

Experimental analysis of the Italian coffee pot “moka”

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I describe an experiment involving the moka Italian coffee pot. The pot is an ingenious device for making coffee that uses the liquid-vapor equation of state of the water and Darcy’s law of linear filtration. The filtration coefficient of coffee is measured and a steam engine model is used to estimate the efficiency of the coffee pot. © 2007 American Association of Physics Teachers.

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I. THE COFFEE POT

The “moka,” the most popular coffee pot in Italy, was invented by Alfonso Bialetti in 1933.¹ It uses the pressure of the saturated vapor to push the water through the ground coffee. The original model is made up of three aluminum parts (see Fig. 1): a boiler with a safety valve, a container in the shape of a funnel, and a pot where the coffee collects. The funnel contains the ground coffee and has a base pierced with holes with a spout at its end (see Fig. 2). The funnel is lowered into the boiler and the length of the funnel’s spout is such that it does not touch the boiler’s depth. The funnel and pot are separated by a metal filter and by a rubber gasket (Fig. 3).

Coffee preparation is simple. Pour the water into the boiler so that it is below the safety valve level, put the funnel into the boiler and fill it with ground coffee, screw on the pot, and put the coffee pot on a low flame. After a few minutes the coffee will begin to rise from the spout at the center of the pot until almost all the water has risen into the pot. The coffee is ready when the famous gurgle, caused by the passage of the residual steam from the boiler to the pot, is heard.

II. HOW DOES THE COFFEE POT WORK?

The operation of the moka has been described in several papers.^{2,3} Saturated water vapor is formed in the highest part of the boiler at a pressure of about 2.3 kPa (assuming an ambient temperature of 20 °C)⁴ in equilibrium with the water below. The steam is heated by the flame and its temperature and consequently its pressure increases.⁴ The steam compresses the water below and, when the internal pressure overcomes the external atmospheric pressure, the water rises through the funnel’s spout (see Fig. 4). Then the water, which is pushed by the steam, spurts through the ground coffee into the funnel and is imbued with aromatic oils. It subsequently spurts through the spout in the central part of the pot and gathers at the bottom of it.

The steam pressure necessary to begin this process is equal to the sum of the atmospheric pressure P_0 and the pressure of filtration P_f . Thus, the pressure necessary for water to pass through the ground coffee and the filter is

$$P = P_0 + P_f. \quad (1)$$

According to Darcy’s law of linear filtration²

$$P_f = \frac{m\eta h}{kS\rho t}, \quad (2)$$

where m is the mass, η is the viscosity coefficient of water, ρ is the density of water, h and S are the height and the surface

area of the funnel, t is the time it takes the water to pass through the filter, and k is the filtration coefficient. The latter depends on the characteristics of the filter and funnel and on the porosity and compactness of the ground coffee.

III. MEASUREMENT OF THE THERMAL POWER OF THE STOVE AND THE BOILING POINT OF WATER UNDER ATMOSPHERIC PRESSURE

We first measured the thermal power of the stove, which in our case was a Bunsen burner. The thermal power is the quantity of heat per second supplied by the Bunsen burner. We used a balance with an accuracy of 0.01 g and measured the mass of the boiler for one cup of coffee and found $M_{boiler}=74.1$ g; the mass of the water in the boiler is $M_{water}=67.7$ g.

To reduce the effects of evaporation we covered the boiler with an aluminum sheet. We inserted a NiCr-Ni temperature probe that was connected to an interface and to a computer to determine the temperature of the water poured into the boiler. We used the on-line system Leybold CassyLab.⁵ We then turned on the Bunsen burner, brought the water to a boil, and started the data collection. The temperature of the water increased linearly at a rate of approximately $\vartheta = 0.23$ °C/s and the boiling point was 98.6 °C (Fig. 5), which corresponds to saturated vapor pressure of $P_0 = 96.4$ kPa (Ref. 4) (equal to the atmospheric pressure).

It is remarkable that the boiling point of the water was lower than 100 °C. The measurement was performed in Scicli, a town in the province of Ragusa in the south east of Sicily, at about 120 m above sea level and on a cloudy day. The physics laboratory weather station reported a sea level atmospheric pressure of approximately 98 kPa.

If we take the specific heat of aluminum and water to be $c_{Al}=880$ J/kg °C and $c_{H_2O}=4.2 \times 10^3$ J/kg °C and neglect the heat given to the ambient air, we can estimate the thermal power as

$$P = \frac{Q_{tot}}{\Delta t} = \frac{(c_{H_2O}M_{water} + c_{Al}M_{boiler})\Delta T}{\Delta t} = (c_{H_2O}M_{water} + c_{Al}M_{boiler})\vartheta, \quad (3)$$

which leads to a numerical value of

$$P = 80 \text{ W}. \quad (4)$$



Fig. 1. The moka coffee pot. From the bottom up we can distinguish the boiler with the safety valve, the container in the shape of a funnel where the ground coffee is placed, and the pot containing the coffee.

IV. MEASUREMENT OF THE FILTRATION PRESSURE

To measure the filtration coefficient, we poured the same quantity of water as in the previous experiment into the boiler and put one temperature probe inside the hole of the safety valve and the other temperature probe inside the spout from where the coffee spurts (see Figs. 6 and 7). The former probe allowed us to estimate the temperature inside the boiler.

After turning on the Bunsen burner with the same intensity as before, we started the data collection. The gray triangles in Fig. 8 represent the values of the temperature recorded by the probe inside the safety valve, and the square black points indicate those recorded inside the spout of the pot. Three stages can be distinguished in Fig. 8:

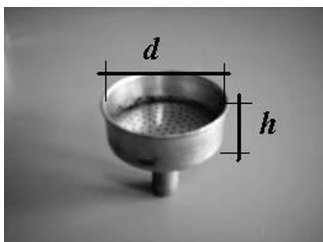


Fig. 2. The details of the funnel.

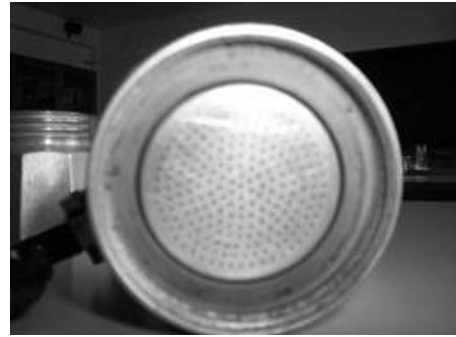


Fig. 3. The details of the pot's lower part showing the filter encircled by the rubber gasket.

- (1) The steam and the water in the boiler are heated for 400 s, with the temperature increasing from 17.3 °C to around 99.5 °C, which corresponds to a saturated vapor pressure of $P_c = 99.6$ kPa.⁴
- (2) The coffee rises into the pot for about 54 s and the boiler temperature is kept uniform.
- (3) The last stage is characterized by the heating of the residual steam, with a sudden increase of the boiler temperature, indicating a large decrease of the heat capacity due to the presence of only steam.

From Fig. 8 we note that in the second stage the temperatures of the valve and the water pouring out of the heater are equal and slightly higher (≈ 1 °C) than the boiling point in the previous experiment (see Fig. 5). This difference means that the pressure P_c reached by the steam in the boiler is higher than the external atmospheric pressure P_0 (see the preceding paragraph), which leads us to estimate that the pressure inside the tightly closed boiler increases to approximately

$$P_f = P_c - P_0 = 99.6 - 96.4 = 3.2 \text{ kPa.} \quad (5)$$

This value represents a reasonable estimate of the overall filtration pressure given by Eq. (2).

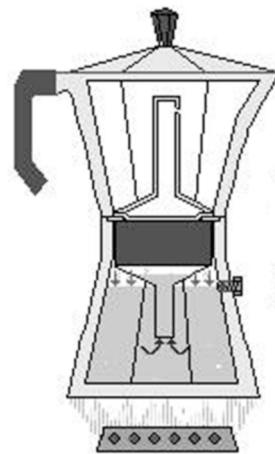


Fig. 4. Pressure of the saturated steam in the highest part of the boiler. It increases with the temperature and, when the pressure equals the sum of the external atmospheric pressure and the filtration pressure, it pushes up the water below, forcing it to go through the filter until it gathers in the pot above (Ref. 3).

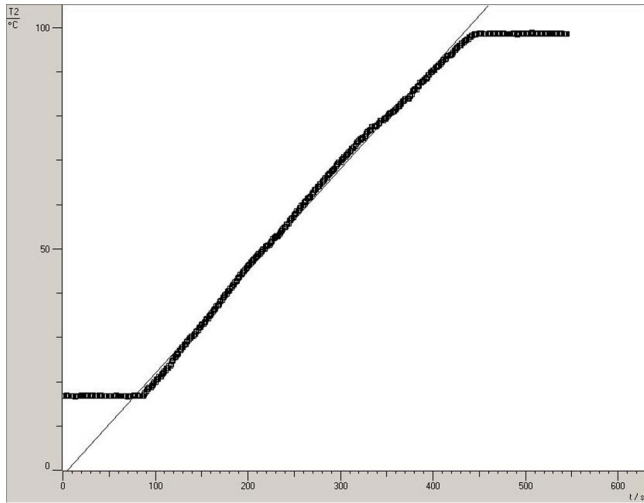


Fig. 5. The time-temperature diagram for the measurement of the thermal power. The temperature of the water increased from 16.8 °C to the boiling point at a rate of approximately 0.23 °C/s.

V. MEASURE OF THE FILTRATION COEFFICIENT OF COFFEE

To estimate the filtration coefficient of the ground coffee we repeated the previous experiment using the same experimental conditions, except with no ground coffee in the special funnel container. As shown in Fig. 9, the three stages can again be distinguished, but, although the first stage has a



Fig. 6. Experimental arrangement of the temperature probes (see text).

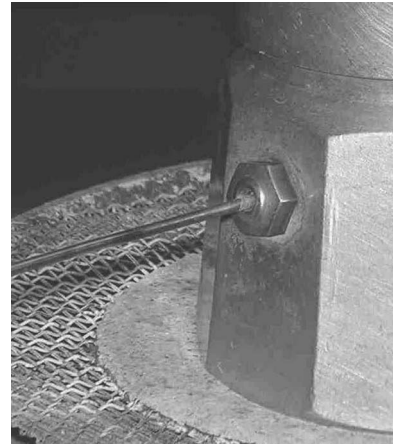


Fig. 7. The arrangement of the temperature probe inside the safety valve hole.

duration of about 400 s as before, the second, in which the steam expands and takes up the water, lasts only 17 s. This reduction occurs because the water does not encounter the ground coffee when it goes up the pot.

The boiling point reached in the boiler is almost the same with or without the ground coffee in the funnel. Therefore, the ground coffee does not significantly increase the boiling temperature.

We can calculate the filtration coefficient of the ground coffee by applying Eq. (2):

$$k = \frac{m \eta l}{P_f S \rho t} = \frac{4m \eta h}{p_f \pi d^2 \rho t}, \quad (6)$$

where d is the diameter and h is the height of the funnel (see Fig. 2). If we let $t_c = 54$ s and $t_{nc} = 17$ s equal the time for the water to go into the pot with and without the ground coffee

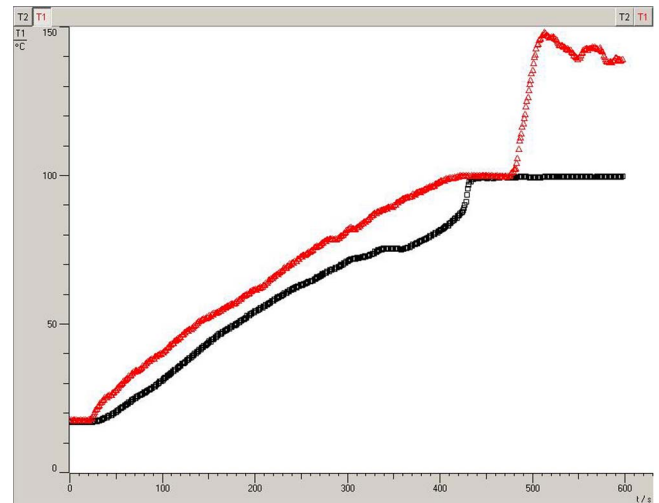


Fig. 8. The time-temperature diagram for the preparation of coffee. The gray triangles are values of the temperature recorded by the probe inside the valve. The black points represent the values of the temperature recorded inside the spout from where the coffee spurts. Three stages can be distinguished from the gray triangles: in the first stage, the steam and the water in the boiler are heated for 400 s, with the temperature increasing from 17.3 °C to around 99.5 °C; in the intermediate stage, about 54 s long, the coffee rises into the pot and the boiler temperature is kept uniform; in the last stage, the residual steam is heated.

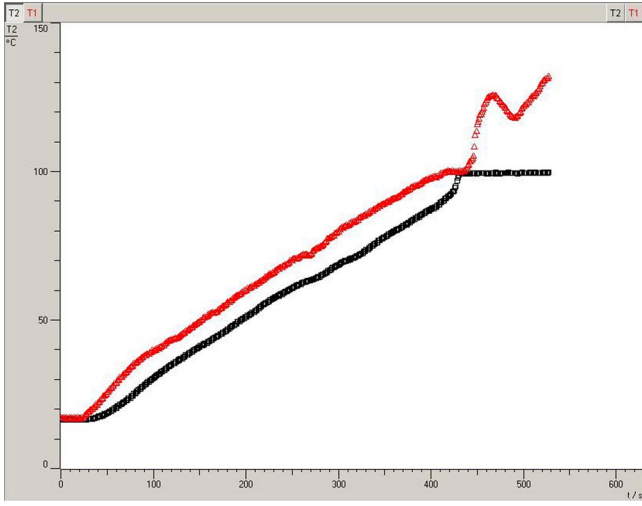


Fig. 9. The time-temperature diagram of the coffee pot without the ground coffee. We can distinguish the same three stages as Fig. 8; the first and the last stages are substantially equal while the intermediate stage is only 17 s long.

in the funnel, we see that the filtration coefficient k_{coffee} is given by subtraction of the filtration coefficients without (k_{nc}) and with (k_c) ground coffee:

$$k_{coffee} = k_{nc} - k_c = \frac{4m\eta h}{p_f \pi d^2 \rho t_{nc}} - \frac{4m\eta h}{p_f \pi d^2 \rho t_c} = \frac{4m\eta h}{P_f \pi d^2 \rho} \left(\frac{1}{t_{nc}} - \frac{1}{t_c} \right). \quad (7)$$

We used a calliper of 0.05 mm accuracy and measured $d=42.7$ mm and $h=13.9$ mm. We estimate that the viscosity of water at a temperature of 99.5 °C is equal to⁶

$$\eta = \eta_L \exp \left[\frac{2W_S}{kT} \right] = 1.7 \times 10^{-6} \exp \left[\frac{2 \times 1.30 \times 10^{-20}}{1.38 \times 10^{-23} \times 372.5} \right] \cong 0.27 \text{ mPas}. \quad (8)$$

For a water density of $\rho=958$ kg/m³,⁷ we find, using Eq. (7), the value of the filtration coefficient given by

$$k_{coffee} = 2.3 \times 10^{-8} \text{ cm}^2, \quad (9)$$

which corresponds to the typical value of sandy silt or clean sand.⁸

VI. EFFICIENCY OF THE COFFEE POT

The coffee pot can be considered as a thermal engine that withdraws heat Q_P from the flame to accomplish useful work L_U with an efficiency equal to

$$r = \frac{L_U}{Q_P}. \quad (10)$$

The useful work is accomplished by the pressure of the steam that is necessary to bring the water from the boiler up to the pot through the filter. To calculate the work done by the pressure, a thermodynamic analysis is necessary of the coffee pot. The latter can be considered as a thermal steam

engine that uses the following cycle:

- (1) Uniform volume compression. The steam has the ambient temperature and a pressure equal to the saturated steam pressure normally found at that temperature (state A). The addition of heat to the steam raises the temperature, keeping the volume uniform until it reaches a pressure sufficient to bring the water up to the pot. Based on our measurements, $T_A=17.3$ °C, with a corresponding pressure of the saturated steam of around 1.9 kPa and a final pressure of 99.6 kPa.⁴ Therefore, during the heating stages, the saturated steam rises to a pressure of $\Delta P = 99.6 - 1.9 = 97.7$ kPa.
- (2) Isobaric expansion. During this process the water changes phase from liquid to vapor, keeping the pressure constant during the expansion. The boiling water increases the amount of steam, which increases the volume, but the pressure remains essentially constant. In this stage the added steam occupies the volume of the water, which is pushed into the pot. We assume that the variation of the steam volume is $\Delta V=67.70$ cm³, which is equal to the volume of the water pushed out of the boiler.
- (3) Pressure decrease at constant volume. After the preparation of the coffee's drink, we turn off the stove, and the steam inside the boiler begins to decrease its temperature and, consequently, its pressure very slowly. This process occurs at constant volume.
- (4) Isobaric compression. The initial situation is restored, filling up the boiler again by an isobaric process.

The useful work can be estimated by a calculation of the area included in the cyclical transformation:

$$L_U = \Delta p \Delta V = 6.61 \text{ J}. \quad (11)$$

The quantity of heat withdrawn by the Bunsen beaker, neglecting the energy wasted in the ambient air, is equal to the thermal power in Eq. (4) multiplied by the time necessary to prepare the coffee, $\Delta t=455$ s; this time is the sum of the time of heating and the time of the steam expansion that pushes the water into the pot. We obtain

$$Q_P = P \Delta t = 80 \times 455 = 36.4 \times 10^3 \text{ J}. \quad (12)$$

The efficiency of the coffee pot is therefore

$$\eta = \frac{L_U}{Q_P} = 1.8 \times 10^{-4} \cong 0.02 \%. \quad (13)$$

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