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MCEN 5151 — Flow Visualization
Team Third Report

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Convection Cells

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1 Introduction

For our final assignment, Anton, Jay, and I decided to experiment with thermal convection to visualize the flow patterns due to temperature gradients in a fluid. We were interested to see how the differences in temperature could form the fluid into cellular structures. Figure 2 displays the convection cells from our experiment, each separated by dark boundaries with a glittery blue/grey appearance. The intent was to visualize the interactions between buoyancy, viscous forces, and surface tension which allow these unique structures to form.

2 Experimental Setup

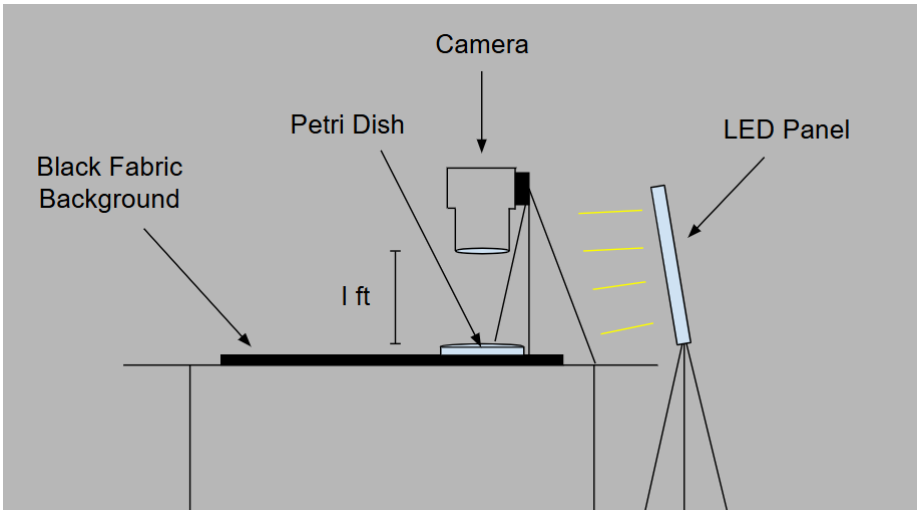


Figure 1: Experimental sketch.

The team prepared a thin layer of cooking oil about 10 mm deep inside a 90 mm glass petri dish. We added about a teaspoon of black mica powder to the oil and mixed with a popsicle stick. A Jetboil was used to heat up the petri dish and create the temperature gradient across the fluid. The Jetboil was turned on low, and we left the petri dish on top for approximately 5 minutes. We then took the petri dish off and positioned it in front of the camera for the photo.

Looking to Figure 1, the camera was positioned approximately 1 ft away from the petri dish, capturing the photo from directly above. Lighting was provided by an LED panel, allowing the reflective mica particles to stand out against the darker regions of the flow and the black fabric background.

3 Flow Physics

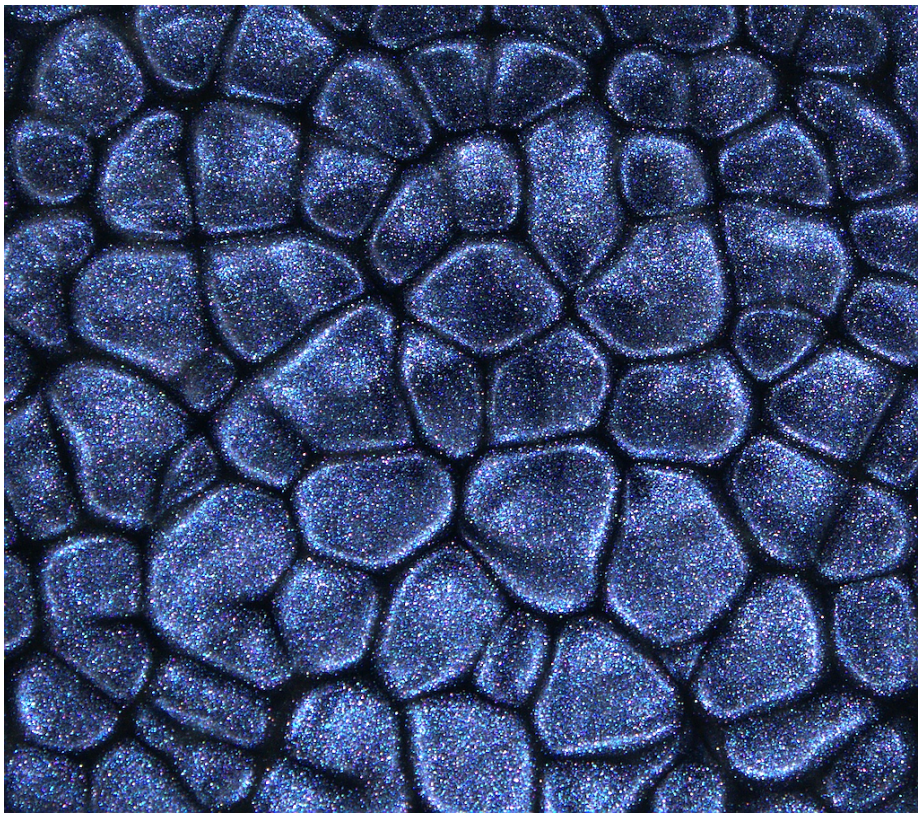


Figure 2: Post-processed visualization of convection cells.

Heating the oil and mica powder mixture from below causes the fluid near the bottom to expand and become less dense. The warmer oil rises because it is more buoyant, and the cooler, denser oil sinks. The continuous circulation of the mixture transports heat through the motion of the oil as well as through conduction. This is the phenomena that is described by Rayleigh–Bénard convection. In the MIT lecture notes, Rothman explains that a larger temperature difference between the bottom and top of the fluid layer makes this circulation more likely to develop. [1].

Figure 2 shows the polygonal cells outlined by dark boundaries. The view from above shows how the cells are arranged and how their shapes and sizes vary across the dish. Determining whether the oil rises at the centers or along the edges would require observations of the motion over time. As it is a three-dimensional moving flow, we received many comments suggesting consideration of a video or in-plane view for future experiments.

It is important to look at how much of an effect the temperature difference across the 10 mm oil layer has on the circulation that produced the cells. The Rayleigh number measures the strength of buoyancy relative to the effects of viscosity and thermal diffusion [1].

$$\mathrm{Ra} = \frac{g\beta\Delta T H^3}{\nu\alpha}, \tag{1}$$

where g is gravitational acceleration, β is the volumetric thermal expansion coefficient, ΔT is the temperature difference between the bottom and top of the layer, H is the oil depth, ν is the kinematic viscosity, and α is the thermal diffusivity.

At a depth of 10 mm, the depth term is $H^3 = 10^{-6}\,\mathrm{m}^3$. To realize the impact of this term, a 10% increase in depth would raise the estimated Rayleigh number by about 33% if the other inputs stayed fixed. This is because it is raised to the third power. To estimate the Rayleigh number, the properties for the canola oil were chosen at 323 K conditions. The following values are estimated from a published source by Garcia Rojas et al.: a volumetric thermal expansion coefficient of $\beta \approx 2.5 \times 10^{-4}\,\mathrm{K}^{-1}$, a kinematic viscosity of $\nu \approx 3.2 \times 10^{-5}\,\mathrm{m}^2/\mathrm{s}$, and a thermal diffusivity of $\alpha \approx 9.2 \times 10^{-8}\,\mathrm{m}^2/\mathrm{s}$ [2]. The temperature difference across the oil was not measured, so $\Delta T = 10\,\mathrm{K}$ is assumed. Using the 10 mm oil depth in Equation 1:

$$\mathrm{Ra} \approx \frac{(9.81)(2.5 \times 10^{-4})(10)(0.010)^3}{(3.2 \times 10^{-5})(9.2 \times 10^{-8})} \approx 8.3 \times 10^2. \tag{2}$$

Using an assumed temperature difference of 10 K, the estimated Rayleigh number is about 830. This is below the critical value of about 1708 for an ideal oil layer between two rigid surfaces held at fixed temperatures [1]. In our experiment, the petri dish had an exposed upper surface which changes the threshold for convection driven by buoyancy. Temperature differences along that surface can also drive circulation through surface tension gradients [3]. Because the temperature difference across the oil was assumed, the estimate is uncertain, but there was likely a combination of both surface tension and buoyancy contribution to the circulation.

4 Visualization Technique and Equipment

The oil was bought from the grocery store, the mica powder was bought from Michaels, and the glass petri dish was purchased from the chemistry lab. The black mica powder made the cellular pattern visible in the oil. Light from the LED panel reflected off the small mica flakes to create the glitter/sparkle effect. The dark regions between cells made their outlines easier to distinguish, and the black fabric reduced distractions in the background. The intensity of the reflected light provides a sufficient contrast to visualize the pattern.

5 Photographic Technique

The photograph was taken with a Sony ILCE-6300 digital camera positioned about 1 ft above the dish and aimed straight down. The camera was set to a focal length of 55 mm, an aperture of f/8, a shutter speed of 1/160 s, and ISO 640. The original RAW image was 6024 × 4024 pixels, and the final processed image was 1018 × 900 pixels.

The 90 mm dish spans approximately 3,400 pixels across in the original image, based on the diameter measured in the image editor. This gives an approximate scale of 0.026 mm per pixel near the oil surface in the original image. At 1/160 s, a particle moving parallel to the image plane at about 4.2 mm/s would travel roughly one original-image pixel during the exposure.

Post-processing included cropping of the image to zoom in on the interesting aspects of the flow and remove glare. Sharpness was increased to improve clarity between cell and cell boundary. Exposure was increased to make the image pop.

6 Conclusion

I like the contrast between the glittery blue-gray interiors and the dark boundaries. The cells form a recognizable pattern, but their shapes and sizes vary enough to make the image quite interesting and fun to look at.

If I repeated the experiment, I would measure the oil depth and the temperatures at the top and bottom when the image is captured. These measurements would allow a more accurate estimate of the Rayleigh number for the specific experiment. I would also record video before and after removing the dish from the heater to see how the cell boundaries move and how long the pattern persists. Overall, I am very happy with this result. It adequately reveals in the physics of the flow and creates a visually appealing photo to look at.

References

[1] D. Rothman, *Fluid Dynamics and Rayleigh–Bénard Convection*. Lectures 17–18, *Nonlinear Dynamics: Chaos*, MIT OpenCourseWare, Fall 2022, sec. 1.5. Public lecture PDF.

[2] E. E. Garcia Rojas, J. S. R. Coimbra, and J. Telis-Romero, "Thermophysical Properties of Cotton, Canola, Sunflower, and Soybean Oils as a Function of Temperature." *International Journal of Food Properties*, vol. 16, no. 7, pp. 1620–1629, 2013. Public full-text PDF.

[3] J. G. Wissink and H. Herlina, "Surface-temperature-induced Marangoni effects on developing buoyancy-driven flow." *Journal of Fluid Mechanics*, vol. 962, A23, 2023. Open-access article.