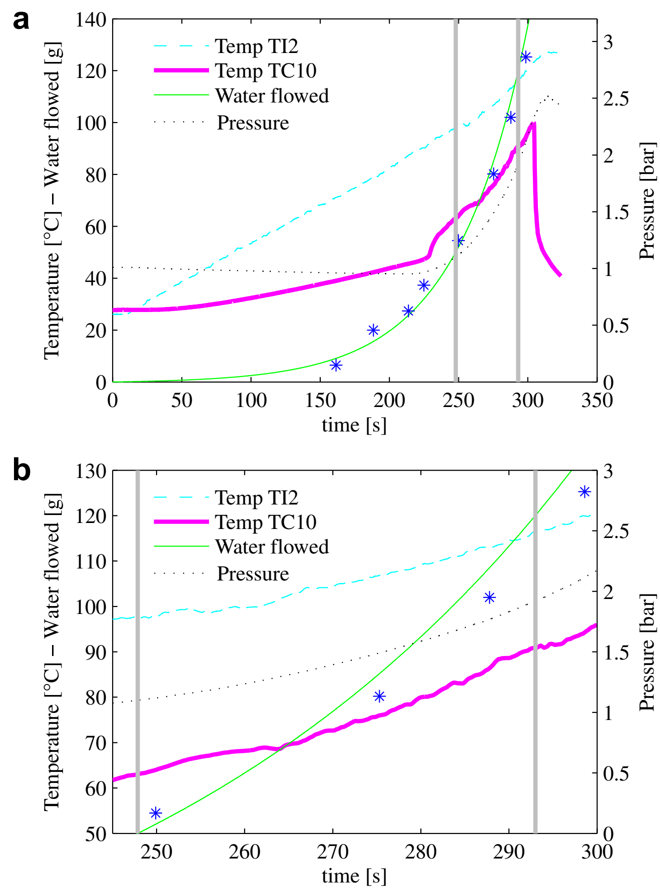

Fig. 7. (a) Aqueous extract temperature at the exit of the coffee bed; (b) detailed view.

Table 2
Temperatures of aqueous extract

Heat flux	Initial		Final		Mean	
	Mean	Std.	Mean	Std.	Mean	Std.
400 W	63.0	2.0	95.8	2.9	78.8	1.5
600 W	61.8	2.5	97.7	2.4	80.5	1.3

A preliminary granulometric analysis of the coffee cake, after the brewing process, reveals an almost uniform distribution, with a variation in both average and medians particle size 9% and 14%, respectively, along the water path. This suggests a linear decay assumption for pressure. Taking into consideration both conductive and advective terms in the transport phenomenon, it can be shown that the temperature profile in the cake is slightly concave but, for simplicity, in the transit through the coffee bed, which in our case is 21 mm thick, pressure and temperature profiles can be considered linear with a good approximation. In Fig. 8 pressure and its saturation temperature are compared to the aqueous extract temperature through the coffee bed at the end of the regular extraction phase, where high in-tank pressure is present. During *regular* extraction, water temperature is always lower than saturation temperature, thus the risk of local evaporation in the bed is avoided.

3.3. Mass flow analysis

Applying Darcy's law, in [9] Gianino derives the permeability of the coffee bed from an integral balance, assuming constant ther-

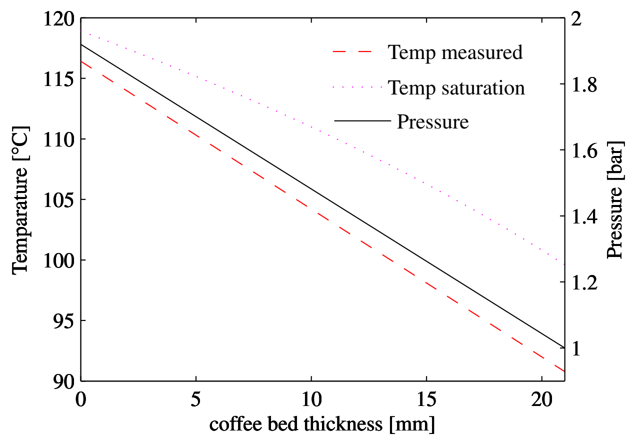

Fig. 8. Temperature profiles in the coffee bed at 120 g of water flowed.

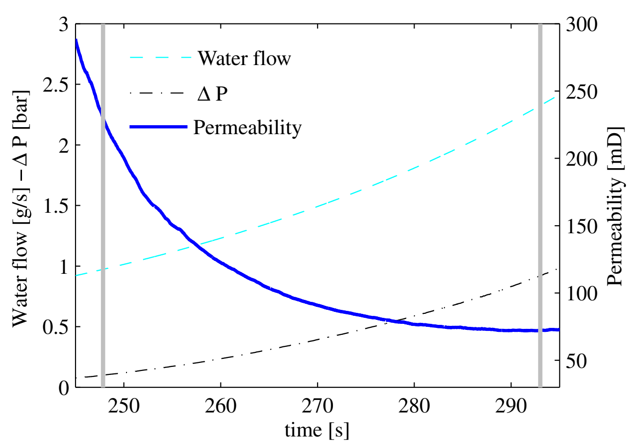

Fig. 9. Time-varying permeability profile.

mophysical properties for water and coffee powder. The value Gianino finds is 2300 millidarcy[1] [mD]. We will show that this is a way too rough approximation.

Again we will consider the limited zone in between the imbibition and strombolian phases (50 g and 120 g of water flowed), where sensible pressure data are obtained, and measurements of the water flow are possible. Darcy's law states:

$$q = -\frac{\kappa}{\mu}\frac{\Delta P}{L}, \tag{5}$$

where $q = \dot{m}/(\rho A)$ is the water volumetric specific flow rate, κ is the permeability of the coffee cake, μ is the dynamic viscosity of water, ΔP is the pressure drop experienced during filtration, and L is the thickness of the bed. During filtration, aromatic substances solve into water, thus changing its rheological properties. Nevertheless, considering pure water as reference point, a time-varying value of κ can be obtained. Fig. 9 depicts the time-varying permeability value for a representative experiment, where the pressure drop has been taken neglecting the head and the friction losses, which give minimal contribution. The value of κ, as expected, gradually decays to an asymptotic condition, which confirms former experiments on *espresso* machines, described in [19]. From Fig. 9 it is evident that typical ranges for κ in the regular extraction region is 70–400 mD, which is more than 10 times lower than the value obtained in [9].

[1] 1 millidarcy = 1×10^{-15} m^2.

4. Conclusions

In this paper, an experimental study of a stove-top coffee maker, known as *moka*, has been described. Despite its quite simple manufacture and functioning, it has been shown that the thermodynamic behaviour of the *moka* device is complex in comparison to other coffee-brewing methods.

The brewing process of *moka* has been divided into two phases. In the *regular extraction* phase liquid–solid extraction occurs, which presents time-varying temperature and water flow rate. In this phase extraction is driven by increasing air–vapour pressure above the water level in the lower tank of the device. The pressure increase is due not only to time increasing flow rate, but also to a non constant rheological behaviour of the coffee cake, whose permeability decreases with time as the coffee undergoes chemical reactions, which in turn decrease its porosity. Moreover, the stove heating power, which is usually constant during the process, exceeds the actual requirement in the final stages of the extraction, when a little fraction of water is still in the tank and consequently its heat capacity diminish, resulting in pressure and flow rate augmentation. An analysis of pressure contributions has highlighted the role played by dry air in the overall phenomenon, which is not negligible as believed by many. The quantity of dry air can influence both temperature and flow rate, thus affecting final extract quality, and it is meant to be the subject of further studies. When water level reaches the end of the funnel, the short-cut between external ambient and air–vapour mixture, which no more drives in-tank water out of the tank, causes an intense evaporation, named *strombolian phase*. In this phase vapour–liquid–solid extraction occurs, with consequent extraction of soluble compounds which are generally noxious for the quality of the final product. The higher the pressure and temperature, the higher the extraction of undesired components.

The detailed measurement of the thermodynamic behaviour of the *moka* which, to the authors' best knowledge, is the first solid experimental attempt of investigation, serves the purpose of an intimate understanding of such a popular, yet mysterious, device, which so much diverges from other coffee-brewing methods, in order to assess possible ways to improve the quality of its product.

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