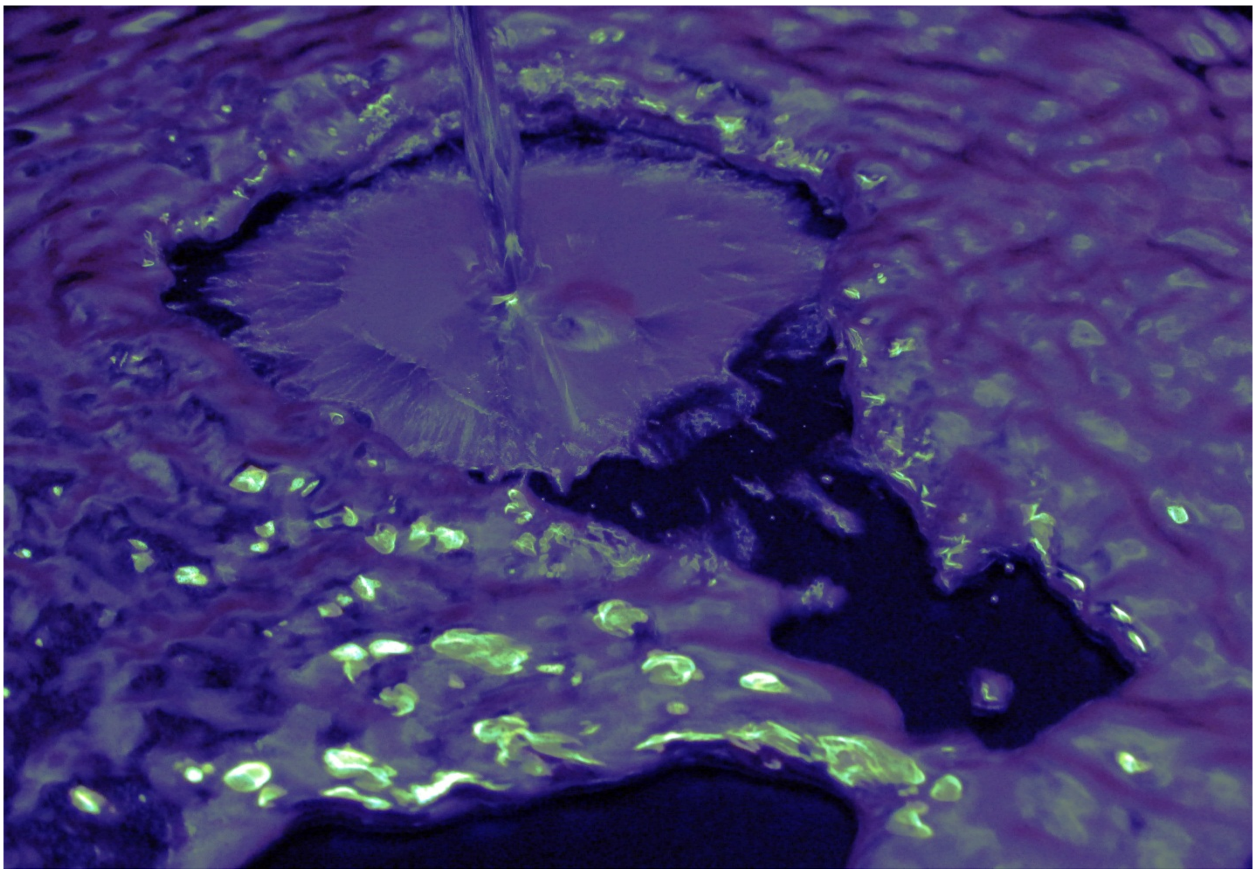
HATTER'S NIGHTMARE

The Art and Physics of the Chaos of Mercury

Project 1: Get Wet



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Origins

Hatter's Nightmare is the result of the first project, called Get Wet, for the Flow Visualization class at the University of Colorado at Boulder. Initial attempts were made to drop mercury through a column of water, oil, and alcohol based dye with the goal of capturing the wake of the mercury streams and drops. This idea failed to produce images of any significance since all mercury streams and drops fragmented upon impact with the top surface and subsequent transitions between fluids. The result was close to a hundred pin-head sized orbs of mercury raining through the column of water. During cleanup of the dye and oil instruments in the sink, the water stream impacting the sink gave rise to another idea, the use of mercury to model this impact phenomenon. With the help of Dillon Thorse, a fellow Flow Visualization student, a photo shoot was performed the following day of mercury poured onto a solid surface.

Experimental Setup

The experiment was setup under a fume hood in the Integrated Teaching and Learning Lab on campus for safety reasons and those handling the mercury wore butyl gloves and safety eyewear. Under the fume hood a base of wax paper was set up beneath a large bin to catch any stray splatter. The impact surface was placed within the bin prior to pouring. The mercury was poured from a nearly full 120 ml glass container. The 115 ml of mercury was poured onto the impact surface using various initial heights and pour rates. Following a pour the mercury was returned to the glass container and poured again. This was done several times to get a variety of photos under different conditions at different intervals during the pour. The flow captured in Hatter's Nightmare is of mercury impacting a dry surface at moderate speed. The pouring was done 25 cm above the container, and the incident column of fluid was near 1.5 cm across.

Physics from Pour to Photo

The flow in Hatter's Nightmare is a gravity driven flow incident on a solid, dry surface. During impact the mercury is governed by the conservations of mass, energy, and momentum as described by the Reynolds Transport Theorem. Equation 1 (dissected in appendix) demonstrates the Reynolds Transport Theorem with 'N' holding the place of the conserved entity, and with 'η' holding the place of velocity with respect to an origin for momentum conservation, the square of this quantity for energy conservation, and simply being one for mass conservation.

$$\frac{DN_{system}}{Dt} = \iiint\limits_{C\,V} \frac{\partial \rho \eta}{\partial t}\, dV + \iint\limits_{C\,S} \rho \eta v_{wrt\ boundary} \cdot \hat{n} d\sigma$$

Equation 1

Following the impact behavior of the mercury, it is governed primarily by four non-dimensional numbers, the Reynolds (Re), Weber (We), Ohnesorge (Oh), and Froude (Fr) numbers. These quantities are listed in Table 1 along with their respective formulas, plugged in parameters, and calculated values.

Table 1: Related dimensionless quantities and their calculations

Quantity	***Formula***	***Plugged in Parameters***	***Calculated Values***
Re	$\frac{vD}{\nu}$	$\frac{(5\ {}^{m}/_{s})(0.015\ m)}{0.114 \times 10^{-6}\ {}^{m^2}/_{s}}$	657,895
We	$\frac{\rho v^2 D}{\sigma}$	$\frac{\left(13579\ {}^{kg}/_{m^3}\right)(5\ {}^{m}/_{s})^2(0.015\ m)}{0.4865\ {}^{N}/_{m}}$	10,467
Oh	$\frac{\sqrt{We}}{Re}$	$\frac{\sqrt{10467}}{657895}$	1.555×10^{-4}
Fr	$\frac{v}{\sqrt{gl}}$	$\frac{5\ {}^{m}/_{s}}{\sqrt{\left(9.81\ {}^{m}/_{s^2}\right)(0.001\ m)}}$	50.5

The Re number being less than 10^6 means that the flow is laminar, and since the Re number is relatively large, the inertial forces dominate over the viscous forces. The We number represents a measure of inertial effects over surface tension effects. A large We number, such as with this flow, implies that inertial forces dominate over surface tension forces. The Oh number compares Re and We, essentially comparing viscous forces to the square root of inertial and surface tension forces. Since the Oh number is extremely small, the viscous effects and forces can be considered relatively nonexistent, and the flow can be modeled as an inviscid flow. The Fr number compares the characteristic velocity of the flow to a characteristic wave propagation velocity (i.e. inertial to gravitational forces). A high Fr number (greater than one), like that for this flow, denotes a supercritical flow where the spreading lamina will tend to thin as it expands as opposed to thicken.

Since the Re, We, and Fr numbers are all high, the lamina resulting from impact behaves in a similar fashion to a rain drop impacting a surface. The spreading phenomenon resulting in the lamina is similar to that explored by Eggers, Fontelos, Josserand, and Zaleski in their paper "Drop dynamics after impact on a solid wall: Theory and simulations." They note that high We numbers imply a spread of radius much greater than that of the incident fluid. The lamina grows radially outward and forms a rim as the fluid begins to retract due to surface tension. The lamina is unstable at very high We numbers resulting in a non-circular shape like that depicted in Hatter's Nightmare [Eggers]. The rim at the edge of the lamina is itself governed by the Rayleigh-Plateau instability phenomenon according to Bremond and Villermaux [Bremond]. This phenomenon gives rise to a near even distribution of rim instabilities which grow into cusps, and eventually jets. These jets then break off from the lamina as projectiles travelling radially outward [Roisman]. This instability progression can be seen in Figure 1.

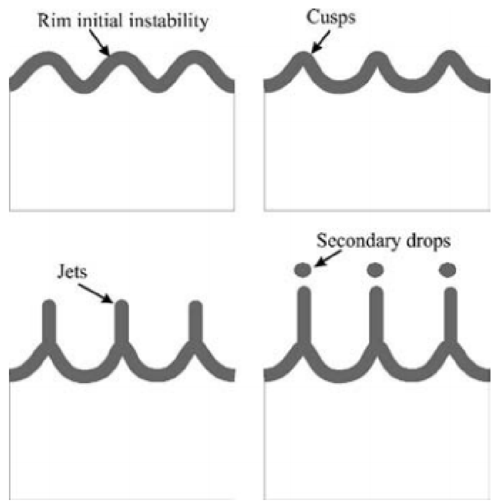

Figure 1: Rim instability progression [Roisman]

The projectiles, or secondary drops, accumulate around the outer edges of the impact surface, eventually forming a ring. The ring is kept from entirely flattening out by the high surface tension of mercury (486.5 $^{mN}/_{m}$). As the ring encroaches on the lamina, the projectiles impact the inner wall of the ring with more energy, helping to drive it back and allowing it to grow even deeper. These impacts at close quarters also result in the ripples observed in the ring in the image.

Flow Visualization Techniques

In order to capture these phenomena the choice was made to use a fluid with a high reflectivity and a lack of transparency. To maximize the effect of the reflections care was taken to minimize oxides, mercury compounds, and other impurities present by using clean plastic and glass surfaces/containers for all mercury contact, allowing for re-use. Top lighting from within the fume-hood was used to capture maximum detail, and a black impact surface was used for maximum contrast.

Photographic Techniques

The camera used was a Canon Power Shot SX 500 IS. A high shutter speed was necessary to avoid motion blur to a large extent (not entirely avoided). For this reason a shutter speed of $^{1}/_{160}$ sec was used. Since more light was required due to this fast exposure, an f-stop of 5.0 was used. This is not the smallest f-stop, but is instead the smallest f-stop providing adequate depth of field. To accommodate the reduced light making it to the recording device, an ISO of 400 was used instead of 100 to brighten the image and still maintain good clarity. The camera was used within 30 cm of the edge of the impact surface in order to fill the entire photo with the mercury and impact surface. A list of all pertinent photo information is found in the appendix. In Photoshop, the image was cropped down to remove surroundings and an overall curve was used to increase contrast. The RGB curves were all adjusted individually to bring out certain colors and shades in the highlights and shadows. Figure 2 shows these curve adjustments for the image.

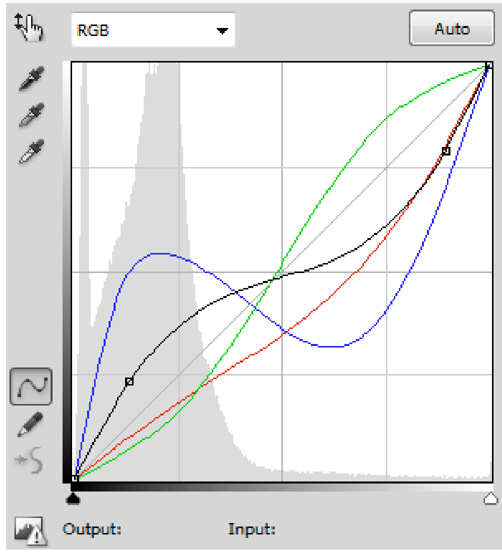

Figure 2: Curves adjusted to produce final image from original.

Discussion

To me the image reveals the chaos of both jet impacts and the liquid metal mercury. The rippling and resulting patterns, as well as the general behavior resulting from the instability of the rim and lamina are the predominant effects responsible for this chaotic flow and image. The overall colors and chaotic calmness resulting when fast meets slow gives the image a relaxing intrigue. The only issue with the image is the loss of some of the physics explanation capability (capturing of the physics). This is because the encroaching ring is so close that the projectiles traveling from lamina to ring is almost unseen. Besides this hidden portion, the physics is depicted fairly well. The only question left unanswered at this point is why the encroaching ring is not itself circular or generally symmetric. The image could have been better if the camera were close enough to minimize the necessary cropping to virtually nil. This would improve clarity and sharpness a small amount. Future developments of this experiment could include coronet (crown) splashes with mercury, Worthington's tori of mercury experiments (replicated), and spray characteristics investigations of mercury.

<u>References</u>

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Appendix

Reynolds Transport Theorem Elaboration:

Equation 1 demonstrates the Reynolds Transport Theorem with 'N' holding the place of the conserved entity, and with 'η' holding the place of velocity with respect to an origin for momentum conservation, the square of this quantity for energy conservation, and simply being one for mass conservation. Here the term on the left is the total derivative with respect to time of the quantity conserved, in the case of mass and energy this value is zero (assuming negligible energy losses during impact in the energy of the flow). For momentum, this term equates (via Newton's second law) to the force acting on the flow from the impact surface. The first integral is an integral over the control volume chosen to include the impacting column and resulting lamina. The integrand is the partial derivative of density and 'η' with respect to time. Note that dV simply corresponds to the volume integral. The second integral is an integral over the control surface chosen to enclose the control volume from the first integral. Here the integrand is the product of density, 'η', and the fluid velocity with respect to the boundary dotted with the normal to the respective surface. Note that dσ simply corresponds to the surface integral.

$$\frac{DN_{system}}{Dt} = \iiint_{C\,V} \frac{\partial \rho\eta}{\partial t} dV + \iint_{C\,S} \rho\eta v_{wrt\ boundary} \cdot \hat{n} d\sigma$$

Equation 1

Photographic Information

Photograph Date and Time	**31 January, 2013 at 22:03**
Camera Type	**Canon PowerShot SX500 IS**
Shutter Speed	**1/160 sec**
Aperture	**f/5.0**
ISO Setting	**400**
Lens Focal Length	**8.8 mm**
Distance from Lens to Impact	**30 cm**
Field of View	**Approximately: 15 x 8.5 cm**
Original Image Size	**4608 x 2592 pixels**
Final Image Size	**3750 x 2592 pixels**

Original Image