ABSTRACT:

Convection in fluids has been studied in nonlinear dynamics for over a century. Henri Bénard did the first studies using whale oil in a single layer cell with a free upper surface [2]. He found that once a certain temperature gradient was reached, hexagonal convection cells would form. However, at higher temperatures, analysis of the motion of the fluids is not so easy. The goal of this project was to try to find, and then hopefully study, a time-dependent convection state of two immiscible fluids at relatively low temperature gradients.

INTRODUCTION:

Multi-layer convection is found in many physical sciences. It can be found in geophysics, astrophysics, atmospheric physics and many other places [3]. Some specific examples would be the case of mantle convection, modeling stellar interiors, and the growth of encapsulated crystals [1]. Despite the various fields where multi-layer convections plays a large role, much about it is still unknown.

When a fluid convects, the fluid heats up and rises and then cools and falls back to the bottom to be heated up again. This pattern will repeat itself for as long as there is enough of a temperature gradient across the fluid. A single layer of fluid, at a moderate temperature difference, will form a static pattern of rolls or cells. However, when there are two fluids, the convection becomes a little more complex.

There are two basic ways for multiple layers of fluids to link together while convecting. The first way is by thermal coupling. In thermal coupling, the flow of heat determines how the rolls align themselves. Warm fluid will be rising at one spot, through both layers, while cooler fluid will be
falling in both layers in another spot. This leads to a roll going to the right at the interface and the other roll going to the left (or vice versa) [3].

The second way for the rolls to link together is by mechanical coupling. In mechanical coupling, the rolls will align in such a way that the fluid is moving in the same direction as the fluid in the adjacent roll in the other layer. This way the rolls will link with rolls from both fluids. In this case, the cell will end up with hotter, rising flow on top of cooler, downward flow in the other layer (or vice versa) [3].

A third type uses both methods of coupling. This third state is a time dependent state of convection. In this state, the fluids will either oscillate between the two types of coupling (a standing wave) or a traveling wave forms that will advance through the cell [3].

There are two large forces that help determine which state the fluids will be in. First is the shear force between the two layers. In thermal coupling, one layer wants to move to the right at the interface, while the other layer wants to move to the left. This causes a shear force at the interface between the fluids. Second is the buoyancy force. Fluid at the bottom is heating up and becoming more buoyant than the fluid in the upper part of the layer. If the warmer fluid cannot move and just keeps warming up, then instability will result. The mode of convection depends on which of these two forces is the dominant force [2].

The two immiscible fluids studied in this experiment were FC-70 (a perfluorinated hydrocarbon oil) and 47V10 (a silicone based oil). These two fluids vary greatly in viscosity. FC-70 forms the bottom layer because it is the most dense. FC-70 and 47V10 are both clear fluids. This makes it hard to directly see what is going on in the cell. To overcome this obstacle, the shadowgraph visualization technique was used.

**SHADOWGRAPH:**

The shadowgraph technique uses the fact that the index of refraction of fluids is typically dependent on temperature. The picture taken by the shadowgraph will have black and white patches. The black spots are where the fluid is hot and diverging the light. The white spots are where there is a
cool packet of fluid that is converging the light [4]. When a beam of light goes through the fluids, it will be either focused or defocused depending on the local state of the fluid, ultimately allowing us to know what the fluid is doing.

**APPARATUS:**

The experiment is set up to observe the cell from above, looking directly down. At the top of the structure, there is an LED light. Light comes from the LED in the shape of a cone and shines down onto the cell below. Before it reaches the cell, the light encounters a collimating lens that orients all the light so that it is normal to the cell. The light reflects off a mirror at the bottom, goes through the cell, and is then reflected off a beam splitter into a CCD camera.

The main consideration that needs to be taken into account with the set up is the mirror. In this experiment, a copper plate coated with electroless nickel served as the mirror and the bottom of the convection cell. A regular mirror would not have worked because the plate needs to be able to be a good thermal conductor. While copper is very conductive, it is also a very soft metal. Therefore, the plate needed to be covered with nickel to help prevent scratching and corrosion, either of which would affect the shadowgraph image.

**THE CELL**

The cell consists of three main parts: a cooling mechanism, the fluids, and a heating mechanism. On top is the cooling chamber. The cooling chamber constantly has water being pumped into it from a water bath. This bath was uniformly maintained at approximately 21.5°C.
Variations in the temperature of the water are so minimal they do not show up on the shadowgraph images. Separating the cooling chamber from the fluid cell is a sapphire window. Sapphire was used instead of glass because of sapphire’s relatively high thermal conductivity.

Below the sapphire window sits the fluid cell. The cell was made from a piece of acrylic. The part of the cell that holds the fluid is only 7.5mm thick. With a fill hole on one side, and an air escape hole on the other, it can be clamped down between the cooling chamber and the hot plate so that it does not leak.

A heat resistive heating pad heats the cell from below. Between the pad and the cell is the large copper plate mentioned above. The pad is as large as the cell and can therefore heat the cell uniformly. It is important for both surfaces of the fluid to be uniform. The uniformity ensures that the convection seen is due to the state it is in and not to variations in temperature or anything else.

**PROCEDURE:**

The whole experiment is based on finding out what the two fluids are doing at certain temperature differences. Therefore, it is important to make sure that the fluids have actually reached the temperature that the thermistor says they are at. To make sure this is true, the fluids must equilibrate for a period of time at each temperature. It also is important to increase the temperature of the cell slowly so each step of convection can be taken note of. A computer program was written in LabView to monitor the increasing temperature increments of the cell along with the picture taking at each temperature step. The runs I did took between twelve and twenty four hours to complete. One took several days. In the shorter runs, the temperature would increase at a rate of 0.1°C/15minutes. In the 58 hour experiment the temperature would increase 0.05°C every 18.5 minutes.

The image data needed to be reduced as well. The reduced images were able to show a clearer image of what was happening in the cell at the time of the picture. Dark spots and scratches on the copper plate were removed from the final picture by using image division. To reduce an image, LabView was used once more. A blank image was taken of the plate while no convection was occurring. This image was used as the reference image. The reference image would then be divided.
out of any of the convecting images. The pictures were then equalized. The equalization made sure the images were using the maximum grayscale range to accurately display what was occurring.

RESULTS:

We began by using 25cc of FC-70 and 42cc of 47V10 silicone oil, resulting in a depth fraction of 37.3% FC-70. As it turns out, the first run was done with a slightly tilted cell. This means that layer thickness was not completely uniform; the lower layer was thicker at one side of the cell and for the opposite side, the top layer was thicker. With the cell set up like that, the onset of convection happened at a temperature difference of 2ºC. At onset, a hexagonal convection pattern would show up in the corner of the cell where the bottom layer was the thickest and then it would make it's way across the cell. As the temperature increases, The pattern seen would change. When the temperature across the cell was between 3.0ºC and 4.5ºC, an oscillatory state was seen. Here the fluids oscillated between rolls and cells. As the temperature continued to increase, the flow became more and more disordered, until the two fluids appeared to be acting independently of each other. The largest temperature difference ever achieved was 9.08ºC.

After the cell was leveled and the experiment was run again, a slightly different thing was noted. The onset of convection was not until ΔT=2.4ºC and it appeared to be rolls instead of a hexagonal pattern at first. Then at ΔT=2.9ºC the cells looked as if they were trying to change to rolls, but something was restraining them from doing so.

A third run was done where some of the bottom fluid was taken out of the cell and more of the top layer was added resulting in a depth ratio of 33.5% FC-70. This run showed a distinct time dependent state of the fluids. At ΔT=2.7ºC there was a strong hexagonal pattern. Then by ΔT=3.28ºC there was a rolls pattern. These rolls then oscillated between “horizontal” rolls and “vertical” rolls(as seen in the images) possibly with a cell pattern also in between. This run was ended at ΔT=3.87ºC and there was still a strong time dependence shown.

![Diagram showing the transition of convection patterns with increasing ΔT.](image)
Fig. 5  States seen in first run

Time=0.0  $\Delta T = 3.479^\circ C$

Fig. 6  Time dependence in first run

Time=1min  $\Delta T = 3.479^\circ C$

Fig. 7  Time Dependence with thinner bottom layer

Time=0.0  $\Delta T = 3.88^\circ C$

Time=2min  $\Delta T = 3.88^\circ C$
CONCLUSION:

A time dependent state was found for the FC-70 and 47V10 convection cell. With 25cc of FC-70 on the bottom and 42cc of 47V10 on the top, the cell displayed hexagonal convection, time dependence and then complete disorder. With less FC-70 and more 47V10, the cell, displayed a strong hexagonal pattern and oscillatory motion between orientations of rolls. With more time, a better analysis could be done.

The next step in this project would be to try to level the cell, and take more pictures of the time dependent state. Then those pictures could be analyzed to find the period and maybe even an equation for the wave.

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