

PAPERS | AUGUST 01 2021

The force required to operate the plunger on a French press

Fabian B. Wadsworth; Caron E. J. Vossen; Michael J. Heap; Alexandra Kushnir; Jamie I. Farquharson; Diana Schmid; Donald B. Dingwell; Lukas Belohlavek; Mila Huebsch; Lucille Carbillet; Jackie E. Kendrick




Am. J. Phys. 89, 769–775 (2021)

<https://doi.org/10.1119/10.0004224>



PHYSICS TODAY
WEBINARS: EDUCATION WORKSHOP SERIES



Free virtual interactive workshops for everyone with a passion for teaching physics

Inspiring Students to Think Like Physicists with Hands-On Data Collection and Real-World Modeling

The force required to operate the plunger on a French press

Fabian B. Wadsworth,^{1,a)} Caron E. J. Vossen,² Michael J. Heap,³ Alexandra Kushnir,⁴ Jamie I. Farquharson,⁵ Diana Schmid,² Donald B. Dingwell,² Lukas Belohlavek,² Mila Huebsch,² Lucille Carbillet,³ and Jackie E. Kendrick⁶

¹Earth Science, Durham University, Science Labs, Durham DL1 3LE, United Kingdom

²Earth and Environmental Science, Ludwig-Maximilians-Universität, Theresienstrasse 41, 80333 Munich, Germany

³CNRS, Institut de Physique du Globe de Strasbourg, Université de Strasbourg, UMR 7516, F-67000 Strasbourg, France

⁴CNRS, École et Observatoire des Sciences de la Terre, Université de Strasbourg, UMS 830, F-67000 Strasbourg, France

⁵Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, Florida 33149-1031

⁶School of Geosciences, University of Edinburgh, Grant Institute, Edinburgh, EH9 3FE, United Kingdom

(Received 15 December 2020; accepted 19 March 2021)

The French press is a popular device for brewing coffee, comprising a cylindrical beaker—or “jug”—fitted with a lid and plunger with a fine wire mesh filter. The plunger is used to drive the solid coffee particles to the bottom of the jug, separating these grounds from hot liquid above. When using the French press in this way, a growing permeable pack of ground coffee is pushed through hot water by applying force to the plunger. We use a combination of kitchen-based and laboratory experiments to determine the force required to push on the plunger as a function of the speed of the plunger and the mass of coffee used. We calculate that for the recommended preparation method, the maximum force is 32 N to complete the pressing action in 50 s. We propose that home coffee preparation provides a fun, low-cost, and relatable learning opportunity for students and for those who are interested in coffee science. © 2021 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

<https://doi.org/10.1119/10.0004224>

I. INTRODUCTION

There are many ways to prepare a cup of coffee. The processes that control extraction and flavor profiles in coffee can be divided into chemical and thermodynamic (reaction) processes and hydrodynamic (flow) processes.^{1–6} In the simplest terms, the chemical and thermodynamic processes control reaction rates and the physico-chemical extraction dynamics local to the particles; while the hydrodynamic processes determine the percolative advection of water through the coffee and overall “contact time.”^{4,5} Coffee preparation is a nuanced science precisely because extraction and flavor are due to these processes being coupled.⁴ The pursuit of good coffee can therefore be a complex endeavor, depending on a great many parameters.^{3,7}

Developments in the technology of coffee have focused on the preparation of espresso coffee, including brew methods using espresso machines⁷ and stove-top moka pots.^{1,2} There is less research into what may be perceived as simple coffee preparation methods, including pour-over, drip coffee,^{4,5} and the French press (or *cafétière-à-piston*) method. In this paper, we focus our attention on the latter system, which is one of the most popular methods of domestic coffee preparation and among the least environmentally impactful.⁸

The most common French press brew method is one in which the plunger is used to force the suspended coffee down out of the brewed coffee. This process is a percolation problem involving pressing a filter plate submerged in hot water onto a growing pack of coffee grounds and forcing this assembly through the fluid. (We note that in the reference frame of the plunger, this is equivalent to saying that the fluid is pushed through the assembly.) The main objective of

this work is to determine the force required to operate the plunger on a French press and to identify the dominant factors that affect its magnitude. From a pedagogic point of view, the analytical and relatively simple nature of our result makes this household problem an excellent way of engaging people in everyday use of mathematics and physics to estimate quantities of genuine general interest. While we do not attempt to answer the subjective question “how do you make the perfect coffee?,” our hope is that our article will help coffee drinkers discuss the physics of coffee preparation in a nuanced and quantitative way.

II. MATERIAL CHARACTERIZATION AND METHODS

We use a 1-liter glass French press with a standard vertical plunger (Fig. 1(a)). To prepare coffee using this French press, we used the plastic scoop provided with the device to measure out an aliquot of dry coffee. The heaped scoop holds approximately 6.75 g of loosely packed coffee, and eight scoops are recommended, resulting in 54 g total recommended coffee mass in the French press. We varied the mass of coffee to achieve different results, ensuring we encompass the recommended dose. We measured the mass of the coffee used before placing it in the bottom of the French press, and we then poured just-boiled water on top to the fill line at 1-liter volume. Once filled, we placed the plunger into the pot, and lowered the filter plate until it was just above the liquid fill level. Before depressing the plunger, we waited 4 or 5 min—the recommended brew time interval.

Using the preparation procedure described above, we performed two types of experiments: (1) at home experiments

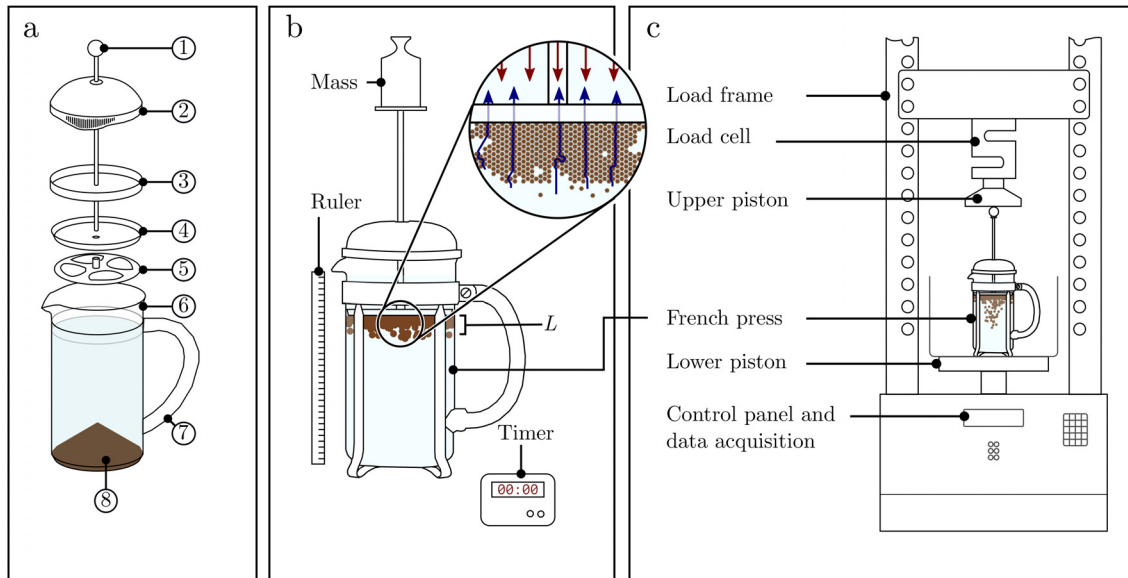


Fig. 1. Schematic representation of the apparatus. (a) The Bodum™ 1 litre French press comprises the following elements: (1) plunger rod and handle; (2) lid; (3) spring disk strainer plate; (4) filtration mesh; (5) base plate or retaining disk; (6) glass coffee jug; (7) handle; and (8) ground coffee. (b) The French press from (a) but with a flat-topped plunger used for the at-home experiments. Inset: a cartoon of the plunger moving down (red arrows indicate the direction) and water moving up between the coffee grains as a result (blue arrows indicate the direction of water flow). (c) The French press loaded in the LoadTracII vertical uniaxial press between two pistons (or platens).

and (2) laboratory validation experiments. The aim of this two-step approach is to first explore an easy-to-replicate home science experiment, and then validate the experiments in the lab to provide a robust further test of the simple model presented here. The experimental designs are shown in Fig. 1.

A. Coffee grind radius and texture

The coffee we selected is a commercial coarse-grind variety, designed for use in a French-press. This type of coffee tends to have grains that are larger and more polydisperse in size than espresso-grade ground coffee.⁴ Figure 2(a) shows the particle size distribution measured using a Beckman Coulter™ LS 230

laser refraction particle size analyzer with a measuring range 0.374–2000 μm . Although the mean particle radius can be computed to be $104 \pm 3 \mu\text{m}$, the distribution is very polydisperse. It is actually bimodal with two characteristic grain radii of 50 μm and 300 μm . The particle size was confirmed using an optical microscope in reflected-light mode to examine the coffee grain radius. We sprinkled a small amount of representative dry coffee 1-grain thick on a microscope slide and used a Leica® DM4 B optical microscope with a calibrated on-screen measurement tool to identify the length of 112 coffee grains selected randomly on the slide. The mean particle radius was $102 \pm 6 \mu\text{m}$, consistent with the results from the particle size analyzer.

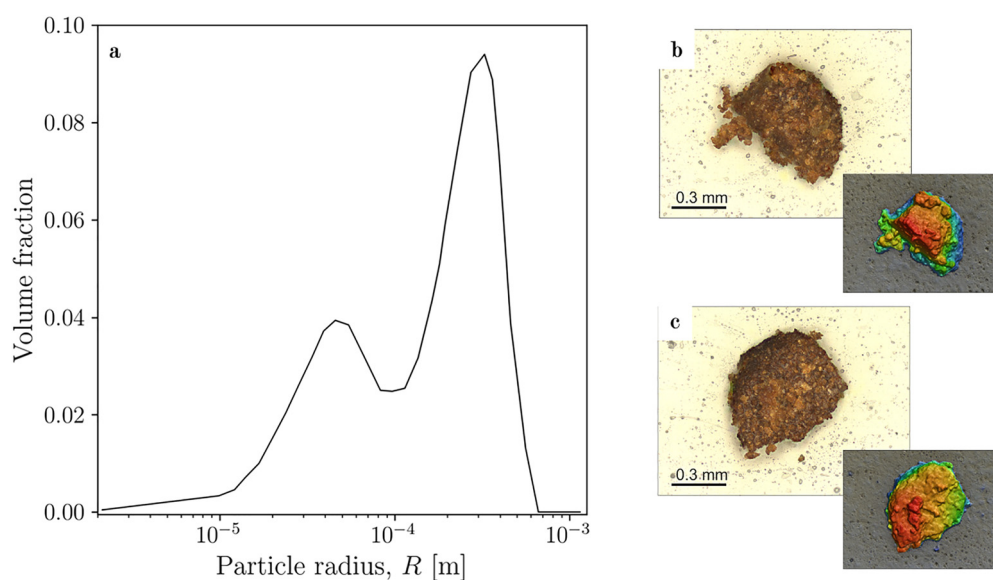


Fig. 2. Characteristics of the ground coffee used in the experiments. (a) A particle radius distribution of the coffee particles cast as a volume fraction as a function of particle radius (25 bins per log unit). (b) and (c) Laser scanning microscopy images of two different individual coffee grains of representative radius. Insets: surface elevation rendering using an arbitrary color scale (the blue-to-red color scale approximately represents a distance of 0.5 mm).

To assess the extent to which grain swell is a factor in our experiment, we measured the grains' radius before and after they were immersed in hot water. The surface texture of 91 coffee grains was observed, using a Keyence VK-X 1000 laser scanning microscope with a spatial resolution of $\sim 0.1 \mu\text{m}$. We found that the grains contained intra-grain porous features, consistent with the previous work that showed that intra-grain porosity can be a relevant factor in coffee preparation.⁴ In Fig. 2, we show images of individual dry coffee grains, captured using the laser scanning microscope. As can be seen, the grains have an aspect ratio of approximate unity. Post-experimental coffee grain radii were within 3% of the pre-experiment values, implying that swelling was negligible. Moreover, using helium pycnometry, we determined the coffee grain density to be $\rho_c = 480 \text{ kg m}^{-3}$, which is less than the density of hot water ρ_f , and therefore coffee grains are initially buoyant.

B. At home experiments

In our home experiments, during a 5-min brew time, a floating coffee pack with discernible top and bottom interfaces developed at the top of the liquid under the plunger. We measured the thickness of this coffee pack using a ruler with millimeter accuracy. For our home experiments, the plunger system had a flat-topped handle (Fig. 1(b)), meaning that we could place objects of known mass onto the plunger system. We performed repeat tests with 0.5 and 1 kg masses on the plunger. Once the masses were placed on its flat-topped handle, the plunger moved downward. Throughout the plunger's motion, we measured the vertical displacement with time, using a ruler and a stopwatch. Uncertainties on the time are dominated by user error associated with logging the displacement and time simultaneously, and are estimated to be maximum 1 s. The displacement and time measurements were used to compute the plunger velocity.

C. Laboratory validation

In the laboratory, we used a mechanical testing apparatus to directly measure the force required to operate the plunger. For these mechanical tests, after the boiling water was

poured onto the coffee, we immediately placed the French press into a mechanical GeocompTM LoadTracII uniaxial press such that the top of the plunger was in contact with the top piston (Fig. 1(c)). Surrounding the French press was a transparent plastic container used as a safety precaution in case the French press leaked or ruptured during the experiment. For these experiments, we were particularly interested in the force required to maintain a constant plunger velocity. Hence, after a 4-min brew-time, the bottom platen was raised at a constant velocity, which pushed the plunger downward. The force and the vertical displacement of the bottom platen were measured continuously using a load cell and a linear variable differential transducer (LVDT), respectively. These parameters were monitored in real-time using the LoadTracII's data-acquisition system with an acquisition rate of 10 Hz. The evolution of the thickness of the coffee pack (layer) during plunging was monitored using optical video recording via a smartphone. We performed additional experiments using the French press with no coffee, no water, and neither coffee nor water, to check for the force associated with overcoming the frictional resistance between the snug-fitting plunger plate and the glass, as well as with the percolation of water through the filtration plate in the plunger. We measured the temperature of the water throughout, using a digital infrared laser thermometer. We found that the water temperature dropped from 97°C to around 75°C over the 4-min brewing time and the experimental time that followed. In this temperature range, the physical properties of water, such as viscosity or density, scarcely change,⁹ and, in the following, we neglect those variations.

The porosity ϕ of the coffee grain pack was determined using the bulk density ρ of the sample (determined using the total coffee mass m and dimensions of the coffee pack), and the solid density ρ_c of the coffee, measured by the pycnometry: $\phi = 1 - \rho/\rho_c$.

III. RESULTS AND ANALYSIS

In this section, we detail the results of our at-home and laboratory experiments. We stress that the at-home experiments are most suitable for use in classrooms or by interested

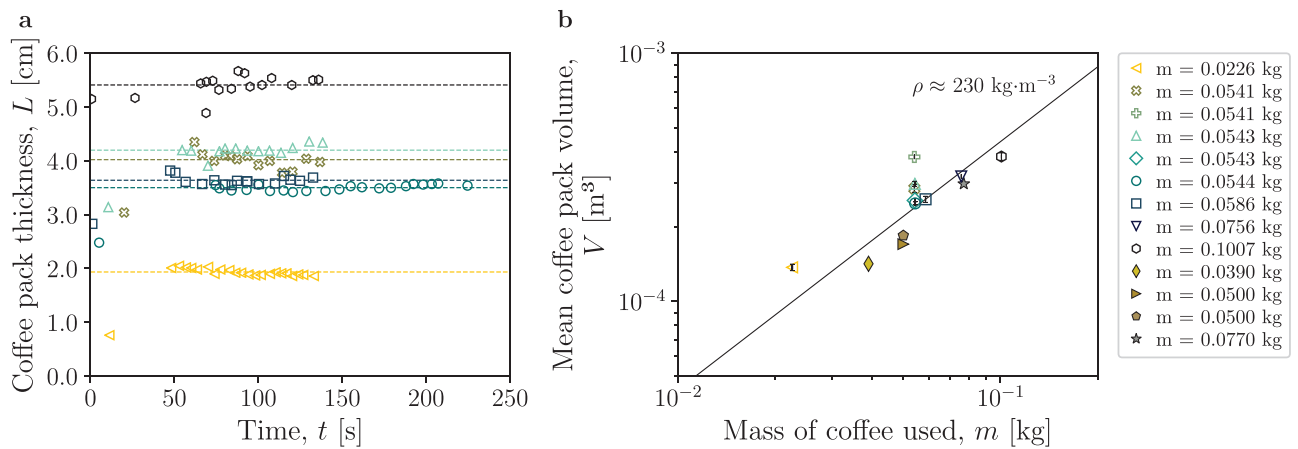


Fig. 3. The coffee pack characteristics. (a) The thickness of the growing coffee pack assessed from videos captured during the laboratory experiments for different ground coffee masses. Time is measured from when the hot water is poured into the jug. The horizontal dashed lines represent the approximate steady-state value of average coffee pack length. (b) The calculated volume $V = \pi B^2 L$ as a function of the mass of coffee used, m . The average coffee pack density ρ is given by the solid line and is approximately consistent across all French press experiments conducted here. We use unfilled symbols for the laboratory experiments and filled symbols for the at-home experiments. The error bars are smaller than the data points in all cases.

coffee enthusiasts. In contrast, the laboratory experiments represent a validation of the at-home experiments for the purposes of this article.

A. The coffee pack

During the 4 or 5 min brew time, coffee rises to the top of the water, and rests beneath the plunger. Most of this “coffee pack” is located within a thickness L from the plunger’s base plate. In the at-home experiments, we measure this thickness prior to operating the plunger and wait an extra minute for the coffee pack to form fully (5 min brew time). In the laboratory experiments, we extract from the videos the thickness of the pack as the plunger moved down the liquid. When the hot water is poured into the jug, the coffee pack thickness progressively increases before it stabilizes and is then constant to within $\pm 3\%$ (Fig. 3(a)). In both experiment types, we find that the equilibrium coffee pack thickness is linearly related to the dry mass of coffee m in the jug. Indeed, as can be seen from Fig. 3(b), the coffee pack volume $V = \pi B^2 L$ (where $B = 4.75$ cm is the jug’s internal radius) scales linearly with m . Taking the bulk density of the coffee pack to be $\rho = m/V$, we find $\rho \approx 230$ kg m $^{-3}$ across all French press experiments. In turn, we can use this to calculate the average porosity of the coffee pack as $\phi \approx 0.53$ (see Sec. II C).

B. At-home experiments

In our at-home experiments, we find that the displacement of the plunger d varies linearly with time t , such that the rate $\langle u \rangle = \Delta d / \Delta t$ is approximately constant, and depends both on the mass applied and on the mass of ground coffee (Fig. 4). Phenomenologically, there is clearly a trade-off between increasing the mass applied to the plunger, which has the effect of increasing the slope of $d(t)$ (increasing $\langle u \rangle$), and increasing the mass of coffee used, which has the effect of decreasing the slope of $d(t)$ (decreasing $\langle u \rangle$). To analyze these results quantitatively, we fit a linear regression to each dataset, to determine the flow velocity for each coffee mass and applied mass. As can be seen from Fig. 4, at-home experiments had flow velocities of the order of $\langle u \rangle \approx 0.05$ cm s $^{-1}$.

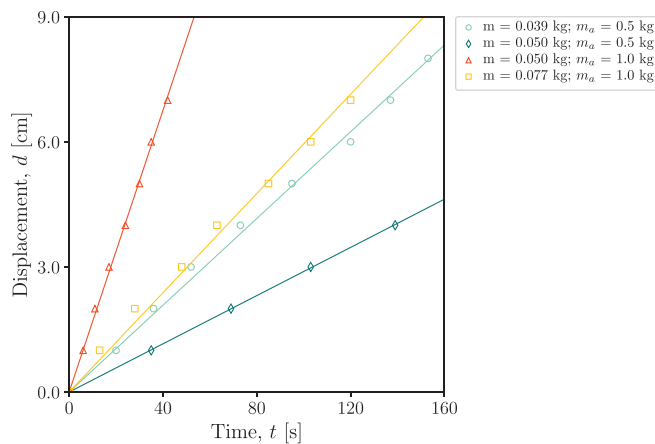


Fig. 4. The displacement d of the plunger with time t during at-home experiments for which the mass of coffee m and the mass applied to the plunger m_a are both given.

C. Using a laboratory press

Here, we analyze the results of the experiments in which a LoadTracII uniaxial press was used to measure the force F need to move the plunger at constant velocity $\langle u \rangle$. In Fig. 5, we show the raw output force with displacement for two coffee masses: the recommended $m = 0.054$ kg, and an extreme value of $m = 0.1$ kg. We see that the force quickly equilibrates to a steady state value. In Fig. 5, we indicate the steady state force with a horizontal dashed line, and the standard deviation corresponding to that steady state with grey areas. It is clear from this result that the force required to operate the plunger depends on the mass of coffee used in the coffee preparation. For the recommended eight scoops of coffee ($m = 0.054$ kg), the steady state force is $F \approx 12.5$ N to operate the plunger at a velocity of $\langle u \rangle \approx 0.1$ mm s $^{-1}$.

IV. A COFFEE PERCOLATION SCALING

In both the at-home and laboratory experiments, we observe that a constant force results in a constant speed of the plunger. Here, we seek to explain that relationship. The force required to operate the plunger can be broken down into components: $F = F_h + F_m + F_B + F_f - gm_p$, where F_h is the hydrodynamic force required to squeeze the hot water through the pack of coffee, F_m is the force required to squeeze the hot water through the plunger’s mesh, F_B is the buoyancy force due to the density difference between the coffee particles and the water, F_f is the frictional force between the plunger and the glass sides of the French press, m_p is the mass of the plunger itself, and g is the acceleration due to gravity. By testing the French press with hot water in it but without coffee, one can find that the operation of the plunger requires substantially less force than when coffee is present, such that we suggest the combination of F_m , F_f , and gm_p are negligible compared with the other components, and

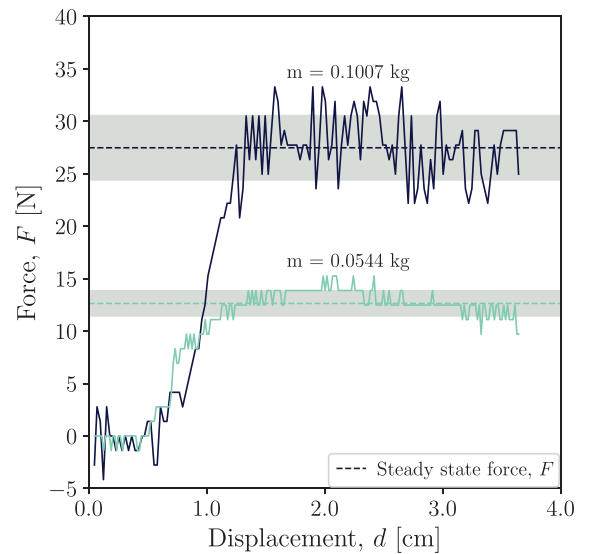


Fig. 5. The force F required to operate the French press as a function of displacement d for two representative laboratory plunger experiments, both conducted at the same pressing velocity $\langle u \rangle \approx 2.8 \times 10^{-4}$ m s $^{-1}$, for two different masses of coffee. The green curve is for the recommended eight scoops of coffee. The horizontal lines represent the average steady state force F , with the standard deviation quoted as the grey area about that force (used for error analysis in subsequent plots).

for this reason we neglect these contributions. This results in $F = F_h + F_B$.

Over short timescales, the coffee particles are not saturated with water, and are buoyant in hot water. Hence, the overall buoyancy force F_B arises because $\rho_c < \rho_f$, the density of the water at the temperature of pressing. The buoyancy force exerted by a single coffee grain F_b can be estimated by using Stokes's formulation¹⁰

$$F_b = (\rho_f - \rho_c)g \frac{4}{3}\pi R^3. \quad (1)$$

As the coffee grains are approximately spherical (cf. Fig. 2), then $4\pi R^3/3 = V_p$, where V_p is the volume of a single coffee particle. The total buoyancy force F_B is then the sum of the contributions of all the grains in the French press $F_B = F_b n$, where n is the number of grains. Since the porosity of the bulk coffee pack is

$$\phi = 1 - \frac{nV_p}{V}, \quad (2)$$

where V is the volume of the coffee pack, Eq. (1) can be rearranged to compute F_B ,

$$F_B = nF_b = (\rho_f - \rho_c)Vg(1 - \phi). \quad (3)$$

Equation (3) shows that the total buoyancy does not depend on the grain radius of the coffee, and instead depends on the total amount of coffee in the pack. A rough calculation shows that the buoyancy force is negligible: if we assume that $\phi \approx 0.5$, $V \approx 3 \times 10^{-4} \text{ m}^3$ (justified in Sec. III), and $\rho_f \approx 1000 \text{ kg m}^{-3}$, we find that for the recommended mass of coffee, $F_B = \mathcal{O}(10^{-1}) \text{ N}$ (where we use \mathcal{O} to denote “of order”), which is negligible compared with the pressing force. Therefore, we can conclude that F_h is the dominant contribution to the force felt when operating the French press.

In order to determine F_h , let us examine the fluid's response to a given pressure gradient ∇P , as given by Darcy's law¹¹

$$\nabla P = -\frac{\mu_f}{k} \langle u \rangle, \quad (4)$$

where $\langle u \rangle$ is the average fluid velocity, μ_f is the fluid viscosity, and k is the permeability of the coffee pack. Darcy's law describes the laminar flow of fluid through a permeable medium. In our case, water flows through coffee grounds, so that the Reynolds number is sufficiently low for the flow to be considered laminar. That is, viscous forces dominate over inertial effects. The pressure gradient across a porous medium, the resultant average fluid velocity, and the fluid viscosity are variables that can be controlled or measured. These variables are related via the permeability, which can be thought of as conceptually related to the efficiency with which fluid can move through the pore spaces from one side of the system to the other.

For our system in which the fluid is an incompressible liquid, the left-hand-side of Eq. (4) can be cast as $\Delta P/L$, where ΔP is the liquid pressure driving flow and L is the coffee pack thickness. If we assume that $\Delta P = F_h/A$, where $A = \pi B^2$ is the cross-sectional area of the filter plate, and that $\langle u \rangle$ is equivalent to the velocity of the plunger, then Eq. (4) can be written as

$$\frac{F_h}{AL} = \frac{\mu_f}{k} \langle u \rangle. \quad (5)$$

Noting that AL is the coffee pack volume $V = m/\rho$

$$F \approx F_h = \frac{\mu_f m}{k \rho} \langle u \rangle. \quad (6)$$

Equation (6) is then a governing equation to be tested herein to determine the value of k . Since $F \approx F_h$, Eq. (6) allows a user to compute the force required to push the plunger downward at a constant velocity $\langle u \rangle$.

V. THE PERMEABILITY OF PACKED COFFEE

In Sec. IV, we left k as an unknown parameter, which precludes direct use of Eq. (6) for forward-calculations of F . Here, we determine k both directly and indirectly. First, we can use the results from the at-home (Fig. 4) and laboratory experiments (Fig. 5) to compute the permeability of the coffee pack during plunging. For the at-home experiments, since $F = gm_a$, we can rearrange Eq. (6) to determine $k = \langle u \rangle m \mu_f / (g \rho m_a)$. Each French press experiment corresponds to a given value for $\langle u \rangle$ (Fig. 4), which can, in turn, be used for an approximate determination of the permeability of the coffee pack, assuming that the plunging resulted in steady-state flow through the coffee pack. For the laboratory experiments, we can take the equilibrium force (Fig. 5) for each experiment and the set velocity of the press apparatus. In Fig. 6, we plot the equilibrium force, cast as a pressure gradient $\nabla P = \Delta P/L = F/(AL)$ for all experiments. The fit in Fig. 6 is Darcy's law (Eq. 4), where the only fit parameter is k . Using a least squares regression method,¹² we determine that $k = (1.34 \pm 0.10) \times 10^{-12} \text{ m}^2$. The linear relation between $\langle u \rangle$ and the pressure gradient confirms that the flow is laminar throughout the experiment. Moreover, it is also a clear indication that the relevant velocity is the average velocity $\langle u \rangle$ of the water, and not the local velocities, which are both larger and highly variable in such a porous medium.

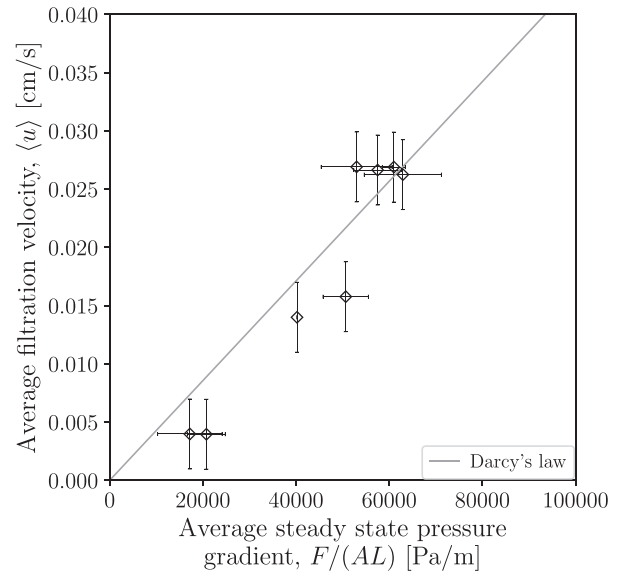


Fig. 6. The filtration velocity $\langle u \rangle$ as a function of the calculated pressure gradient driving the flow $F/(AL)$. The solid curve is the fit to Darcy's law with k as a free parameter. Here, $k = (1.34 \pm 0.10) \times 10^{-12} \text{ m}^2$, where the error is computed from the goodness of fit of Darcy's law to the data.

It is important to note that the measurements we have made of k are specific to the coffee particle size distribution used here (Fig. 2(a)). If that distribution were replicated, then anyone could use the permeability we determine to find the force required to operate the French press (via Eq. (6)). However, in order to generalize this result so that any coffee could be used, we have to find a model that relates k to the particle sizes in the ground coffee. To do this, we compare our results for k against a form of the Kozeny-Carman model¹³ that has been shown to provide a reasonable description of the permeability of ground coffee¹⁴

$$k = \frac{\phi^3 R_x^2}{C(1 - \phi)^2}, \quad (7)$$

where C is a constant and R_x is a characteristic lengthscale. For packs of spheres, $R_x = R$. However, for packs of rough particles, such as coffee packs, R_x is taken to be the Sauter radius.¹⁴ The Sauter radius can be thought of a characteristic lengthscale for rough particles. While we did not measure the Sauter radius for our coffee, we note that our mean radius $R = 104 \mu\text{m}$, the shape of the particle size distribution studied here (Fig. 2(a)), and the particle sphericity (see particle shape in Figs. 2(b) and 2(c)) are all within measurement error of a coffee studied by Corrochano *et al.*¹⁴ Therefore, we take their Sauter radius, which they measure to be $R_x \approx 80 \mu\text{m}$. Previous work has suggested that $C = 180$, although we highlight that this is usually an empirical fit-parameter.¹⁴ Comparing this prediction with our experimental data shows reasonable agreement (Fig. 7).

VI. TAKE-HOME MESSAGES FOR HOUSEHOLD USE

We broke down the problem of operating the plunger on a French press into nested physical problems: (1) the buoyancy force of coffee against the plunger and (2) the laminar contributions to the force required to push water through the coffee and plunger system. We show that the buoyancy force contribution is relatively minor. Therefore, to arrive at an order-of-

magnitude force estimate, we can use Eq. (6). Using the inputs of $m = 0.054 \text{ kg}$, $\rho = 230 \text{ kg m}^{-3}$ (average coffee pack density; Fig. 3), $\mu_f = 8.9 \times 10^{-4} \text{ Pa s}$ (viscosity of water at brew temperature), and the apparent permeability $k \approx 1 \times 10^{-11} \text{ m}^2$ (Fig. 7), we can estimate F for any plunging velocity $\langle u \rangle$. If we assume that the brewer would want to complete the plunging action gently in 60 s, and that the distance the plunger must travel is around 10 cm, we can compute $\langle u \rangle = 17 \text{ mm s}^{-1}$. This results in a steady-state force of around 32 N (or approximately 3.2 kg equivalent mass applied by the human hand). For a smaller French press (smaller B), this force would be lower simply because m would be smaller. Localisation of flow through channels formed in the coffee pack is a common feature of large forces and may reduce the force required to operate the French press.

We propose that the physics of the French press is an accessible problem that can lead to an understanding of percolative flow,^{15,16} the wider suite of problems associated with the physics of coffee,¹⁷ and could inspire students to apply physics to quantitative studies of the world around them.

ACKNOWLEDGMENTS

The authors are grateful to Ed Llewellyn and Jason Coumans for insightful coffee discussions and to Pauline Harlé for her assistance with aspects of the experimental campaign. Thanks go to anonymous reviewers.

^{a)} Author to whom correspondence should be addressed. Electronic mail: fabian.b.wadsworth@durham.ac.uk

¹L. Navarini, Enrico Nobile, F. Pinto, A. Scheri, and F. Sugli-Liverani, "Experimental investigation of steam pressure coffee extraction in a stove-top coffee maker," *Appl. Therm. Eng.* **29**(5-6), 998–1004 (2009).

²C. Gianino, "Experimental analysis of the Italian coffee pot 'moka,'" *Am. J. Phys.* **75**(1), 43–47 (2007).

³A. Illy and R. Viani, Eds., *Espresso Coffee: The Science of Quality* (Academic Press, Cambridge, MA, 2005).

⁴K. M. Moroney, W. T. Lee, F. Suijver, and J. Marra, "Modelling of coffee extraction during brewing using multiscale methods: An experimentally validated model," *Chem. Eng. Sci.* **137**, 216–234 (2015).

⁵Kevin M. Moroney, William T. Lee, Stephen B. G. O'Brien, Freek Suijver, and Johan Marra, "Coffee extraction kinetics in a well mixed system," *J. Math. Indus.* **7**(1), 1–19 (2016).

⁶K. M. Moroney, W. T. Lee, S. O. Brien, F. Suijver, and J. Marra, "Asymptotic analysis of the dominant mechanisms in the coffee extraction process," *SIAM J. Appl. Math.* **76**(6), 2196–2217 (2016).

⁷Michael I. Cameron, Dechen Morisco, Daniel Hofstetter, Erol Uman, Justin Wilkinson, Zachary C. Kennedy, Sean A. Fontenot, William T. Lee, Christopher H. Hendon, and Jamie M. Foster, "Systematically improving espresso: Insights from mathematical modeling and experiment," *Matter* **2**(3), 631–648 (2020).

⁸Eva Brommer, Britta Stratmann, and Dietlinde Quack, "Environmental impacts of different methods of coffee preparation," *Int. J. Consumer Stud.* **35**(2), 212–220 (2011).

⁹Lawrence Korson, Walter Drost-Hansen, and Frank J. Millero, "Viscosity of water at various temperatures," *J. Phys. Chem.* **73**(1), 34–39 (1969).

¹⁰R. Clift, J. R. Grace, and M. E. Weber, *Bubbles, Drops, and Particles* (Dover, New York, 2005).

¹¹H. Darcy, *Les Fontaines Publiques de La Ville de Dijon (The Public Fountains of the City of Dijon)* (Victor Dalmont, Paris, 1856), Appendix D.

¹²Gerdi Kemmer and Sandro Keller, "Nonlinear least-squares data fitting in Excel spreadsheets," *Nat. Protocols* **5**(2), 267–281 (2010).

¹³P. Carman, "Permeability of saturated sands, soils and clays," *J. Agricult. Sci.* **29**(2), 262–273 (1939).

¹⁴B. R. Corrochano, J. R. Melrose, A. C. Bentley, P. J. Fryer, and S. Bakalis, "A new methodology to estimate the steady-state permeability of

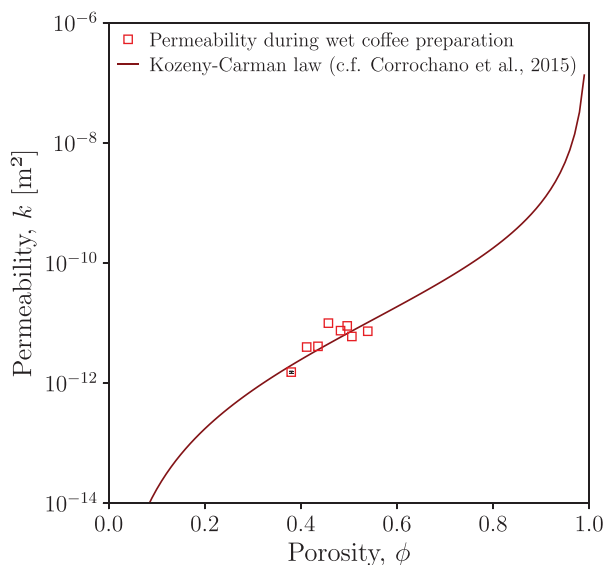
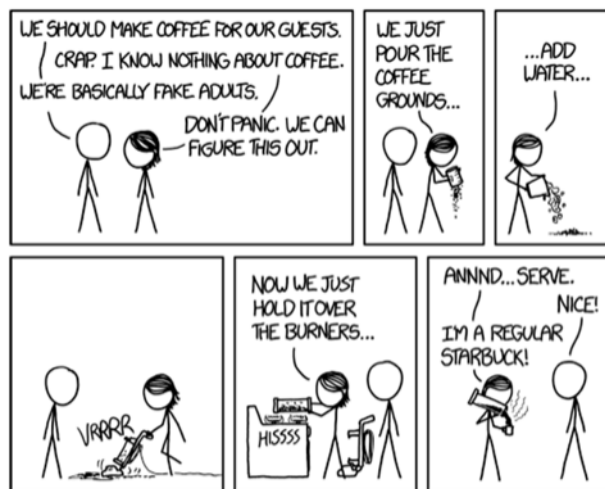


Fig. 7. The fitted permeability k as a function of porosity ϕ for coffee experiments. The solid curve is a solution to the Kozeny-Carman model with $C = 180$ using the Sauter coffee grind radius (Eq. (7)) (Ref. 14).

- roast and ground coffee in packed beds,” *J. Food Eng.* **150**, 106–116 (2015).
- ¹⁵Fabian B Wadsworth, Caron E. J. Vossen, Diana Schmid, Mathieu Colombier, Michael J. Heap, Bettina Scheu, and Donald B. Dingwell, “Determination of permeability using a classic Darcy water column,” *Am. J. Phys.* **88**(1), 20–24 (2020).
- ¹⁶Fabian B. Wadsworth, Jérémie Vasseur, Edward W. Llewellyn, Katherine J. Dobson, Mathieu Colombier, Felix W. Von Aulock, Julie L. Fife *et al.*, “Topological inversions in coalescing granular media control fluid-flow regimes,” *Phys. Rev. E* **96**(3), 033113 (2017).
- ¹⁷A. Varlamov and L. G. Aslamazov, *The Wonders of Physics* (World Scientific, Singapore, 2018), p. 379.



COFFEE

Remind me to order another pack of coffee filters from Dyson. Man, these things are EXPENSIVE. (Source: <https://xkcd.com/1743/>)