Bénard-Marangoni Convection

Flow Visualization Group Project -1

Submitted by: Vigneshwaran Selvaraju

Bénard-Marangoni Convection simulated by Flow Visualization Spring'14 – Team# 2

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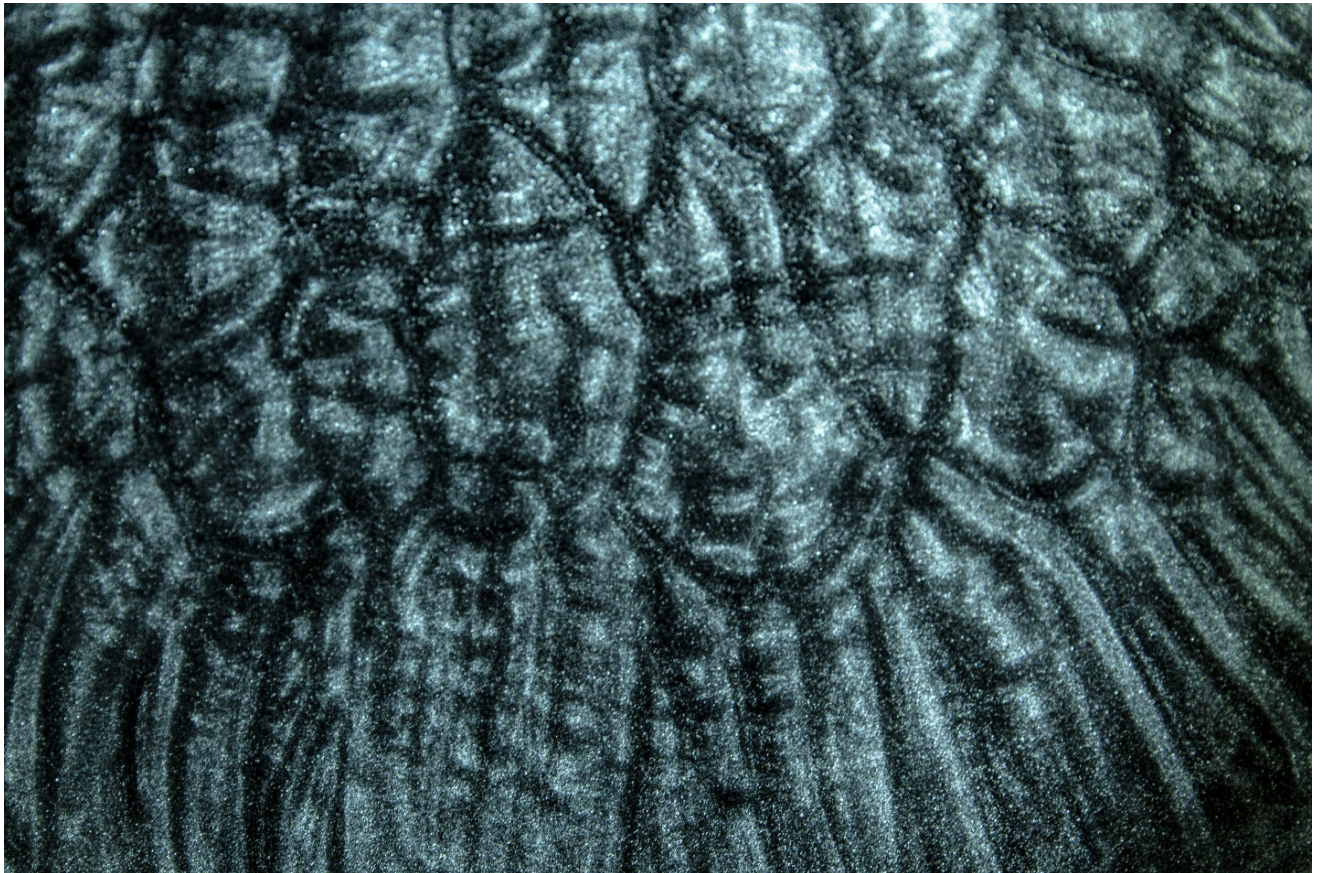
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Fig: 1 **'Forgotten'**   - Final picture portraying Bénard -Marangoni convection (and many other things).

'Forgotten'

Introduction:

The image 'Forgotten' was submitted as a part of coursework for Flow visualization Group project -1. The basis of the project is visualization of the Marangoni effect.

Physical phenomena:

To understand the Marangoni effect it is essential to understand Rayleigh-Bénard instability. The Rayleigh-Bénard convection instability occurs in a plane horizontal layer of fluid heated from the bottom. The fluid develops a regular pattern of convection cells known as Bénard cells. The convection patterns are a self-organizing nonlinear systems. [1]

Gravity and hence buoyancy is the major driving force for the Rayleigh-Bénard-Marangoni convection instability. The initial movement is the upwelling of lesser density fluid from the heated bottom layer. This upwelling spontaneously organizes into a regular pattern of cells called Bénard cells.

The dimensionless Rayleigh number (Ra_L), which essentially expresses the balance between gravity and viscous forces is given by

$$Ra_L = \frac{g\beta}{\nu\alpha}(T_b - T_u)L^3$$

Where,

- T_u is the Temperature of the top plate
- T_b is the Temperature of the bottom plate
- L is the height of the container.
- g is the acceleration due to gravity.
- ν is the kinematic viscosity.
- α is the Thermal diffusivity
- β is the Thermal expansion coefficient

The critical Rayleigh number (R_C) is the threshold over which the convection cells appear. R_C ~ 1100.65 for a Marangoni set up with controlled boundary conditions.

Rayleigh-Bénard convection experiments use fluids heated from below with a confining plate on the top surface. For the case of Bénard-Marangoni convection arrangement, the top surface does not have a confining plate and is free to move and deform. This second instability mechanism involving gradients in the surface tension, which in general coexists with Rayleigh's buoyancy mechanism, but dominates in thin layers. The situation, now called Bénard-Marangoni convection or Thermo capillary effect or Gibbs-Marangoni effect or simply Marangoni Effect. [2]

In a Marangoni experiment, a positive temperature fluctuation on the free surface leads to a local decrease in the surface tension, if the temperature derivative of the surface tension is negative. Gradients in the surface tension cause surface traction forces away from the warmer spot. These forces drive flows in the bulk of the layer and deform the surface. The flows in the bulk pump warm fluid up from the lower part of the layer, reinforcing the initial temperature fluctuation, leading to an instability and a flow which is driven by surface tension forces. The cooling of the top surface is often aided by

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evaporation. This instability does not essentially involve gravity, so it may be expected even under zero-gravity.[3]

In case of a free liquid surface in contact with air, buoyancy and surface tension effects will also play a role in how the convection patterns develop. Liquids flow from places of lower surface tension to places of higher surface tension. This is called the Marangoni effect. When applying heat from below, the temperature at the top layer will show temperature fluctuations. With increasing temperature, surface tension decreases. Thus a lateral flow of liquid at the surface will take place, from warmer areas to cooler areas. In order to preserve a horizontal (or nearly horizontal) liquid surface, cooler surface liquid will descend. This down-welling of cooler liquid contributes to the driving force of the convection cells. The specific case of temperature gradient-driven surface tension variations is Bénard–Marangoni convection.

The dimensionless Marangoni number (Mg) is given by

$$\mathrm{Mg} = -\frac{d\sigma}{dT}\frac{L\Delta T}{\eta\alpha}$$

Where,

- σ: surface tension, (SI units: N/m);
- L: characteristic length, (SI units: m);
- α: thermal diffusivity, (SI units: m2/s);
- η: dynamic viscosity, (SI units: kg/(s·m));
- ΔT: temperature difference, (SI units: K).

Visualization:

The visualization of the Marangoni convection effect was done using a setup that essentially has the following components.

1. A circular hot plate of 15cm radius with circumferential brim of 2 cm height to hold liquid.
2. Flat Aluminum flakes as indicators distributed in silicone oil. (A ratio of mixing would work.)
3. A suitable variable power supply considering the hot plate and power supply.

When the setup is heated the Rayleigh Bernard Marangoni instability kicks in and the vortices are formed. The aluminum flakes trace the path of the fluid particles and serves an indicator for us to view the flow pattern. Initially the flow pattern is not easy to see but when taken a closer look, the flakes can be seen travelling along the imaginary flow lines indicating the vortex.

The whole apparatus was sourced from Prof. Alan Scott Kittleman of Atmospheric and Oceanic Sciences (ATOC) at CU Boulder.

LED illumination was used to give a neutral color and to avoid radiative heat input to the system due to incandescent lighting. The LED was held at a height and angle with respect to the camera and silicone oil surface so as to avoid reflection into the camera and in the same time providing adequate lighting.

The approximate height used during visualization was 1 meter above the silicone oil surface at an angle of 30° from the normal to the surface. The room lights were turned off and the LED was the only source of illumination. The room temperature was around 25°C and the hot plate was at an approximate temperature of 60°C.
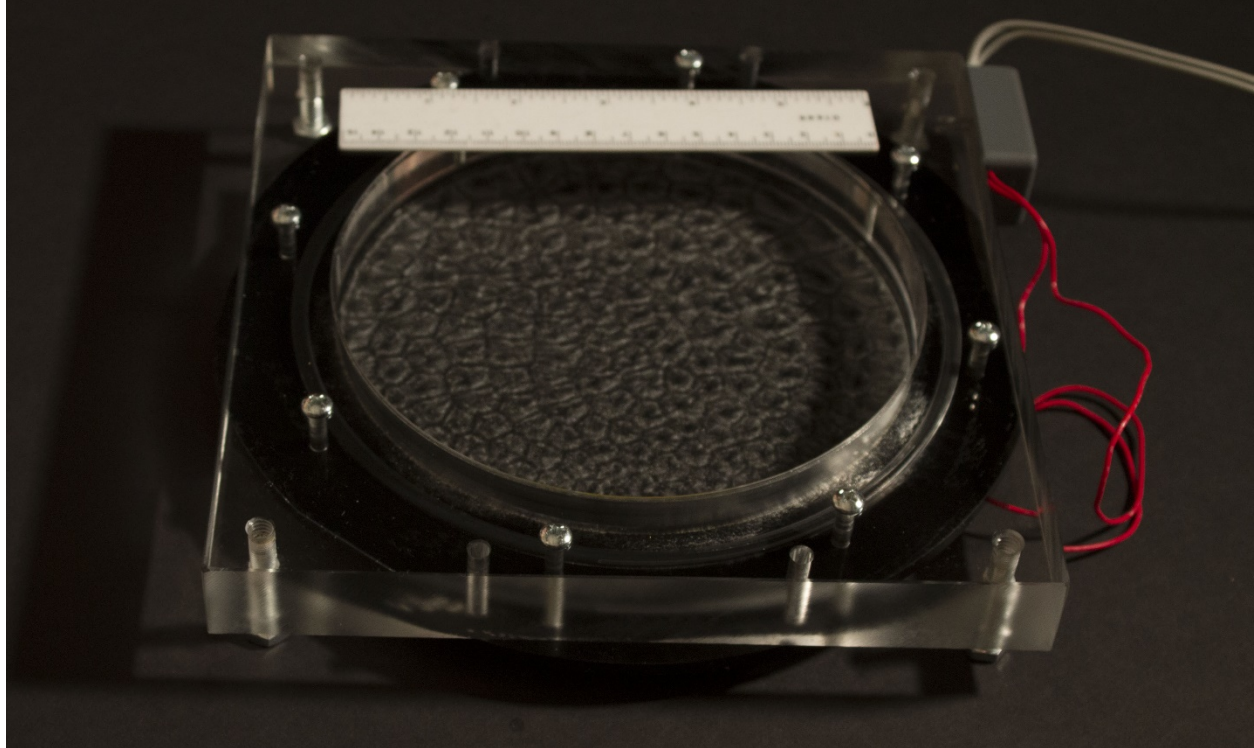

Fig 2: **Setup of simulation**

Photography:

Camera: Canon EOS REBEL T3   S/N: 322074096363

Lens: EF-S18-55mm f/3.5-5.6 IS II   S/N: 0000701f35

Image Size: 4272 × 2848

Resolution: 240 Pixel per Inch

Focus/Focal length: Manual / 55.0 mm

Exposure: 1/25 sec;   f/10;   ISO 100

Field of view: 3cm X 4 cm

Post Processing:

Post processing was done using Adobe Photoshop CS6, licensed to University of Colorado, Boulder.

The color temperature was lowered towards blue and a faint green tint was given to bring out an algal teal /old tablet outlook. The contrast was lowered to reduce reflection off aluminum flakes, making contours more visible. Highlights were also lowered with the shadows bolstered to enhance the contours.

The depth of field during photography made the upper portion less focused. The top half was divided into two layers and

Two layers of unsharpen mask was applied to the upper half of the picture to enhance the detail in a way that it appeals but not appear for the human eye.

Perspective:

The final picture 'Forgotten' generates a wide range of thought or imagination in the mind of the observer depending on their perception or state of mind. However, as a creator, the mind perspective while making the picture is described. This would also explain the choice of colors, camera settings and post processing choices made. The image is pictured as an ancient tablet containing pictures of strange looking extraterrestrials known to our predecessors and unfamiliar to the present generation. The philosophy can be explained through the words of the 4th CE Tamil poet Auvaiyaar (ஒளவையார்) that features on NASA's cosmic questions exhibit.

"What we have learned

Is like a handful of earth;

What we have yet to learn

Is like the whole world"

- Auvaiyaar [5]

This lays the emphasis on the unknown and urges the present generation to have a reality check. The thought promotes humility and points us towards an infinite potential for research in all directions.

End note:

Though the picture does a good work in describing Marangoni effect, there is still scope for improvement. In this case, the 'Forgotten' theme was decided after looking at different pictures taken on the day of simulation. A whole lot of post processing followed the decision to depict the theme. This could have been avoided if a theme was decided before the photo shoot or with another photo session. As it always goes, a clear original picture is always the best thing to have supplemented with a little bit of post processing.

For future work, a continuous macro video should be tried to explain Marangoini effect in the best possible scientific way. However, if it is going to be a thing of art, a picture will be the best bet. A stable long exposure photograph can also be attempted to create an effect similar to the waterfall effect where the streaks represent the locus of each aluminum flake.

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References:

[1] Cellular flow patterns and their evolutionary scenarios in three-dimensional Rayleigh-Bénard convection - April 2003. A. V. Getling-Institute of Nuclear Physics, Lomonosov Moscow State University, 119992 Moscow, Russia & O. Brausch, Institute of Physics, University of Bayreuth, D-95440 Bayreuth, Germany

[2] The Earth Systems Research Laboratory
http://www.esrl.noaa.gov/psd/outreach/education/science/convection/RBCells.html

[3] http://www.scientificlib.com/en/Physics/Hydrodynamics/BénardCells.html

[4] KERSTIN ECKERT, MICHAEL BESTEHORN and ANDRÉ THESS (1998). Square cells in surface-tension-driven Bénard convection: experiment and theory. Journal of Fluid Mechanics, 356, pp 155-197 doi:10.1017/S0022112097007842

[5] NASA Educator – 'Cosmic questions' exhibit link
http://www.nasa.gov/audience/foreducators/informal/features/F_Cosmic_Questions_prt.htm

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