Team Second Report

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MCEN 5151-002 Flow Visualization

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Purpose and context

This image was taken for the Team Second assignment in Flow Visualization (Fall 2023, MCEN 5151) with Professor Hertzberg. The end goal for the assignment was an image that artistically demonstrated a fluid phenomenon. I photographed the liquid rope coiling of honey as it was poured. Initially, this image was taken to calibrate the camera settings given the object position and the lighting set up; however, I found this image more interesting and more entrancing lighting than the later photos we took because of the movement captured in the coiling behavior. I initially submitted an image that more clearly illustrates the liquid rope coiling behavior of the honey, but the limitations of the image quality make this image more intriguing. The former image is included to the right.

Materials and methods

The set up for this flow image was very simple (deceptively so in the context of a complex fluid phenomenon). A clouded plastic plate was placed upside down on top of a light table. Honey was poured from a squeeze bottle container about 20 cm above the surface of the plate. The room temperature was approximately 21C. The honey used was Signature Select Clover Honey in a 40 Oz squeeze bottle. *Fluid data:* Honey is variously characterized as Newtonian and non-Newtonian depending on its source [1], [2]. This change in properties is attributed to pollen grain concentration and composition, sugar percentages, and water content [1]. In this case, the clover honey is undiluted and not sourced from places where non-Newtonian honey has been reported. Further, some reports suggest that the high-pressure filtration used by most US grocery brands removes all pollen content [3]. The dynamic viscosity of honey is variable, but approximated her as 18.39 Ns/m^2 [4]. *Flow rate and geometry:* Honey was poured from the bottle at an approximate rate of 0.75 mL/s (as measured by timing the filling of a tablespoon), from a height of 20 – 30 cm. The height in the featured image of this report was approximately 20 cm and the height in the coiling photograph above was about 30 cm. At the outlet of the bottle, the diameter of the flow was approximately 3 mm and narrowed to less than 1 mm at the point where it reached the honey coil. Both the above images were taken about 30 seconds into the honey pour, so that a puddle of honey had formed on the dish.

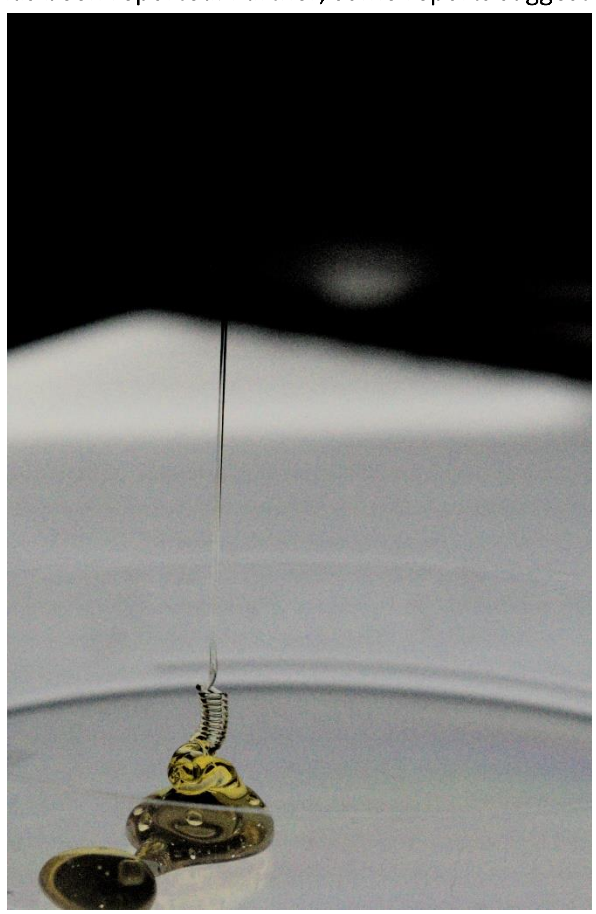


Figure 2: Liquid rope coiling behavior

Fluid Dynamics

In the simplest terms, the honey rope coiling effect is the result of the honey at the bottom of the stream needing to "get out of the way" of honey flowing

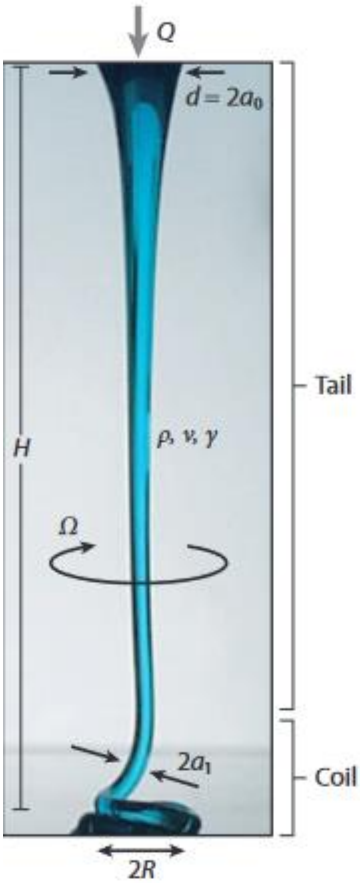


Figure 3 Liquid rope coiling parameters. Image adapted from Ribe et al. 2012 where it was cited as modified from a previous 2004 paper by the same author.

downward [5]. The coiling behavior arises from a buckling instability: when the the vertical stream of fluid stretches and thins the compression of axial flow creates a buckling instability, bending the stream and resulting in a directional spin that starts upstream of the stream's contact point with the coil [6], [7].

In liquid rope coiling different patterns appear based on fall height, viscosity, diameter, mass flow rate, and gravity based acceleration [10]. Combinations of these parameters can generate different coiling frequencies and different coiling regimes. Four distinct coiling regimes—viscous, gravitational, inertia-gravitational, and inertial—describe differing patterns of coil formation. These four regimes can be described by total height *H*, which is the summed height of the coil and the tail of the stream [5]. The diameter of the tail decreases from the outflow, narrowing down to the coil due to stretching and thinning [6]. The coiling behavior can be characterized and partially predicted using the density ρ, kinematic viscosity v, and surface tension coefficient, γ, of the fluid along with the diameter of the outlet $2\alpha_0$, diameter of the base of the stream $2\alpha_1$, diameter of the coil $2R$, coiling angular frequency Ω, fall height H, and volumetric flow rate, $Q = \pi\alpha_0^2 U_0$, where U_0 is the ejection speed [6]. These parameters are illustrated in Figure 3, the image is adapted from Ribe et al. 2012).

We approximate these parameters for the flow in the featured image in Table 1.

Based on a flow rate of 0.65ml/s, we calculate the mass flow rate using the density of the honey, $Q = V * \rho = (0.65mL/s)(1415\ g/mL) = 0.92g/s$. Kinematic viscosity is the ratio of dynamic viscosity (5 Pa*s [4]) to fluid density, so that $v = \mu/\rho = 5Pa * s/1415kg/m^3 = 3.5e - 03m^2/s$.

Parameter	Value (or approximation)
Mass flow rate, Q	0.92 g/s
Outlet diameter, $2\alpha_0$	3 mm
Final diameter, $2\alpha_1$	0.5 mm
Density, ρ	1.415 g/mL [8]
Kinematic viscosity, v	3.5e-03 m^2/s
Surface tension coefficient, γ	0.315 N/m [9]
Fall height, H	20 cm
Unique to Figure 2	
Coil radius, $2R$	5 mm
Empirical $2\alpha_1$	1.48 mm
Coiling frequency, Ω	
Fall height	30 cm

The parameters of the flow are related differently depending on the coiling regime (viscous, gravitational, inertia-gravitational, and inertial) [5]. The four coiling regimes are named with reference to the primary force driving the flow behavior.

With a low fall height, the coiling is generally in the viscous regime where both gravity and fluid inertia are negligible relative to the viscous forces [6]. The stream does not thin between the outlet and the contact and the coils are slow with each coil ring sinking into the surface before stacking[5], [6]. In the gravitational regime, coiling frequency increases with fall height [10]. In this regime gravity is balancing viscous bending forces in the coil and viscous stretching forces in the tail [6]. In the inertia-gravitational regime a single fall height can result in different coiling frequencies as a consequence of inertia interacting differently with inertia and gravity in the tail and the coil [6]. Visually, this coiling regime is dominated by a sporadically interrupted coiling pattern [5]. The final coiling regime is inertial, where the tail of the coil is very near vertical and the viscous forces resisting bending are countered by the inertia of the fluid [6].

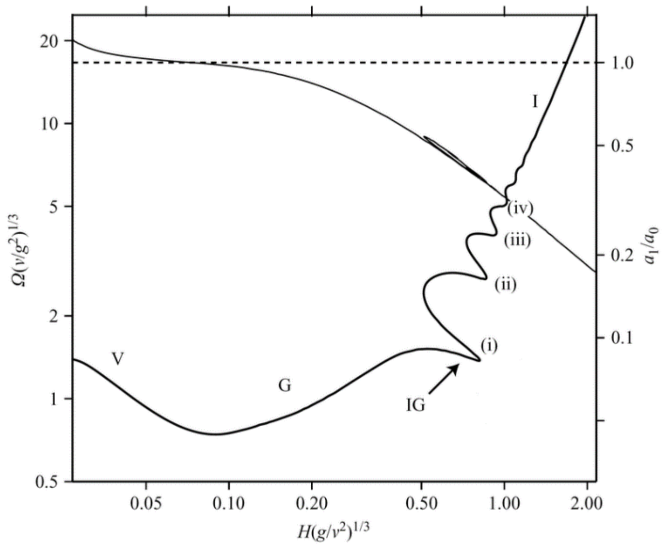


Figure 4: Relationships between dimensionless fall height, dimensionless coiling rate and a ratio between the initial and final stream radius. Figure originally from Habibi 2007.

Dimensionless fall height is used to partly distinguish between fall regimes: $\widehat{H} = H(g/v^2)^{1/3}$. For the featured photo, \hat{H} = 0.2 m * (9.18 m/s^2 / (.0035 m^2/s)^2)^{1/3} = 18, suggesting the flow inertia range [11]. Even so, the flow in the image resembles the inconsistency of the inertia-gravitational range. The sporadic coiling is evidenced in this image by the tangled, collapsed coil at the contact point. As a result of the inertial-gravitational interactions, there are potentially multiple coiling rates for matched fall height and fluid characteristics. This is partly supported by the ratio of the initial and final stream radii, was $\alpha_1/\alpha_0 = 0.5/3 = 0.167$. Using the plot in Figure 4, we can identify the α_1/α_0 in the inertia-gravitational regime [11].

For the coiling photo in figure 2, the primary change is the fall height and $\widehat{H} = 27$. This falls in the inertial regime and accordingly, th coiling in figure 2, complete with secondary buckling in the coil structure is similar to that observed in stacked coils in the inertial regime and included as Figure 5 [11]. In the inertial regime, the coiling frequency is predicted by an equation that incorporates the mass flow rate, the final stream radius, and the kinematic viscosity. The final stream radius is predicted by the equation \alpha_1 ~ (Q^2/gH)^{1/4} = 0.92^2/(9.18*0.3)^{1/4} = 0.74mm. Then the coiling frequency is approximated by $\Omega \sim (Q^4/v\alpha_1^{10})^{1/3} = (.92)^4/(0.0035 * 0.00074)^{1/3} = 9.8$ coils per second.

Throughout our imaging session, the honey rope coiling made fascinating patterns and braiding paths that slow sunk into the surface.

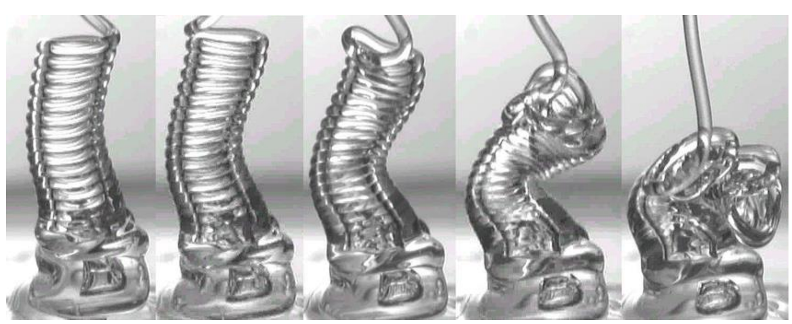


Figure 5: secondary buckling in the coil over a 0.1s time course. Published by Habibi 2007.

Imaging technique

A Sony α6000 DSLR camera was used to capture a series of photos.

The camera was set to an automatic action setting. The camera settings are described in Table 1.

Table 1. Camera settings

Camera settings	**Sony α6000** (ILCE-6000)
Focal length	50 mm
Field of View	With a 50 mm lens at a distance of 0.5 m from the subject, the field of view is approximately W 26.6°, H 17.9°, and D 31.7°[12]
Depth of field	Span = 0.02 m, ranging from 0.49 to 0.51 m [13], [14]
Aperture	f/ 4
Exposure time	1/160 s
ISO	1600
Pixels	6000 x 3376
Sensor size	23.5 x 15.6 mm
Lens	**SEL50F18**
Optical Steady Shot (OSS)	Image stabilization [14]

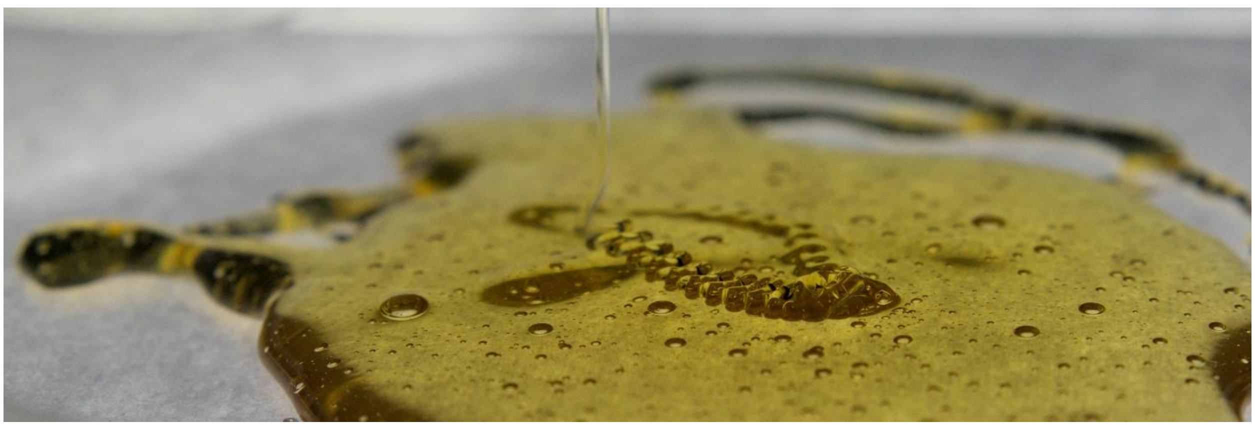


Figure 6:Honey braiding during pour

The lighting in the image is from a light table positioned below the frosted plastic plate. The light table was an NXENTC A4 Tracing Light Pad purchased on Amazon [15]. The light source is LED diffused through white plastic with a rate power of 6W and a brightness around 4000 lux. The light was further diffused through a sheet of paper placed directly on top of the light pad. Due to the offset created by the plastic plate, the surface of the light pad was about 2 cm below the plate surface supporting the honey.

The camera was positioned about 50 cm from the subject and aligned approximately level with the plate surface. At this proximity, the depth of field was low, with a span of about 2 cm as visible in the rapidly out of focus background in figure 6 [13]. The field of view as relatively narrow for this same reason [12].

The photo is spatially resolved, though the high ISO and the bright reflectivity of the honey limited the available contrast for the coil structure.

The image includes some motion blur at the top of the coil structure where the stream is rapidly circling to lay down the coil. The motion is blurred across about 30 pixels in an image that was originally 6000 pixels wide. The plate in the image, which is approximately 2/3 of the frame is 20 cm across, so that the field of view is approximately 30 cm. Then the coiling honey moved 0.15 cm during the 1/160s exposure time which is a velocity of 28 cm/s. This is imperfect temporal resolution, but the motion blur adds a pleasing smokiness to the flow action.

In post processing, the image was cropped to remove the edge of the plate my teammate's arm in the background. I deepened the shadows in the image to highlight the coiling layers as well as the bubbles trapped in the honey and illuminated from below. I also increased the exposure slightly to add +0.7EV.

Image reflection

Short on time for this submission, I struggled to choose the photo that I thought best met the objectives of an interesting flow phenomenon and an artistic image. Ultimately, the limitations of my original image (included as figure 2), which included high ISO, low resolution after cropping, and the placement of the petri dish bisecting the flow, meant that it did not meet the artistic standards despite the multiscale buckling captured. Instead, this photo shows the roping coil flow and balances it with the light and color of the honey. It is this kind of glassy gold color that brings to mind the honey and ambrosia of the ancient gods.

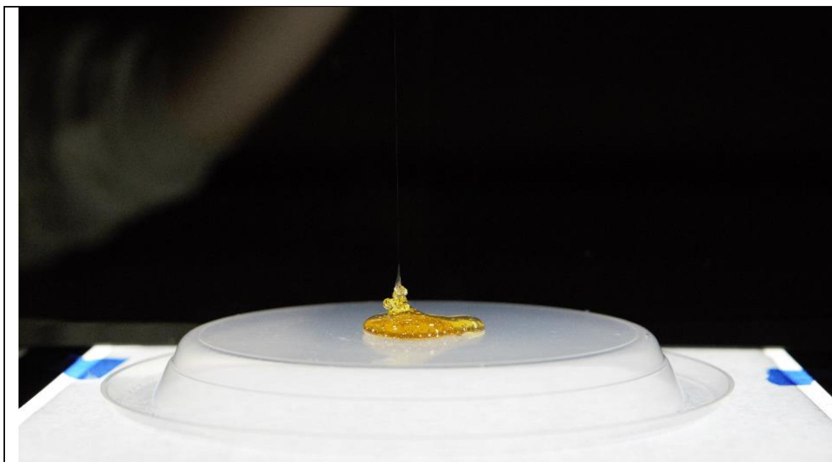
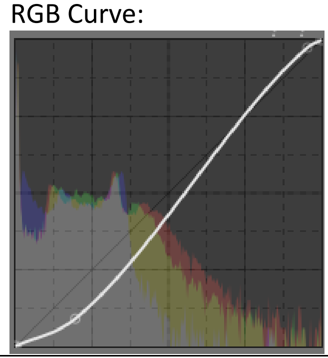


Figure 5	
Unedited photo	Edited photo
Dimensions: 6000 x 3376	Dimensions: 1441 x 2106
	RGB Curve: 

Citations:

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