Two Visualizations of Rayleigh-Benard Convection Cells

Submitted to

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Introduction

The following two images were taken as part of the third group project in the Flow Visualization course at the University of Colorado at Boulder. The intent of this project was to visualize Rayleigh-Benard convection cells in fluids using primarily household materials for the purpose of both art and science. The resulting images are shown below in Figures 1 and 2.

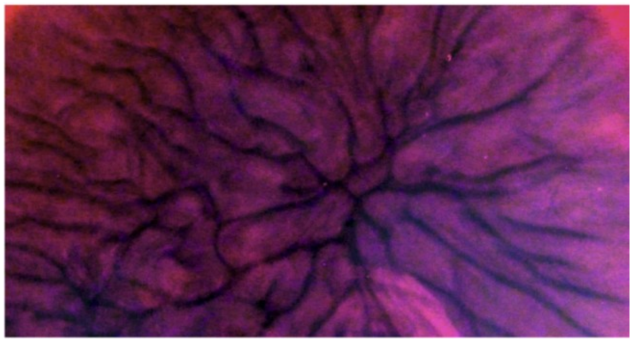

Figure 1. Rayleigh-Benard convection cells visualized in water with shampoo

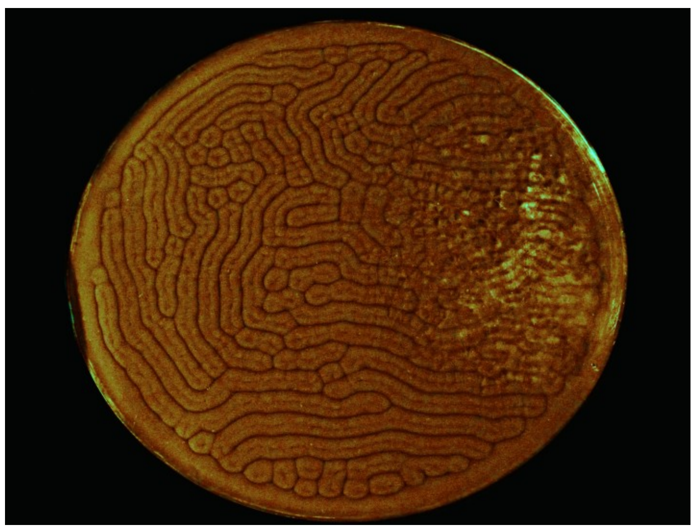

Figure 2. Rayleigh-Benard convection cells visualized in a mixture of olive oil and canola oil with aluminum and magnesium filings

Methods

The two experiments were conducted in the kitchens of the engineers. The two different images required two different, although similar, techniques and experimental setups.

Image One

Experimental Methods

In the first image, shown in Figure 1, the convection cells were visualized with dyed water and shampoo. For this image, a pot of water was placed on a natural gas burner on the lowest setting possible and a pie tin was placed on top of the pot of simmering water in a double-boiler type configuration as shown in Figure 3, below. The light was aimed from the left and the camera was directly above the flow.

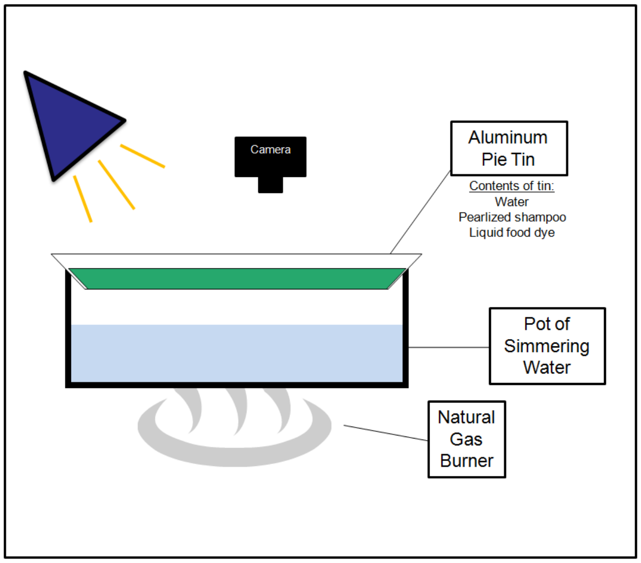

Figure 3. Experimental setup for first image

The pie tin was filled halfway with water and several drops of green food coloring. Then, about ten squirts of shampoo were added and stirred until the shampoo broke up into clumps throughout the pan. The clumps of shampoo proceeded to flow with the water.

Photographic Methods
To adequately capture this image, the camera was held approximately one foot directly above the flow. The camera used was a digital Canon PowerShot SX 120 IS. F-stop value of f/2.8 was selected to maximize the amount of light and allow for shortest exposure time to minimize motion blur. Sensitivity was set to ISO 160 to reduce image noise. The flash did not fire, but the light source used was a 13 W fluorescent light which was shone about a foot above and about six inches to the left of the flow. The focal length of the camera was 6 mm or 37mm (35mm equivalent). The field of view of the original image was about ten inches high and wide. The original image was 3648 pixels wide by 2736 pixels high at a resolution of 180 dpi.

To enhance the field of view of the photo, the image was cropped to highlight the most interesting parts of the flow. The resulting field of view is approximately four inches high by eight inches wide. The cropped image is 1677 pixels wide by 885 pixels high at a resolution of 180 dpi. The crop did successfully highlight the most interesting part of the photo. The image's contrast was increased on each individual RGB channel until a pleasing combination was found, and then it was filtered through the "underwater" filter in Photoshop. These changes allow the viewer to perceive the depth of the fluid and the details of the convection cell boundaries in the flow.

Image Two
Experimental Methods
The second image, shown in Figure 5, is a visualization of Rayleigh-Benard convection cells using a blend of canola and olive oils seeded with a blend of mainly magnesium dust. The cell was formed by machining an 80 mm dia. x 1.5 mm deep cavity in a 9.5 mm

thick circular aluminum plate. The top surface was formed by standard 3/32" thick window glass. Seed particles were manufactured by sanding magnesium sheet with 600 grit SiC sandpaper in the base oil and are estimated to be 3 micrometer in size. Magnesium was chosen as the lightest particle (compared to oil) that was easily obtainable. Oils were chosen based on the very high smoke point. The cell was placed directly on a natural gas (kitchen stove) burner on a medium setting.

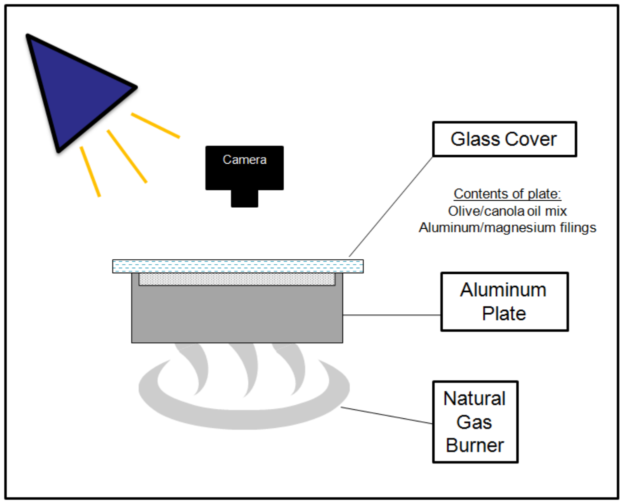

Figure 4. Experimental setup for second image

Photographic Methods

For this image, the camera was also held approximately one foot directly above the flow. The camera used was a digital Canon PowerShot SX 120 IS. The engineers chose to use an F-stop value of f/8 with an aperture value of f/8. The ISO was set at 800 with a shutter speed of 1/320 sec. The flash did not fire, but the light source used was a 500 W fluorescent light which was shone about a foot above and to the left of the cell. The focal length of the camera was 20.1 mm or 121mm (35mm equivalent). The field of view of the original image was about 100 x 175mm. The original image was 3648 pixels wide by 2736 pixels high.

This image was not cropped at all. The background of the image was completely blacked out using a paintbrush in Photoshop. The only additional enhancements made to this photograph were an increase in contrast and the use of an orange filter to help heighten the contrast and improve the aesthetic effect of an otherwise grayscale image.

Analysis

When relatively shallow bodies of fluid are exposed to negative vertical temperature gradients (with heat source below) in the presence of gravity, fluid forms a positive density gradient that drives a convective flow pattern. If the temperature gradient is sufficiently small, the heat flux can be accommodated through conductivity alone. The nature of heat transfer mode can be determined by calculating Rayleigh number using the equation below where α, κ and ν are explained in the table below.

$$R = \alpha g \Delta T d^3 / \kappa \nu,$$

Rayleigh numbers above a critical value of ~1700 (1100 for open surface) determine the transition to convection. If the heating pattern is sufficiently uniform, a global circulation cannot establish itself and the fluid breaks down into small convective cells establishing a so called Rayleigh-Benard convection pattern. Within each cell, the fluid forms a closed circulation loop, rising at the center of the cell sinking at the edges.

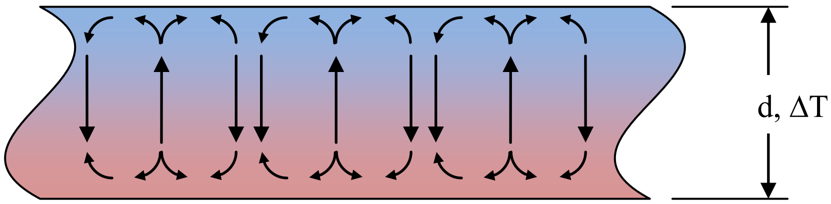

Figure 5. Benard convection cells.

The table below illustrates the estimation of temperature gradient required to create a critical Rayleigh number and drive Rayleigh-Benard convection.

	Oil	Water
Coefficient of Thermal Expansion, α (K^{-1})	6.90E-04	$4.5365 \cdot 10^{-04}$
Kinematic Viscosity, ν (m^2/s)	1.00E-06	$0.553 x 10^{-6}$
Thermal Diffusivity, κ (m^2/s)	7.99E-08	$0.15 x 10^{-2}$
Rayleigh Number	1700	1100
Prandtl Number		3.56
Calculated ΔT (K)	6	0.02

Values from www.EngineeringToolBox.com

The estimates of the temperature gradient are based on the Rayleigh number being at critical. However, typical engineering applications involve Rayleigh numbers several order of magnitude higher. Thus it is reasonable to assume that much higher temperature gradients were actually present. In addition, certain assumptions had to be made in the calculation of the Rayleigh number due to unavailability of better fluid property data. Water viscosity was assumed to be unaffected by the addition of the shampoo and was extrapolated for the oil. Temperatures were estimated based on human touch and oil smoking point.

Conclusion

The intent of the engineers was fully realized with these images. The images successfully reveal the physics and beauty achieved with Rayleigh-Benard convection cells. The biggest flaw of the images is the photographic techniques used. The engineers would choose to improve the surrounding lighting in order to more easily visualize the contrasting cells without having to digitally alter the contrast and other aspects of the photographs. Additionally, the resolution of each image could have been improved for a less grainy and more pleasing image. This idea could be developed further by visualizing the same phenomenon using different fluids seeded with different tracing particles.

Bibliography

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