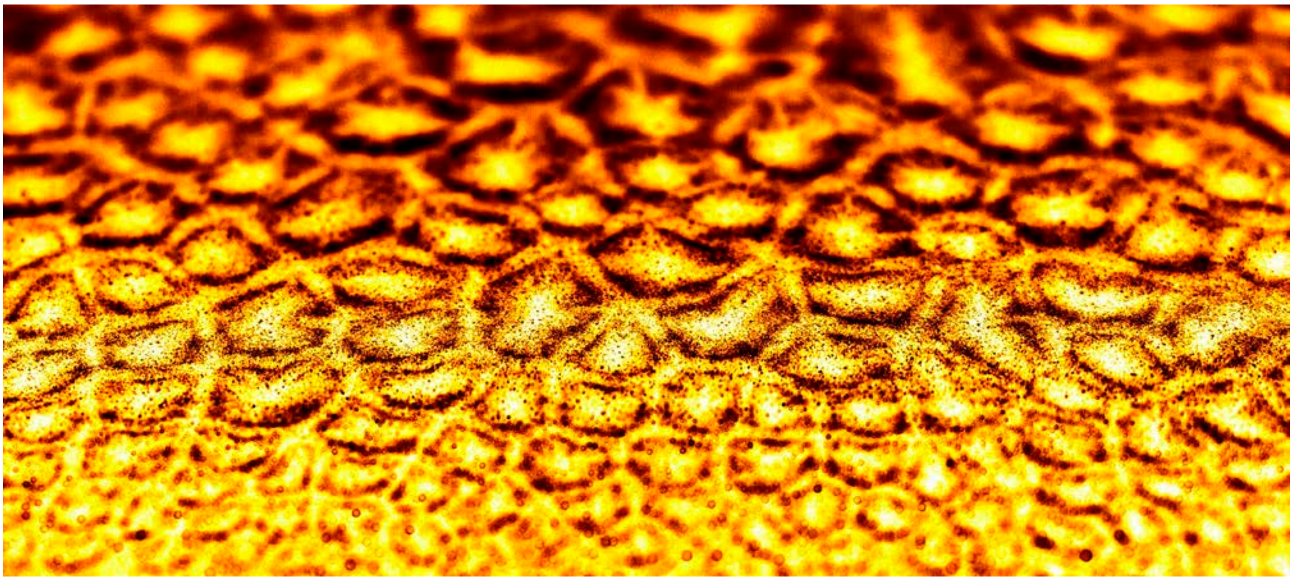

Team Project #1: Marangoni Convection

Millie Blackstun 3/20/2014

Project Objective

The goal of this project was to artistically demonstrate Marangoni convection. The team stumbled upon this phenomenon upon talking with Scott Kittleman about his Kevin Helmoholtz instability demonstrator. Scott was getting ready to leave the country, so the K-H experiment wasn't practical. Instead he gave us a tour of the ATOC lab and offered us other experimental set ups. Upon showing the Marangoni hot plate device, he mentioned that he had yet to find a good way to artistically demonstrate Marangoni convection. The team took that as an opportunity to thank Scott for access to his lab, so we began preparing the convection cell. Athena Ross, Vigneshwaran Selvaraju, and Amanda Kennedy were all present to help prepare, shoot images of, and tear down the experiment.

Experimental Apparatus and Flow Phenomenon

The experimental setup, shown in Figure 1, was rather simple. A hot plate underneath a pool of silicon oil laced with aluminum flakes (viscosity=37centiStokes) provides a heat source. Natural convection at the oil-air interface provides the heat sink. The oil was poured into the cooled device to a depth of 5cm. Once dispensed, the hot plate was connected to a Veristat to control the voltage going to the hot plate. A voltage of about 5V was enough to keep the plate heated for long periods of time with out burning the oil. A few minutes after the plate begins to heat, an observer can see the characteristic polygons of Marangoni Convection start to form. The steady state temperatures of the oil-air interface and hot plate were $\approx 71°C$ and $90°C$, respectively.

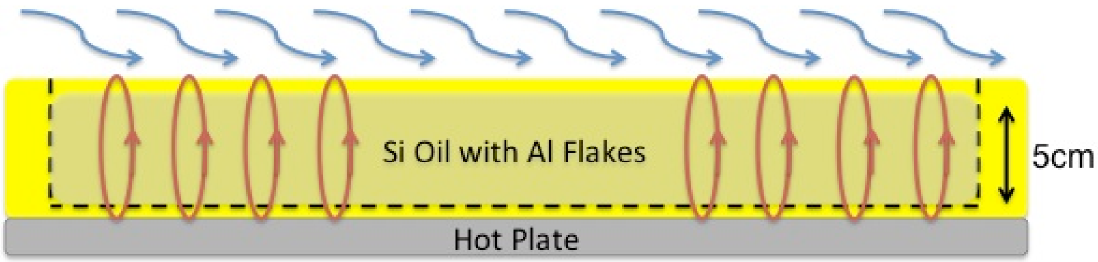

Figure 1: Experimental Setup for Marangoni Convection

Marangoni convection is most widely recognized due to its occurrence at the surface of the Sun.[i] At the core, the primary method of heat transfer is radiation. However towards the outer surface, the gas layer is thick enough, and the temperature gradient large enough, that Marangoni convection will occur. Pictures of the Sun's surface reveal the polygons characteristic of Marangoni convection. Anywhere there is a heat source, heat sink, and the right depth of fluid in between, Marangoni convection will take place, but its manifestation on the Sun that was the inspiration for this image. The pattern may be stable or unstable, depending on the details of the temperature dependence and fluid properties. For the purposes of this experiment, the flow pattern was stable. As the layer of the fluid heat up, it becomes less dense, and buoyancy causes the fluid to want to rise. A fluid parcel must be buoyant enough to overcome viscous dissipation and thermal diffusion.[ii] When the experiment has a free surface (as ours did), surface tension effects also come into play. This flow phenomenon is often confused for the Rayleigh-Bernard convection, but Marangoni convection is the term used when the cooling surface is a free surface, introducing other flow instabilities.[ii]

Tilting the experimental setup results in a liquid layer of varying depth. The size of Marangoni convection polygons is directly dependent on the cube of the depth of the fluid. As fluid depth increases, the polygons become smaller and smaller until they no longer form and pure convection has been reached. As the fluid depth decreases, the polygons become larger and larger and the Rayleigh number decreases. Once the Rayleigh number hits the critical number, 1101, Marangoni convection dissolves into just conduction, and the polygons disappear. The Rayleigh number determines what phenomenon will occur in the fluid, and can be approximated as follows in Equation 1.

$$Ra = \frac{g\alpha\Delta T}{\kappa\nu} d^3$$

Equation 1: Rayleigh Number Dependence in Terms of Fluid Depth[i]

In this expression, g is simply gravitational acceleration, α is the volume coefficient of expansion, κ is thermal diffusivity, and υ is kinematic viscosity. For this experiment, the constants of the silicon oil are as follows: $\nu = .37\, {cm^2}/{s}$, $\kappa = 7.7 \times 10^{-4}\, {cm^2}/{s}$, $\alpha = 1.04 \times 10^{-3} {}^{\circ}C^{-1}$, and $g = 9.81\, {m}/{s^2}$. This results in an approximate relationship between Rayleigh number and depth, shown in Equation 2.

$$Ra \approx 3{,}580 d^3$$

Equation 2: Rayleigh Number in Correlation with Depth[i]

If necessary, this correlation can be manipulated to control polygon size and areas of varying heat transfer methods. This tight of control was not necessary for this experiment, however.

It is "possible" to mathematically determine the size and shape of the polygons, but only through approximation methods.[iii] Two scientists in turkey recently published a complicated mathematical derivation to predict Marangoni convection behavior. Using Padé approximation and a fourth order Runga Kutta method to compare with a variable iteration method.[iii] For the purposes of this paper, the approximation method is too complicated and unnecessary for the goals of the experiment.

The relationship between depth of fluid and size of the polygons makes it possible to achieve interesting perspective effects. By tilting the plate, different sized polygons began to form, giving the illusion of observing the curved surface of the Sun. Tilting offered the perspective needed to achieve the goal of this image, and post processing the color delivered the necessary tones and hues to achieve an impression of the Sun.

Flow Visualization Technique

As mentioned previously, Marangoni convection can be achieved simply with just a heat source, heat sink, and controlled depth of fluid. Viscous fluids work better, hence the silicon oil. To visualize the convection phenomenon, however, aluminum flakes are added to the oil. The aluminum flakes will follow the streamlines of the fluid as it is undergoing convection. They will lie parallel to the fluid surface as they move across the face of the polygon, reflecting light and making the convection more visible to the naked eye. As the aluminum flakes hit the edge of the polygons, they turn perpendicular to the surface of the oil, and reflect little to no light, resulting in the dark edges of the polygons.

Halogen lamps were bounced off of a white poster board to create full and bright light to illuminate the set up. By bouncing the light off of another surface, reflections of the light source were avoided.

Photographic Technique

Approximate numbers for capturing the image are given in Table 1.

Field of View	7 in.
Distance from Object to Lens	15 in.
Lens Focal Length	18-55 mm.
Type of Camera	Canon T3 Rebel DSLR
Final Picture Size	3764 × 1671 pixels
Exposure	Aperture: 6.3 Shutter Speed: 1/15s ISO: 800
Post-Editing	Cropping, inverting colors for better definition, color channels added to produce reds, oranges, and yellows, Straightened

Table 1: Photgraphic Specs

An f-stop of 6.3 was chosen to give a controlled depth of field focused on the center of the "Sun." This also contributed to the curved perspective of the image. There was quite a bit of light bouncing off the poster board, so an average shutter speed and lower ISO were all that was necessary to deliver bright pictures. The before image is provided below in Figure 2 for comparison.

Figure 2: Original Photo

Results

The original intent of the experiment was to artistically represent Marangoni convection. I endeavored to have it mimic the Sun, which I feel was realized with perspective tricks and post color processing. The final image clearly demonstrates the Marangoni polygons, with the help of silicon oil, so I feel the goal was achieved. If I were to repeat the experiment, I may increase the f-stop to allow for a larger depth of field. The intent was to add to the perspective, and it does, but perhaps a little too dramatically. The depth of field could be widened to give a wider view into the Marangoni convection.

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[i] Kittelman, Alan Scott. "Marangoni Convection." Personal interview. 21 Feb. 2014.

[ii] University of Toronto. "Rayleigh-Bénard and Bénard-Marangoni Convection."*Experimental Nonlinear Physics*. The Experimental Nonlinear Physics Group, Dept. of Physics, University of Toronto, n.d. Web. 14 Mar. 2014. <http://www.physics.utoronto.ca/~nonlin/thermal.html>.

[iii] Karaolu, Onur, and Galip Oturançb. "A Study on Marangoni Convection by the Variational Iteration Method." *AIP Conference Proceedings* (2012): 402-06.*Chinook-University of Colorado Libraries*. Web. 14 Mar. 2014. <http://rpucolo.colorado.edu/ebsco-w-b/ehost/pdfviewer/pdfviewer?sid=9110cead-c581-4c9b-9a78-9c2f93419082%40sessionmgr115&vid=2&hid=108>.