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Ernest Park ; Margot Young ; Arnold J. T. M. Mathijssen

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Ernest Park, Margot Young, and Arnold J. T. M. Mathijssen[a)]

AFFILIATIONS

Department of Physics and Astronomy, University of Pennsylvania, 209 S 33rd St., Philadelphia, Pennsylvania 19104, USA

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[a)]**Author to whom correspondence should be addressed:** amaths@upenn.edu

ABSTRACT

Coffee is one of the most consumed beverages in the world. However, issues such as climate change threaten the growth of the temperature-sensitive *Coffea arabica* plant, more commonly known as Arabica coffee. Therefore, it is crucial to make beverages more efficient by using less coffee while still meeting the high demand for the beverage. Here, we explore pour-over filter coffees, in which a water jet impinges on a water layer above a granular bed. To reveal its internal dynamics, we first substitute opaque coffee grounds with silica gel particles in a glass cone, imaged with a laser sheet and a high-speed camera. We discover an avalanche effect that leads to strong mixing at various pour heights, even with a gentle pour-over jet. We also find that this mixing is not significantly impacted by a layer of floating grains, which is often present in pour-overs. Next, we perform experiments with real coffee grounds to measure the extraction yield of total dissolved solids. Together, these results indicate that the extraction of the coffee can be tuned by prolonging the mixing time with slower but more effective pours using avalanche dynamics. This suggests that instead of increasing the amount of beans, the sensory profile and the strength of the beverage can be adjusted by varying the flow rate and the pour height. In this way, the extraction efficiency could be better controlled to help alleviate the demand on coffee beans worldwide.

I. INTRODUCTION

Coffee is among the most consumed drinks in the world, with 10.5×10^9 kg being consumed in 2021–2022.[1,2] A popular method of making coffee is a pour-over, in which a laminar water jet from a gooseneck kettle impacts a bed of ground coffee before seeping through a metal or paper filter.[3–9] This brewing method primarily uses gravity to push water a single time through coarse, loosely packed coffee grounds. Other popular methods of coffee production include espresso,[9–21] which uses high pressure to drive water through densely packed, fine coffee; the coffee percolator, which continuously recirculates water through the grounds;[22,23] the French press,[2,24–26] which immerses coarse coffee grinds with water before separating them with a plunger; various coffee brew tools such as the moka pot[27–30] and AeroPress;[25,26] and the electric drip coffee maker, in which the distribution and flow rate on the bed of the coffee is fixed.[31] However, less has been explored in pour-over coffees, where the pour height and the flow rate can be adjusted freely.

Owing to the globally changing climate,[32] however, it is increasingly difficult to cultivate *Coffea arabica*,[33] which is the most common and popular species of coffee consumed around the world.[1] Efforts are being made to search for arabica alternatives, such as *Coffea canephora*, more commonly known as robusta,[33] which, due to its different genetic makeup and growth conditions, has a very different flavor profile compared to arabica.[34] Therefore, it is essential to use coffee more efficiently. According to work done with different types of coffee,[35] the amount of soluble solids in the final coffee and the percentage of coffee extracted from the beans is more important than other factors when it comes to sensory coffee taste. Therefore, if coffee with the same extraction can be created with fewer grounds, coffee production can be made more material-efficient and the demand on coffee products lessened. Studying how water poured into a pour-over coffee impacts the bed is essential—increasing the contact between coffee grounds and the water increases extraction, and extracting more soluble compounds from the grounds could lower the demand for difficult-to-grow arabica coffee beans. There have been recent efforts to improve this issue for espresso[19] but not for pour-over coffees, which often require similar amounts of coffee in the most common recipes.

Pour-over coffees can be made in a variety of ways, but they all include several fundamental features: coffee grounds, a laminar flow of water, a funnel-shaped cone, and a filter [Fig. 1(a)]. Even using just

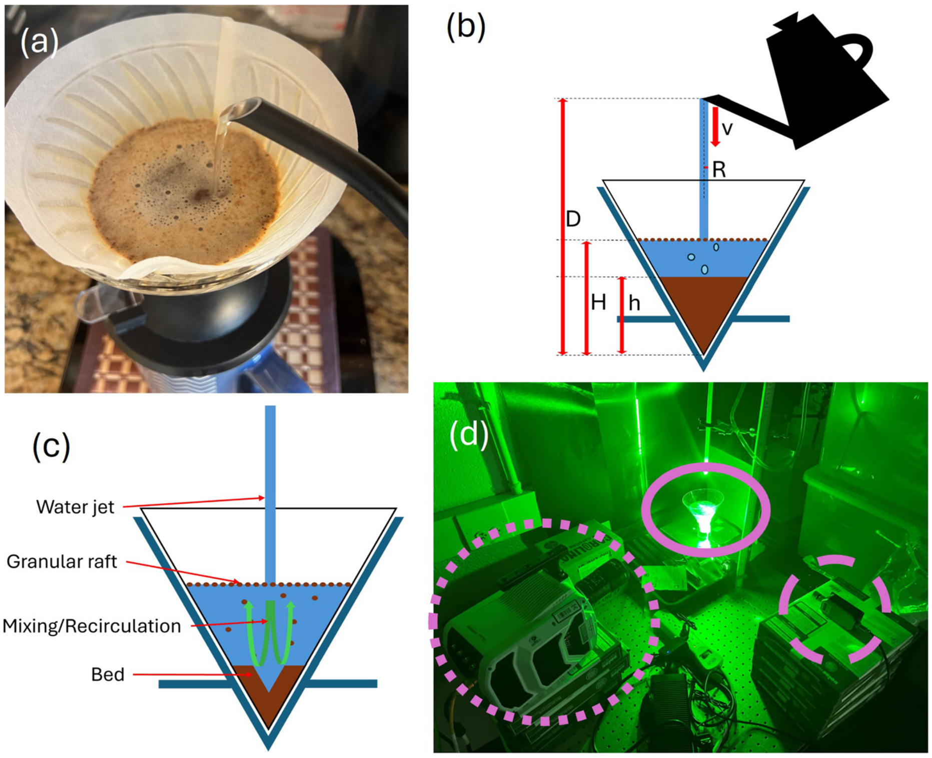

FIG. 1. Dynamics of a pour-over coffee. (a) Image of a pour-over coffee. (b) Parameters associated with a pour-over coffee, including the bed height, h, and water height, H, as well as the pour-over jet height, D, the jet radius, R, and the flow velocity, v. We keep h and H constant throughout the experiments. (c) Erosion of the coffee bed at the bottom of the cone caused by the impinging jet. (d) Image of experimental system with laser sheet and high-speed camera. The solid line circle is the glass funnel used as the coffee cone in this experiment. Circled in the dotted line is the high-speed camera equipped with a macro lens. Circled in the dashed line is the laser sheet pointing orthogonally toward the funnel and high-speed camera.

these basic elements, there is a wealth of free parameters that can be tuned to change the outcome of a cup of coffee, including the amount of coffee and water, the jet radius, the pour height, and the flow velocity [Fig. 1(b)]. These parameters all influence how the water jet interacts with the coffee bed. Depending on the pour, this interaction can drive efficient mixing that leads to higher coffee extraction and therefore a richer cup. A typical preparation method also includes a "bloom," where the coffee grounds are wet minimally to release carbon dioxide,[3] and a floating granular raft [Fig. 1(c)]. This bloom is then followed by one or more pours until the desired amount of liquid is reached. Besides the parameters described above, one can also vary the bloom time, which changes the amount of carbon dioxide released from the beans; the grind size, which often goes hand-in-hand with the flow rate and how long the grinds are in contact with the water; and the water temperature, which may solubilize different molecules at different rates. Changing these parameters can impact the resulting chemistry, taste, and sensory profile of the final coffee.

In all pour-over recipes, the water jet[36] from the gooseneck kettle is the primary driver of the hydrodynamic flow. The jet carries momentum, which allows it to impact surfaces, alter flow patterns, and displace granular materials,[37,38] such as the coffee bed. If the water is poured too slowly, the jet can stick to the spout due to adhesion and surface tension, which is known as the teapot effect.[2,39] It is also known that water jets experience a Plateau–Rayleigh instability,[36] which can increase the amount of air entrainment of the jet as it impinges the surface, and therefore decrease the jet's momentum as it impacts the grounds below.[40] However, it is not known how this may impact the amount of agitation the coffee grounds experience in the context of pour-over brews. In addition to the fluid mechanics of the liquid, we must also understand the granular flows.[37] Granular materials exhibit avalanches,[41–44] where granules suddenly slide and form large-scale flows. Previous works have addressed water jets and granular materials separately, but much less is known about water jets impinging on a liquid surface with a granular material underneath. Moreover, there are relatively few studies that directly visualize the granular particles interacting with multiphase flows.[45,46] In an effort to make coffee brewing more material-efficient, these dynamics must be addressed to better control coffee extraction.

Understanding the interplay between a liquid jet and a submerged granular bed is not only important for pour-over coffees. In Earth and environmental sciences, important examples are soil erosion due to waterfalls[47] and large-scale impinging jets on rocks.[48,49] In engineering, a crucial structural issue is dam scouring,[5,40] where a water jet slowly removes the solid ground behind the dam. Studying this system will help determine, albeit at a smaller scale, what kind of flows and flow parameters will most damage the ground underneath and may help in understanding how to improve dam health.

In this paper, we consider the hydrodynamics of pour-over coffees, especially how a liquid jet interacts with a granular bed of submerged coffee grounds. We first use transparent silica gel particles as a model system, and then we verify our results with actual coffee extraction experiments. To image the flows and the particle dynamics, we point a high-speed camera toward the experimental pour-over cone and shine a laser sheet orthogonal to the camera's optical axis while a laminar water jet is flowed into the system [Fig. 1(d)]. Using this setup, we first demonstrate how higher pour heights can lead to greater granular agitation. We then compare pour-overs with and without a floating granular raft. In addition to analyzing the mixing at the top of the cone, we also measure the amount of granular erosion at the bottom, for both thick and thin water jets. We discover that this erosion leads to avalanche dynamics that drives strong mixing. Finally, we conduct pour-over experiments with real coffee grounds to measure the total amount of dissolved solids as a metric for coffee extraction efficiency for different pour parameters. These results suggest new strategies for enhancing granular agitation and coffee extraction so that less coffee can be used to achieve the same result, aiding in the issue of strained *C. arabica* production.

II. MATERIALS AND METHODS

A. Pour-over cone and granular bed setup

A transparent borosilicate glass funnel with a 60° incline (120 mm, Eisco) is used as a coffee cone, which is similar in size and shape to the popular v60 pour-over cone, as well as other popular products such as the Chemex and Kalita Wave brewers. This funnel is plugged at the outlet to make the experiment more reproducible. Silica gel particles (0.2 − 1 mm, Millipore Sigma) are used as a model system for coffee grains without darkening the mixture for observation. These particles are analyzed using a high resolution camera (Apple iPhone; 12 MP Sony IMX703 3024 × 4032), and the resulting particle size distribution is shown in the supplementary material. This particle size distribution mimics the size distribution of coffee grounds,[4,22,50] which we also measured and presented in the supplementary material. Finally, small polystyrene beads (0.08–0.12in, Juvale) are used for the floating raft experiments, which are used to represent floating coffee granules.

B. Controlling water flow

A water jet is created using a carboy with a tube outlet, and the flow rate adjusted by changing the carboy height with respect to the tube opening. Similar to most gooseneck kettles, we use a 1/4-in. inner diameter tube for the outlet. We also use a 1/8-in. inner diameter tube to test the effect of thinner water jets. The carboy's height is set so the flow rate of around 20 g/s for the 1/4-in. tube, which is comparable to typical pour-over coffee recipes. To create a relatively symmetrical flow pattern, the tube points straight down vertically into the cone. The cone is placed on a lab jack so the height of the cone with respect to the opening of the flow can be adjusted. The water level starts at 6 cm above the bottom of the funnel, and additional water is flowed into the system until it is 8 cm above the bottom of the funnel, so that H and h remain constant across experiments [see Fig. 1(b)].

C. Laser and imaging equipment

A high-speed camera (V1840, Phantom) equipped with a macro lens (100 mm f/2.8 2× Ultra Macro APO, Laowa) is placed in the same horizontal plane as the funnel. A laser sheet (Powell 520 nm 1 W, Civil Laser) is emitted in the same horizontal plane, orthogonal to the optical axis of the high-speed camera. The high-speed camera is set to capture videos at 200 frames per second for the thicker tube outlet and 100 frames per second for the thinner tube outlet. Videos have an image depth of 12 bits and a resolution of 2048 × 1952 pixels (4 Mpx).

D. Image analysis

Images from the high-speed camera are analyzed with custom-made code using Python and Matlab. The videos are used to quantify the dynamics of the silica gel particles, their mixing, erosion, and avalanche dynamics, as described below. The images are cropped to exclude unwanted pixels outside the cone in Figs. 2 and 3. For the polystyrene layer experiment described in Fig. 3, the polystyrene layer is overexposed, so the highest pixel intensity is filtered out.

E. Pour-over brews with real coffee

Pour-overs are made using a well-known Hario V60 clear plastic cone with compatible filters (Hario VCF-02-100W). We use 10 g of

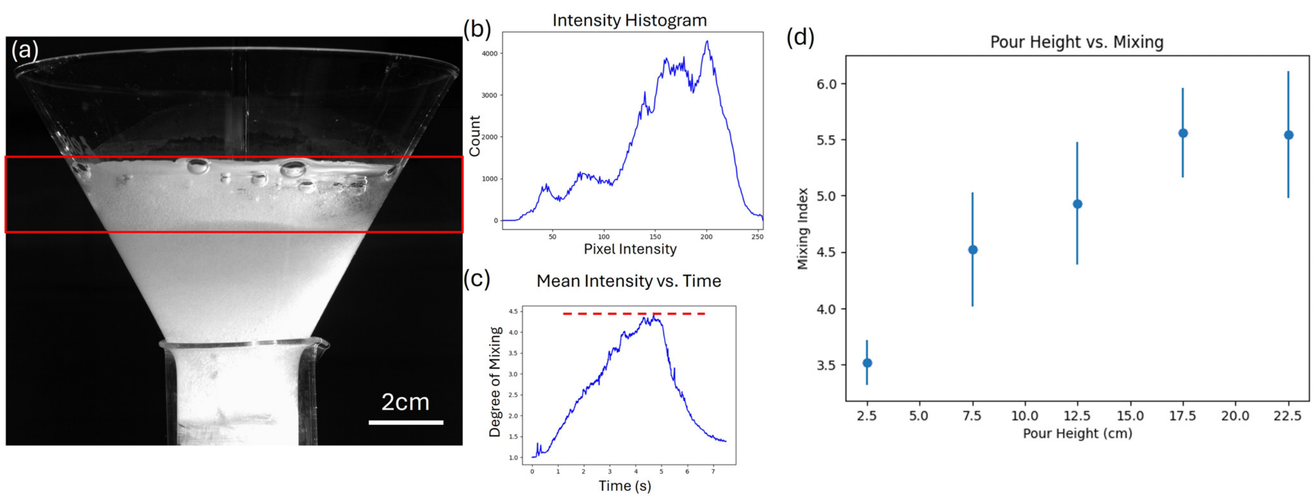

FIG. 2. Mixing at the top of the coffee cone vs pour height. Keeping the water jet pour rate constant, the intensity of the water layer above the silica gel is measured over various pour heights. (a) An image of the cone while a water jet impinges from above. The red box shows the analysis area above the granular bed. (b) An intensity histogram in the area encircled in (a). Lower intensities are cut out to exclude empty black areas. This is plotted for each frame, leading to (c) a plot of the mean intensity, normalized to the intensity histogram at t = 0, over time. The normalized mean intensity is redefined in this plot as the degree of mixing. (d) A plot of the maximum value of the degree of mixing, redefined as the mixing index, for different pour heights. Multimedia available online.

Simply Nature Organic Honduras whole coffee beans, which are ground using a Eureka Mignon Silenzio (setting -1). The coffee grains are analyzed using a high-resolution camera (Apple iPhone; 12 MP Sony IMX703 3024 × 4032), and the resulting particle size distribution is shown in the supplementary material. The coffee is brewed using 150 g of water at a temperature of 95 °C and poured from a commercial gooseneck kettle (KitchenAid KEK1032) at two flow rates: one at around 15 g/s, producing a "thick" water jet with a diameter of $3-5$ mm, and another at around 5 g/s, producing a "thin" water jet with a diameter of $1-2$ mm. After the pour-over is made, we measure the total dissolved solids by placing 20 g of the brewed coffee in a beaker in an oven at 100 °C for 14–16 h (when the weight of the coffee plateaus) to evaporate the liquid. The quantity of total dissolved solids (TDSs) (%) is then calculated using

$$\mathrm{TDS}(\%) = \frac{m_{\text{dried brew}} - m_{\text{beaker}}}{m_{\text{brew}}} \times 100\%. \tag{1}$$

Since the same amount of coffee grounds is used in each pour, the extraction % is directly correlated with the TDS, so only the TDS is reported.

III. RESULTS

A. Pour height increases mixing of the coffee grounds

The agitation of the granular bed is directly affected by the jet's momentum, but it is unclear how this momentum changes with pour height. A higher pour height increases the velocity of the jet upon impact; however, this increased pour height increases the Plateau–Rayleigh instability of the jet, entraining more air upon impact and potentially lowering jet momentum. We explore this question in Fig. 2: keeping the height and flow rate of the water jet the same, the height of the funnel is changed to vary the pour height, and the resulting amount of agitation is characterized. Figure 2(a) (Multimedia view) shows an image of the experimental system, and the red box indicates the analysis window.

First, the dynamics above the bed are observed. To quantify the mixing of the silica gel, the pixel intensity in the water layer above the bed is tracked over each frame [Fig. 2(b)]. The mean of this pixel intensity (normalized to the intensity histogram at $t=0$), which we define as the degree of mixing, is obtained for each frame in the movie [Fig. 2(c)]. The degree of mixing's maximum value, defined as the mixing index, is extracted for each pour height [Fig. 2(d)]. We find that the mixing index generally increases with pour height, demonstrating more agitation at higher pours. It is worth noting that although the Plateau–Rayleigh instability visually increases for higher pour heights, there is no visible drop in agitation at the highest tested pour heights (for pour heights typically used to brew coffee).

B. Dimensionless number analysis

The Reynolds number for the system is calculated using

$$\mathrm{Re} = \frac{\rho u L}{\mu}, \tag{2}$$

where ρ is the density of the liquid, u is the flow rate, L is the characteristic length scale, and μ is the dynamic viscosity. For our pour-over system, the density is $\rho = 1000\,\mathrm{kg/m^3}$, the velocity of the jet is $u \sim 1\,\mathrm{m/s}$, the viscosity is $\mu = 8.9 \times 10^{-4}\,\mathrm{Pa\,s}$, and for the length scale L, we use the width of the cone, which is around 0.1 m. Hence, the Reynolds number of the whole system is approximately $Re \sim 10^5$, which is well within the turbulent regime where liquid mixing is abundant.

We also calculate the Reynolds number for the jets using the same formula [Eq. (2)] but with the jet diameter as the length scale and the velocity of the jet upon impact, which is calculated using the difference in height between the carboy's water height and the jet impact point. For the thicker jets used in Figs. 2–4 (produced from a 1/4-in. diameter tube), the diameter upon impact is around 4 mm, while for the thinner jets in Fig. 5, it is 2.75 mm. For the velocity of the jet upon impact, rough estimates were calculated using Bernoulli's equation,

$$\frac{1}{2}\rho v_1^2 + \rho g h_1 = \frac{1}{2}\rho v_2^2 + \rho g h_2, \tag{3}$$

where ρ is the density, v_1 and v_2 are the velocities at the top of the water in the reservoir and velocity of the jet upon impact, respectively, h_1 and h_2 are the heights at the top of the water inside the carboy and the water–air interface that the jet impinges, respectively, and g is the

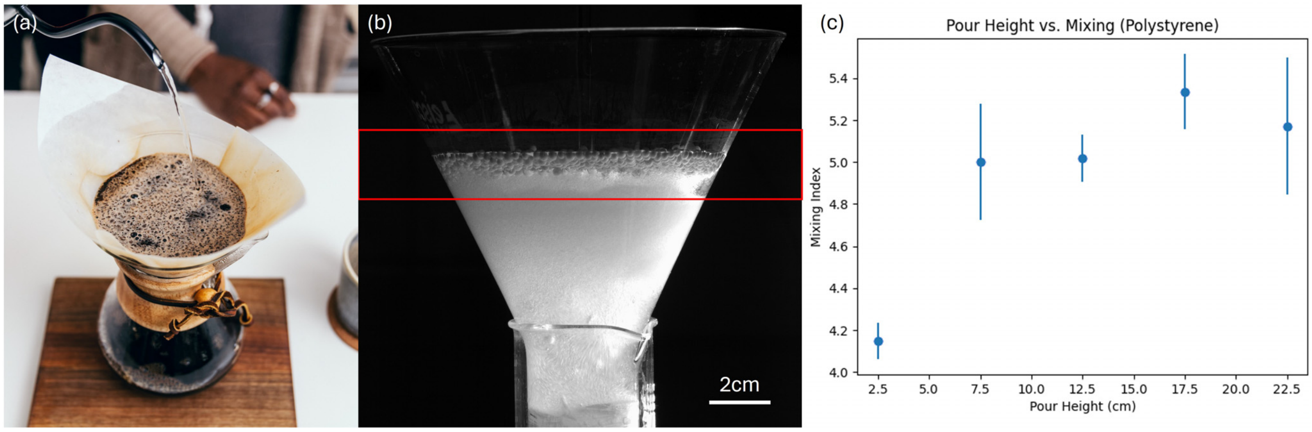

FIG. 3. Silica with floating polystyrene layer intensity vs height. (a) Image of a pour-over featuring many floating granules. Image by Matthew Henry, licensed under Burst Some Rights Reserved. (b) A floating polystyrene monolayer cast on top of the silica gel before the pour-over. (c) A plot of the mixing index vs pour height. Multimedia available online.

acceleration due to gravity. Since the reservoir is open, the pressures at both heights are atmospheric. Because the top surface of the water in the carboy is much larger than the outlet diameter, we have that $v_1 \ll v_2$. Hence, we obtain the jet velocity $v_2 = \sqrt{2g(h_1 - h_2)}$.

Using this equation, we calculate a velocity range of approximately $2.5 - 3.5$ m/s, and using the jet diameter as the representative length scale, we find a range of jet Reynolds numbers. For the larger tube diameter (4 mm), we find $Re \sim 10\,000 - 15\,000$, with smaller Re corresponding to lower pour heights. For the thinner tube diameter (2.5 mm), we find $Re \sim 7000 - 9000$. As these are all within the same turbulent Re regime, we do not expect significant differences in dynamics due to differences in Re.

The Weber number is also calculated using the equation

$$\mathrm{We} = \frac{\rho v^2 l}{\sigma}, \tag{4}$$

where $\sigma = 0.07$ N/m is the surface tension of water and the length l is the diameter of the jet. Using the same jet velocity values calculated above, we find a range for the Weber number of $We \sim 400 - 600$ for the thicker jet and $We \sim 270 - 415$ for the thinner jet. The ranges for the Weber number are also within the same regime, in which forces are dominated by inertia, rather than surface tension. When considering the experiment using the thinner tube and lower carboy height, we calculate $Re \sim 3000$ and $We \sim 75$ in Fig. 5(c).

As shown in these Re and We number calculations, all of the pours are well into the turbulent regime, but we still see a marked increase of agitation in the system. This shows that flow turbulence is not the entire story for this system, and that an interaction between the jet and the granular bed is needed to explain this agitation increase.

C. Floating granular rafts do not significantly affect mixing

Oftentimes, as shown in Fig. 3(a), floating coffee granules or bubbles float on the top surface during a pour. This effect is especially pronounced during the first pour (the bloom), in which carbon dioxide is released from the coffee grounds. It is not known whether this layer affects the water jet's momentum as it impinges on the water surface. To answer this question, the same experiment is performed with a floating granular layer [Fig. 3(b)] (Multimedia view). As with the previous pour-over experiment, Fig. 3(c) again shows the mixing index over different pour heights with the addition of a polystyrene layer. We hypothesized that this layer may disrupt the momentum of the incoming water jet flow and therefore decrease the mixing index. However, we find that there are minimal differences in the trend of the mixing index with the addition of the polystyrene bead layer.

D. Erosion at the bottom of the funnel

If a pour is concentrated to one location, the liquid jet can dig through the coffee bed to the bottom of the cone. This erodes the bed and displaces many coffee grounds, which recirculate in the liquid toward the top surface. There, they accrete and settle at the edges of the cone. However, it is not known whether changing the pour height impacts this digging process. Pouring from too low could decrease the momentum of the jet upon impact, and pouring from too high could increase the entrainment of air into the liquid, similarly reducing momentum. To investigate this effect, the bottom portion of the pour-over is analyzed, as shown in Fig. 4(a). For each frame of the movie, the pixel intensity histogram is again obtained [Fig. 4(b)]. As the silica gel is dug out from the bottom, the intensity values will decrease, with lower values corresponding to lower silica gel concentration and more erosion. Therefore, the minimum normalized mean intensity, defined as the density, is considered in this region in Fig. 4(c). The minimum density, called the density index, is plotted for each pour height in Fig. 4(d). We find that the density index is smaller for lower pour heights in both the plain silica gel and silica gel with polystyrene experiments, indicating that lower pours are better at digging toward the bottom of the cone than higher pours. In addition to air

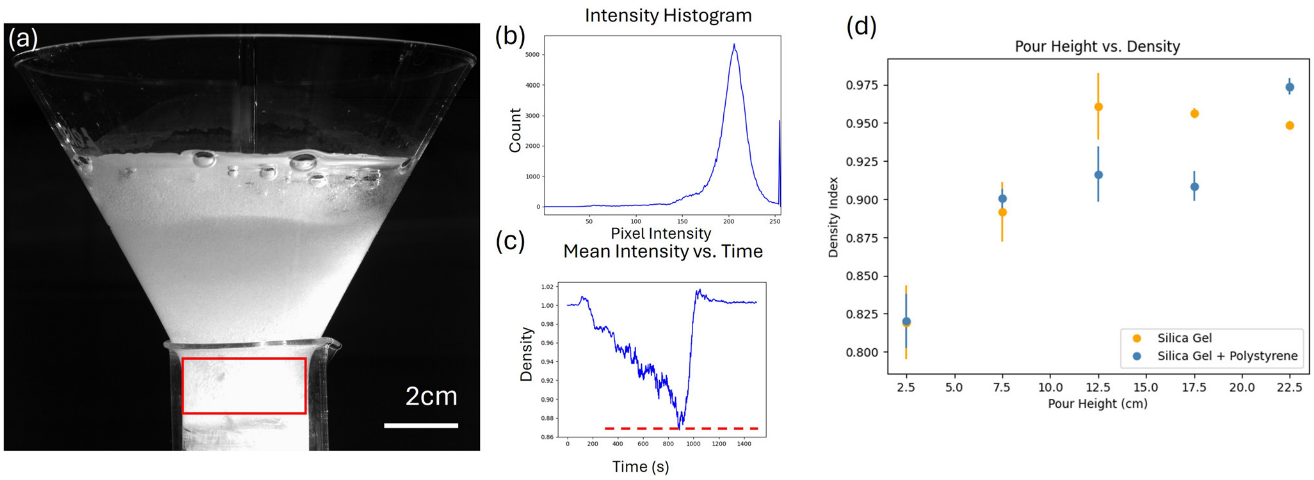

FIG. 4. Erosion of granules at the bottom of the cone vs pour height. (a) The bottom of the cone, in the red square, is analyzed to determine how many granules there are dug out. (b) The histogram for the intensities in the enclosed area in (a) is plotted. (c) The normalized mean intensity redefined simply to density is monitored over time. (d) The minimum of the density, redefined as the density index, is plotted over different pour heights, for both the plain silica gel experiment and the silica gel with a polystyrene monolayer experiment.

entrainment, this could be because the jet penetration depth does not necessarily scale linearly with the jet velocity at higher Reynolds numbers.[51]

E. Thinner jet does not impact bed at higher pours

Although the mixing index increases for higher pour heights for the larger (1/4-in.) diameter jet, this may not necessarily be true for smaller jet diameters. Therefore, we conduct the same experiment using an outlet with a smaller diameter (1/8-in.) to see if the dynamics change. We find that for the pours in which the flow remains laminar [Fig. 5(a)] (Multimedia view), the jet digs to the bottom of the bed, similar to the larger jet diameter pours. However, for the highest pour height, in which the jet becomes unstable before impact, the bed is barely impacted [Fig. 5(b)] (Multimedia view). In this case, the jet's energy is insufficient to overcome bubble buoyancy, so the jet is unable to dig through the bed. We also test the lower limit, in which the jet has a much slower pour speed but still remains laminar [Fig. 5(c)] (Multimedia view). This is achieved by lowering the carboy height with respect to the outlet, decreasing the kinetic energy of the water as it exits the outlet. In this case, we find that the bed is also not impacted, so there is a lower jet velocity limit required to dig through the bed.

F. Avalanche dynamics enables strong coffee mixing even with gentle pour-over jets

When the liquid jet is able to dig into the granular bed and displace the grains at the bottom of the cone, the grains on the side become unstable against gravity. This causes avalanches of grains that slide down the side of the cone. We use a kymograph plot to visualize this dynamic (Fig. 6). Using Fiji,[52] a profile line is created along the edge of the cone [Fig. 6(a)], and a kymograph is created using this profile line [Fig. 6(b)]. As can be seen in Fig. 6(c), the dynamics are not linear, showing periods of high and low activity, or avalanches and stutters. From this finding, we suggest a mechanism for the dynamics observed: first, the water jet starts eroding the granular bed and suspending the granules into the water layer [Fig. 6(d)]. This jet eventually hollows out the bed and the grounds accrete toward the edge of the cone [Fig. 6(e)]. Due to gravity and the density gradient created by the hollowed bed and the accreted edges, the bed collapses [Fig. 6(f)], restarting the process of suspension and accretion. This mechanism allows for strong global mixing to occur continuously, as long as the water jet is able to dig out and suspend the granules at the bottom of the cone.

G. Experiments with real coffee beans show that total dissolved solids increase with increasing pour height

In this study, we have explored the granular dynamics across different pour heights using transparent silica gels. To test how these dynamics translate to coffee, we use a pour-over protocol similar to the one outlined by Chen *et al.*[3] to find a relationship between pour height and the resulting brew strength for different jet diameters. We use the metric of total dissolved solids [TDS%, see Eq. (1)] in the coffee to quantify strength. We find that higher pours result in stronger brews when using a thicker water jet [Fig. 7(a)]. This increasing extraction agrees with the increase in granular agitation found in the silica gel experiments. With a thinner water jet, the extractions did not differ greatly among the pour heights and were all fairly high [Fig. 7(b)]. The overall increase in extraction for lower pours may be due to the longer pour time required to reach the target liquid quantity with the slower flow rate.

IV. CONCLUSION

We show that the mixing index increases with higher pour heights, for both silica gel particles and a combination of a silica gel layer with a monolayer of floating polystyrene. This suggests that with a higher pour height, even in the presence of floating granular particles (or grains and bubbles in the case of an actual coffee) a higher extraction can be achieved with only a higher pour height. We also show that for lower pour heights, the density index decreases at the bottom of the cone, suggesting that more laminar flows are better able to pierce through the silica gel bed. Finally, we find that the digging at the bottom of the cone and subsequent suspension of the granules causes the bed to collapse, as shown in the avalanching patterns extracted from the kymograph in Fig. 6(c). This mechanism occurs only while the jet is impacting the bed, which suggests that for longer pours, this avalanching will allow more granules to be resuspended, thereby increasing the extraction rate.

Temperature effects may also change the way coffee grounds are extracted. Previous work shows that brew temperature does not have a significant impact on the sensory experience of a coffee (though they tested 87 °C and greater) and that the total dissolved solids and percent

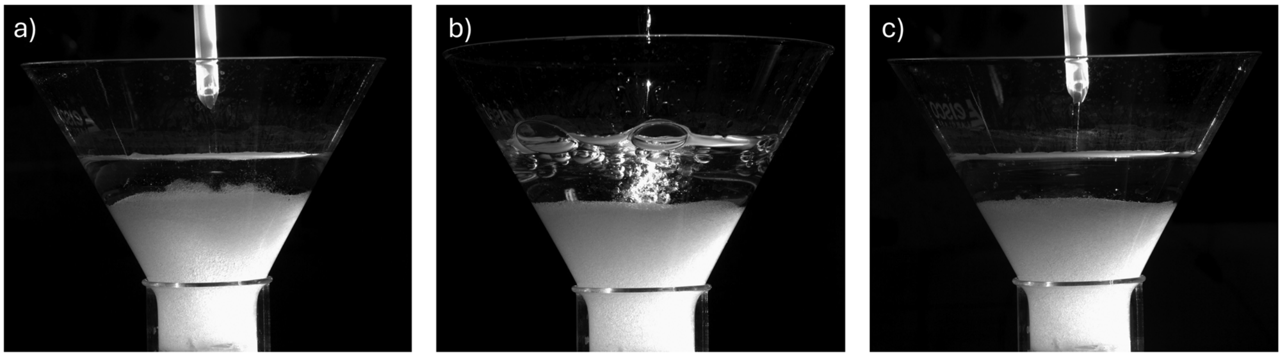

FIG. 5. Smaller jet diameter impact on dynamics. (a) Image of jet with halved diameter impacting bed at 2.5 cm above the bed. (b) Jet impacting bed at 22.5 cm above the bed. (c) Jet with lower flow velocity impacting bed at 2.5 cm above the bed. Multimedia available online.

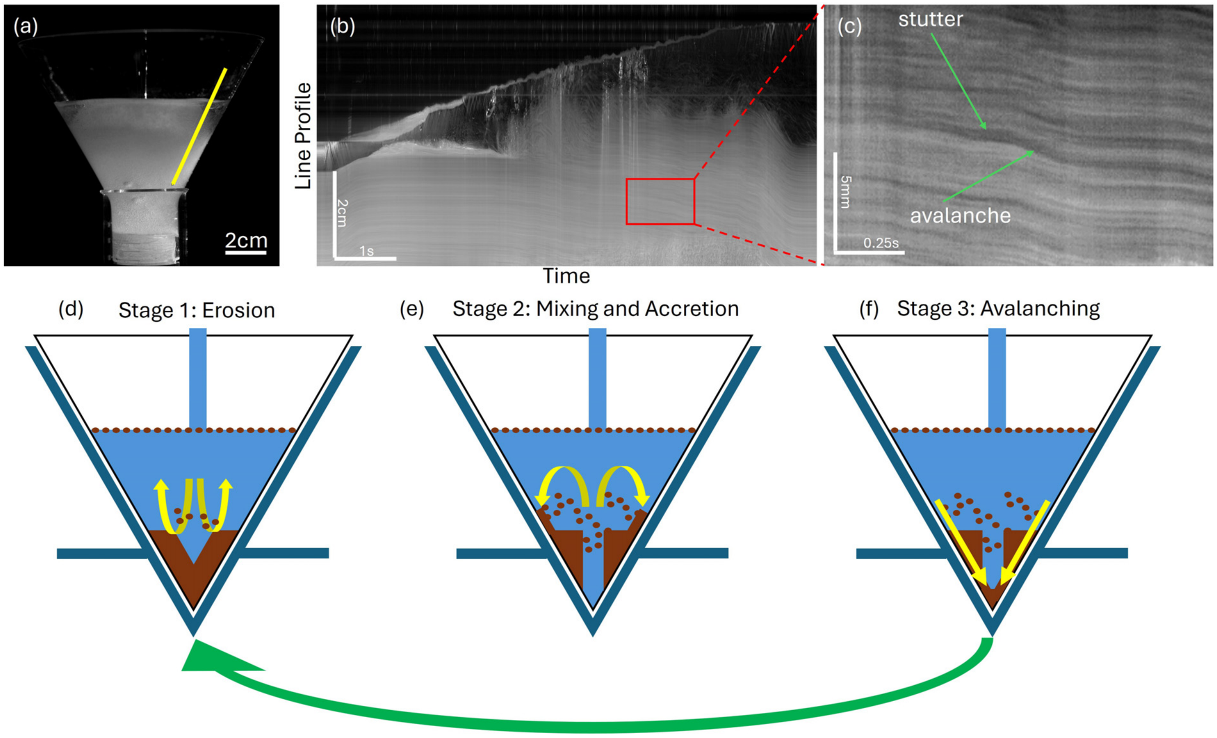

FIG. 6. Avalanche dynamics of the granular bed. (a) An image of the cone being impinged upon by the water jet. A yellow line shows the profile that is tracked across time in (b). (b) Kymograph showing the dynamics of the granular bed along the cone wall. The y-axis shows the intensity at different locations along the yellow line, while the x-axis shows these intensities across time. The origin is defined as the intensity at the bottom tip of the line at $t = 0$. (c) A zoom-in of the avalanching part of the bed. A steeper slope indicates a faster bed collapse. (d)–(f) Stages of continuous avalanche dynamics, indicated by the yellow arrows, in pour-over coffee. First, the water jet impinges on the water surface and starts to erode the coffee bed. As the bed is eroded, the granules are suspended and mixed into the water layer. These granules eventually accrete outward toward the edge of the bed. Finally, the distribution of the granules from the bottom to the top edge of the cone causes the bed to collapse inward. This process is repeated (green arrow) as long as the water jet continues to impact the bed.

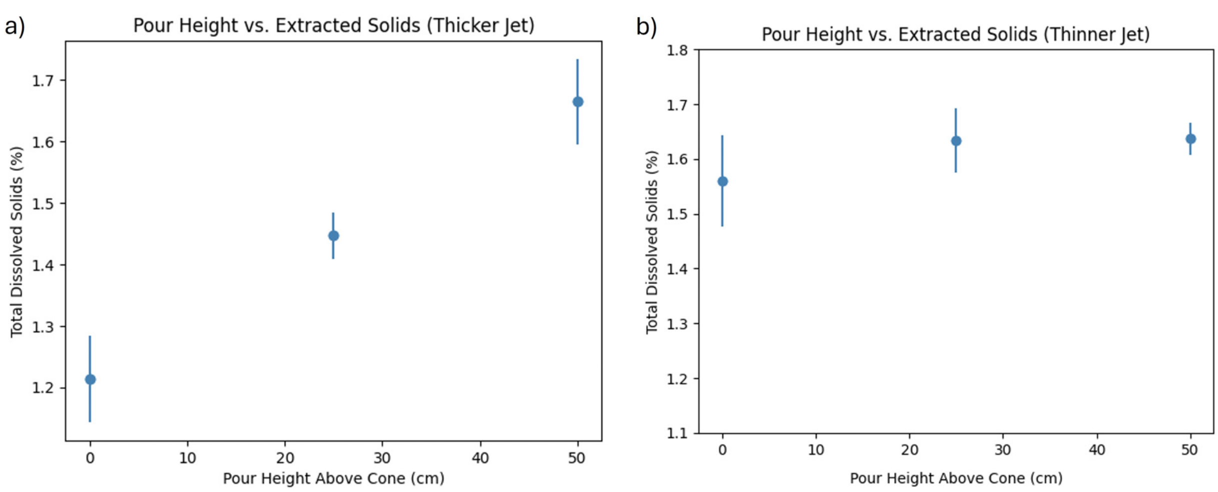

FIG. 7. Extraction experiments with real coffee. After making a pour-over using a Hario V60 cone, the resulting beverage is dried in the oven to determine the amount of contents extracted from the coffee grounds. (a) Total dissolved solids (%) against pour height in pour-over coffee using a higher and (b) lower flow rate from a gooseneck kettle, changing the radius of the jet.

extraction have a much larger role in sensory profiles.[53] However, we would like to point out a separation of timescales. Although temperature can impact the chemistry of the system, the time it takes for the temperature to form a gradient sufficient to impact the avalanche dynamics is much longer than the avalanching process itself, and so we speculate that temperature should not impact the dynamics of the system.

We test a few jet diameters in this experiment, but further work is needed to find a more detailed relationship between the jet size and granular dynamics. We also explore a single size distribution of silica gel particles and coffee grounds, but other ranges of granular sizes may change the dynamics, which should be investigated in future work.

In light of these results, if one would like to use less coffee beans, we suggest increasing the distance between the pour-over kettle and the cone to maximize mixing, as well as reducing the flow rate to increase extraction time. The flow should be kept laminar, so that the jet can induce avalanching, which also increases mixing. These alterations assist in extracting and dispersing the flavorful compounds in coffee grounds effectively while reducing the necessary mass of grounds.

This work also has implications in dam systems, in which a liquid jet also impinges onto a liquid reservoir that scours the ground underneath.[40] Studying this type of system is crucial in predicting and maintaining dam health for safety purposes. For the parameters we tested here, we find that if a jet impinges on the liquid surface from a higher height, it increases the erosion and resuspension of the granular bed. Although dams operate on a much larger scale, they may undergo similar dynamics, and finding ways to decrease the jet height in dams may decrease erosion and elongate dam health. Our findings may also be relevant in natural rock erosion caused by waterfalls,[49,54,55] as high waterfalls impacting a reservoir may increase the erosion of the rock underneath. This research may also be pertinent to wastewater treatment, where liquid jets are used to mix and aerate wastewater to allow aerobic biodegradation of the organic materials.[56]

With the changing climate, it is becoming more difficult to grow coffee. However, this paper demonstrates a potential method to decrease the quantity of coffee beans required to brew a pour-over coffee, simply by changing the way in which one pours the liquid jet.

Finally, this type of "kitchen flow" research[2] may also help make science more accessible, affordable, and curiosity-driven.[57] The experiments presented in this paper could be adapted for a typical classroom setting to encourage students to think about how the physics of fluids impacts their daily lives through food and beverages.[58,59]

SUPPLEMENTARY MATERIAL

See the supplementary material for details on the particle size distributions of silica gel particles and coffee grounds used in the paper.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Ernest Park: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Margot Young:** Data curation (equal); Investigation (equal); Methodology (equal); Writing – review & editing (equal). **Arnold Mathijssen:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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