

# **Hiding in the Shadows of Convection**

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## ***Introduction***

The image shown in Figure 1 was taken for the Team First assignment, a continuation of the get wet assignment with a team to help create more complex flows and photos. For this image, my team and I discussed multiple phenomena we wanted to capture and ended up deciding on photographing quenching: hot metal rapidly cooled in water. After running a few experiments with small pieces of metal and setting off a smoke alarm, we had some success getting a photo of bubbles on a thin metal rod. Evan wanted to take this further and get a better visual of the convective process of quenching. We experimented on using a larger piece of metal, specifically a stainless-steel espresso tamper, and managed to produce a longer reaction that was easier to photograph. After taking a couple of videos, we noticed an interesting visual effect occurring from the shadow cast off the water. We wanted to record these effects firsthand, so we changed our intention of the image to capture this unique visual.

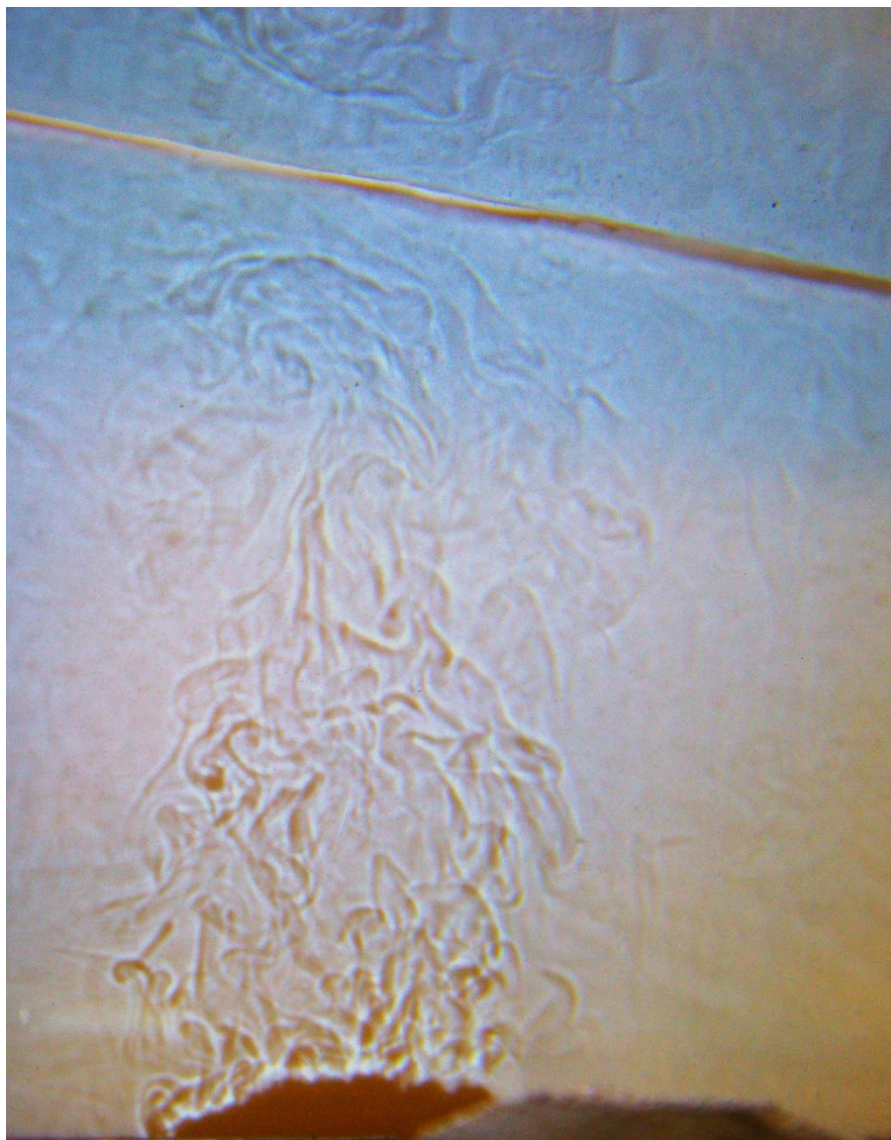


*Figure 1: Final Image*

## Experiment Setup

To create the flow apparatus for this image, we used a 12"x6"x8" tank filled with water from a faucet. We placed a white board directly behind the tank and illuminated the entire setup with four lightbulbs, distributing the light around the camera. This configuration was placed on a box, with the camera resting on the surface and pointing at the tank. A photograph of the setup is provided in Figure 2, seen below.



Figure 2: Photo of experiment setup

To run our experiment, we took a 2" diameter stainless steel espresso tamper and heated it on a stovetop until glowing hot. In our actual experimental testing, we heated the tamper to a wide range of temperatures. The tamper is then placed into the bottom of the tank of water with a thermally nonconductive lifter and the camera starts rolling.

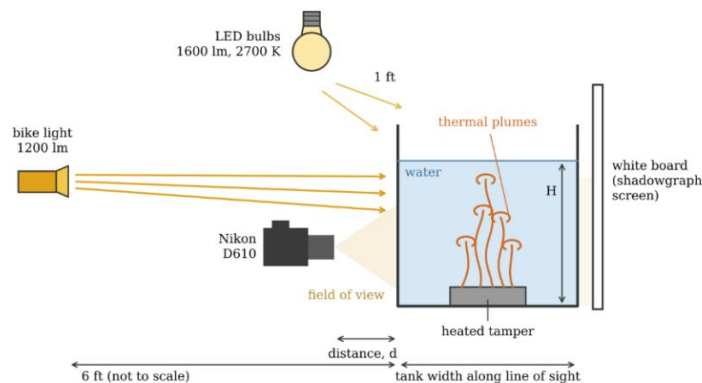


Figure 3: Apparatus Sketch

## Fluid Mechanics

To describe the fluid motion, I will break it down into components. The main principle that applies to this experiment is convection. Heat leaves the tamper primarily by natural convection, in which buoyancy alone drives the flow (Eaton n.d.). The water in contact with the hot tamper gains energy and expands, causing its density to fall below that of the surrounding water. This density difference is acted on by the force of gravity, resulting in a net upward buoyancy force that causes warm water to plume. Cooler water moves in from along the bottom of the tank to replace the rising plume, producing the circulation visible in Figure 1. The visual effect we captured in this image comes from the large temperature difference between the tamper and the fluid. The refractive index of water decreases as it warms, so the rising plume of warm water bends light, creating a shadow effect on the white backdrop.

To analyze the convective flow characteristics, I treated this as a simple closed system containing a single plume with a diameter of 2mm. Due to our lack of measurements, I did not measure a definitive temperature delta for the tamper and the water, so I will estimate this to be around 50 °C. To find characteristics of the flow, I will use the following nondimensional numbers and associated equations:

Grashof Number:

$$Gr = g'L^3/\nu^2$$

Reynolds Number:

$$Re = UL/\nu$$

Rayleigh Number:

$$Ra = Gr * Pr$$

With water at room temperature (25 °C), we can assume the following:

$$\beta = 2.6 \cdot 10^{-4} \text{ 1/K}$$

$$\nu = 8.9 \cdot 10^{-7} \text{ m}^2/\text{s}$$

$$Pr = 6.1$$

Due to buoyant forces acting on this system, we cannot assume that the force of gravity  $g = 9.8 \text{ m/s}^2$ . Rather we need to use the formula for buoyant force as follows:

$$g' = g\beta\Delta T = 0.127 \text{ m/s}^2 \quad \text{this gives: } U = \sqrt{g'L} = 0.016 \text{ m/s}$$

We can now calculate the nondimensional numbers as follows:

$$Gr = 1290$$

$$Re = 35.9$$

$$Ra = 7850$$

Using these nondimensional numbers, we can draw definitive conclusions about this flow. Looking at the Rayleigh number, we see that it is a very low value proving that this flow has not transitioned to turbulent, therefore we can conclude that the plumes created follow a laminar flow. A Rayleigh number above  $10^9$  implies that the convection causes a turbulent flow, and the calculated value is magnitudes below this. The Reynolds number supports this claim, as a low Reynolds number of 36 means that the flow of each plume is laminar, with continuous edges that do not break up into turbulent flow.

### ***Visualization Technique***

The main technique that is used in taking this image is Schlieren photography. Schlieren photography is when a transparent media is used to visualize something invisible to the human eye. The specific style of Schlieren photography my team and I used in this photo is shadowgraphy, the use of natural light and shadows to create the Schlieren effect. The physical phenomenon is described in the fluid motion section, where the hot water has a smaller index of refraction resulting in shadows (Settles, 2001). We used a white backdrop to capture these shadows and provide a contrast for the camera to focus on. The bending of light creates large wisps that are not proportional to the fluid's internal plumes, the shadows are distorted images as light struggles to pass through the tank of water. To clearly see the shadow effect, we used four separate lights placed around the camera and tank to ensure the entire white background is illuminated. We used a VASTFIRE VA-B01 bike light with 15 watts and 1200 lumens to illuminate the entire setup, and placed this light around 6 feet away from the camera. Three LED light bulbs with 13.5 watts and 1600 lumens were placed around the camera lens itself, creating the shadow offset seen in Figure 1. The camera itself was propped up against the glass of the tank, and a short lens was used to capture a wide view of the tank.

### ***Photographic Technique***

This image was taken using Evan's camera, a Nikon D610 using a Nikon variable 24-85mm lens with a focal length of 48 mm and a sensor that is 35.9 x 24mm. The exposure was set to f/4.2, 1/4000s, and an ISO of 3200. The original image was 6016 x 4016 px, and the final image was cropped down to 2843 x 3627 px. The camera was up close to the tank, around 2" from the glass and 4" from the tamper. This setup gives a computed field of view of 215 x 144mm, and the cropped image comes out to 102 x 130mm. To process this image, I used the integrated image editor in Microsoft and messed around with different contrasts and brightnesses, trying to get the plumes in detail and outlined. I eventually landed on the following settings to edit my image:

| Property   | Initial image | After editing |
|------------|---------------|---------------|
| Contrast   | 16            | 27            |
| Shadows    | 98            | 57            |
| Highlights | 0.08          | 0.26          |

## **Discussion and Reflection**

The image reveals a network of buoyant thermal plumes rising from a stainless steel tamper. Near the base the shadows form small, tightly curled structures where heated water and vapor plumes are first created. Higher up, the plume strands merge into broader strands and curl into a wide head as the plume slows around cooler, denser water. Because a shadowgraph responds to the refractive index rather than to temperature itself (Settles 2001), the image outlines the edges of the plumes instead of filling them in. At the assumed 2 mm length scale, the Rayleigh number of about  $8 \times 10^3$  suggests laminar flow and the Reynolds number of 36 supports this claim. Since the temperature difference was assumed, these values are order-of-magnitude estimates. The intent of capturing the shadow effect was met, and the fine detail is the strongest aspect of the image. The image is weakened due to the high grain from ISO 3200 amplified during editing and the tamper cropped at the frame edge. A brighter, smaller light source, a screen placed farther from the tank, and a measured temperature difference would improve future attempts. AI assistance on this report was used to cross-check calculations, read camera metadata, generate relevant figures, and recommend editing changes. Overall, I really enjoyed the process of creating this image, I never knew about shadowgraphy and this was an amazing hands on experience.

## References:

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