VORTEX ENERGY LOSS AND DETACHMENT IN SUPERFLUID HELIUM

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ABSTRACT

This summer I worked with superfluid helium to see how end shape of a cell affects vortex detachment from a wire. A cylinder with a wire running down the center was filled with superfluid helium and different cap shapes (flat, cone, & bump) were attached to each end. When circulation was present, it was knocked off and the end from which it detaches is known. Also, simulations were created to show how a vortex loses energy when precessing through a vortex mesh. I saw that there are different factors that promote energy loss in the vortex.

BACKGROUND

At 4.2K, helium changes from a gas to liquid. As helium is cooled further to 2.2K, the fluid develops superfluid properties. It has no viscosity and circulation is quantized. This allows an integer value of circulation to be trapped on the wire. We are trying to trap one quantum of circulation and knock off the vortex by heating it. Once this is done, the end from which the vortex detached from can be found and therefore which end has less energy. This is found through the precession of the vortex to zero circulation.

te the cells. From left lat, cone and bump. These two are used at once and the can be compared.

Since the vortex's energy is proportional to its length, it is reasonable to think that the vortex would like to lose length as opposed to gain length. The vortex needs energy to reach the wall of the cell and so the cap with the shortest distance from the center to the cell along the surface would be the most likely to have the vortex knocked off from first. Therefore, the bump end would not be likely to have a vortex detach from it.

Theorists suggest, from solving Gaussian curvature equations, that there is enough force in the vortex to sit at a saddle point to overcome the vortex's desire to be as short as possible. This means that the vortex would sit at the point were the bump meets the flat part of the cap as opposed to the top of the bump were its length would be shorter. This is tested by looking at a vortex's precession. The cells used actually have two different radii so when the vortex is in the section with a larger radius, the period of precession is larger than when the vortex is in the section with a smaller radius. The period of precession can then be used to figure out from which end the vortex detached.

Once the cell if filled with superfluid helium and placed in a magnetic field, a current is sent through the wire to deflect it. The current is stopped and the wire vibrates back to its original position and is damped by the normal fluid still present in the cell. Because the wire is vibrating in a magnetic field, an EMF is induced. The frequency of this observed EMF is given by:

$$\omega_{observed}^2 = \omega_{asymmetry}^2 + \omega_{circulation}^2$$

The frequency due to asymmetry is what can be observed with or without circulation on the wire. It is due to the asymmetry of the wire since we do not use a wire with perfect modes. The frequency due to circulation is only present when there is a vortex on the wire. The amount of circulation on the wire changes the frequency and what we observe. This $\omega_{observed}$ is plotted versus time to see the amount of circulation on the wire.

The period of precession, which tells which end of the cell the vortex detached from, happens because the wire is not exactly in the center of the cell. This makes the free part of the vortex move at different speeds through the cell. This extra energy comes from the part of the vortex on the wire and so the length on the wire oscillates. This oscillation is then seen when we measure the circulation on the wire.

The other problem I dealt with is how the vortex loses energy as it precesses. It is known that the vortex has a strong interaction with the wall because the vortex can be pinned to a single spot when precessing and not lose anymore energy. This leads us to conclude that there is some interaction with the wall that causes energy loss. When the cell is rotated to get circulation, a bunch of vortices are created. One of these vortices attaches to the wire while others might pin to the wall. The orientation, length, and density might contribute to why the vortex loses energy.

Using a computer simulation adapted from Schwarz but written by Dr. Zieve, we model a mesh of small vortices on the wall of the cell and see what parameters make the vortex decrease in length, i.e. energy. The simulation set up vortices in an area of the wall of a cylinder and one main vortex partway on the wire. The vortex then gained or lost length through reconnections with the vortices on the wall. The length, orientation and density of these wall vortices change the behavior of the vortex attached to the wall.

APPARATUS/TECHNIQUES

I created cells with different end shapes that could be tested. These cells are made of copper which is drilled to the appropriate thicknesses. Stycast caps are then drilled and attached to the ends using more Stycast. A wire is stretched taught from each end using holes drilled in the center of the Stycast ends. The holes are not exactly in the center which lends to the measurement of the period of precession. If the wire was exactly in the center of the cylinder, we would not be able to see which end the vortex detached from because there would not be any period of precession.

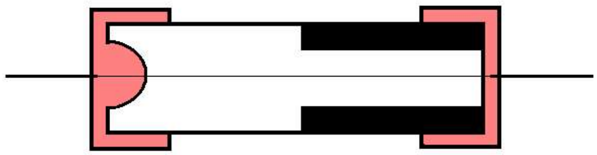
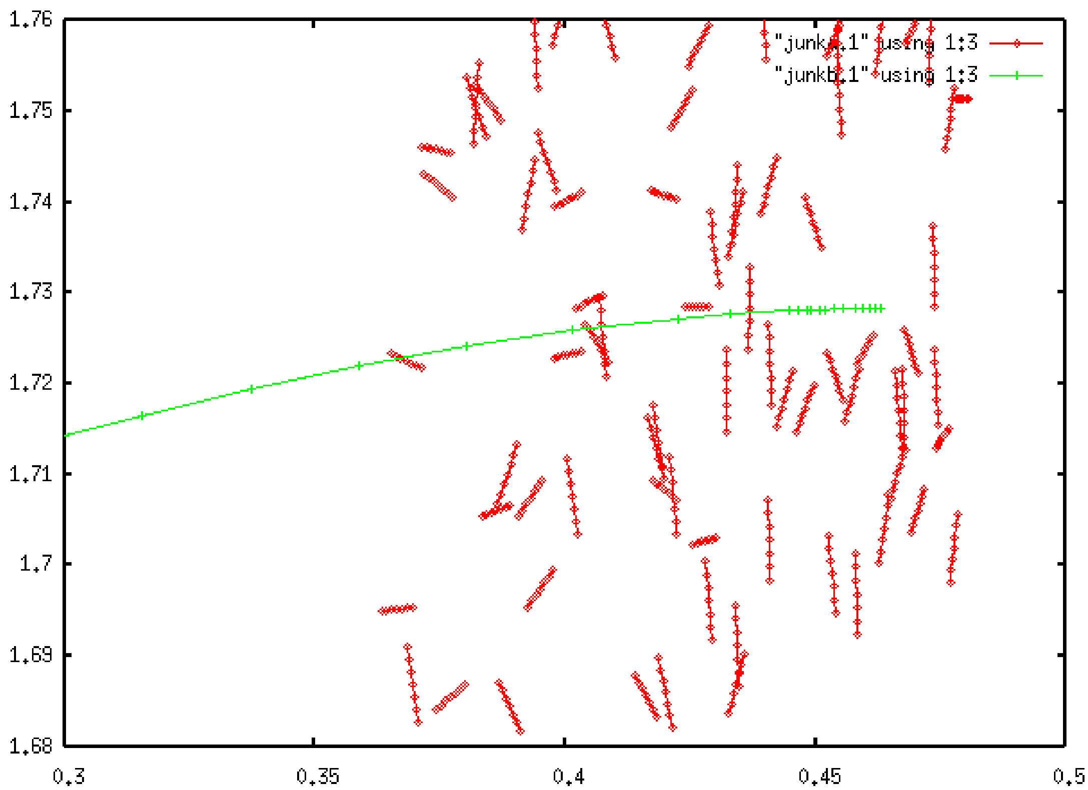


FIGURE 2: An example of how the caps are attached to the cell and the different radii of the cell. These inner radii are used to show which end the vortex detaches from first. The cell is about 2.0” long with inner radii of ~1/4” and ~1/8”.

The frequency is plotted versus time to see precession. Zero circulation is found by plucking the wire when the fridge has not been rotated. The technique to find N=1 circulation is to rotate the cell and find a stable state above N=0. Once N=1 circulation is achieved, the fridge is heated slowly until the vortex detaches from the wire at which point the fridge isn’t heated anymore and data is taken. Once the circulation is again at N=0, the different periods of precession can be seen and the side that the vortex detached from.

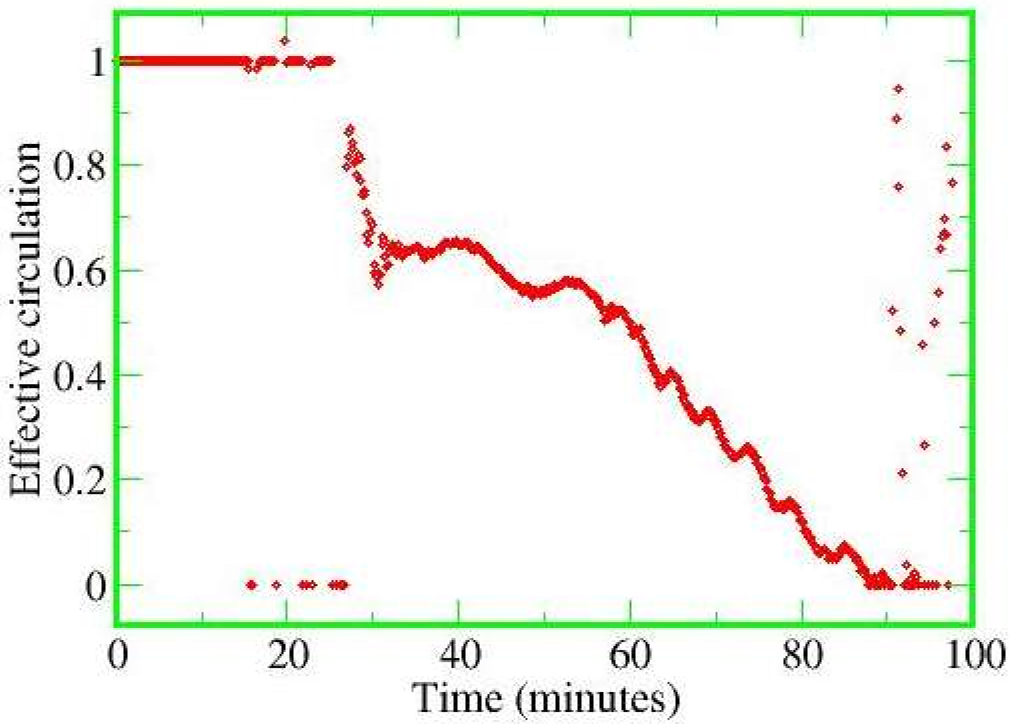


GRAPH 1: The red lines are the vortex mesh on the wall while the green is the main vortex. It interacts with the wall on the right side and is attached to the wire to the left.

The computer simulation was started with different parameters for vortex length, orientation and number of vortices in a given region. These vortices affect the wire vortex by adding or taking away length of the main vortex. The part of the main vortex that interacts with the wall is projected onto the z-axis (height from bottom of the cylinder) and is taken as the length of the vortex on the wire. As the vortex is moved along the wall by the circulation, the vortices on the wall move the vortex up and down as well as changing the length of the main vortex. From this we can get an idea of what the vortices on the wall look like and how the vortex loses energy.

RESULTS & DISCUSSION

For the one cell that was tested, it was found that the vortex would detach from the bump as opposed to the flat end. The bump was on the end with a larger radius and so a larger period of precession was seen first before the smaller period of precession from the smaller radius of the flat end. This adds support to the idea that the vortex was not attached fully to the wire but was instead caught in the saddle point off to the side of the bump.



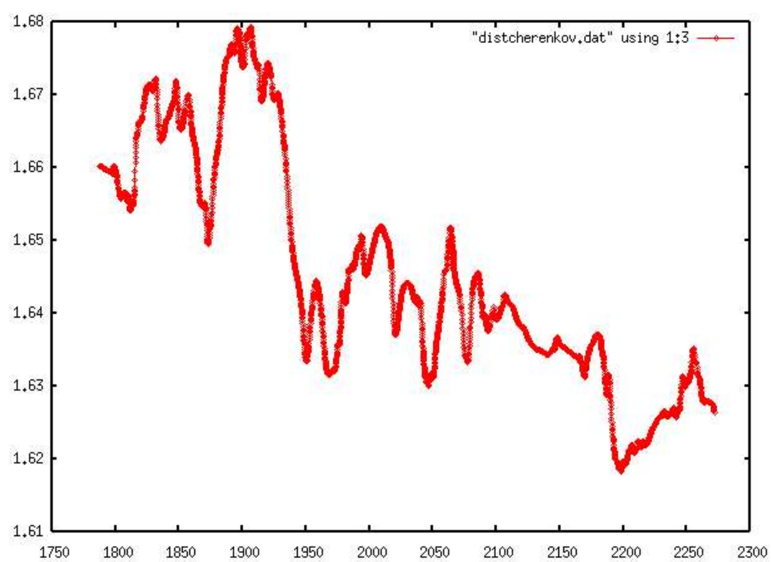
GRAPH 2: The vortex precessing from N=1 to N=0, showing that the vortex detached from the end with a larger radius.

The computer simulations are somewhat mysterious. After running 6 different combinations, it can be seen that there are definitely some that are decreasing while others are harder to believe. To change the density of the vortex mesh, I kept the same number of vortices but made the area they were in larger. All of the runs started out with 80 vortices. The first run was an arbitrary arrangement of parameters taken from Dr. Zieve. Every other run only had one thing different from this first run. The other ones changed density, length of the wall vortices, loop orientation and one where each wall vortex was randomized between two lengths.

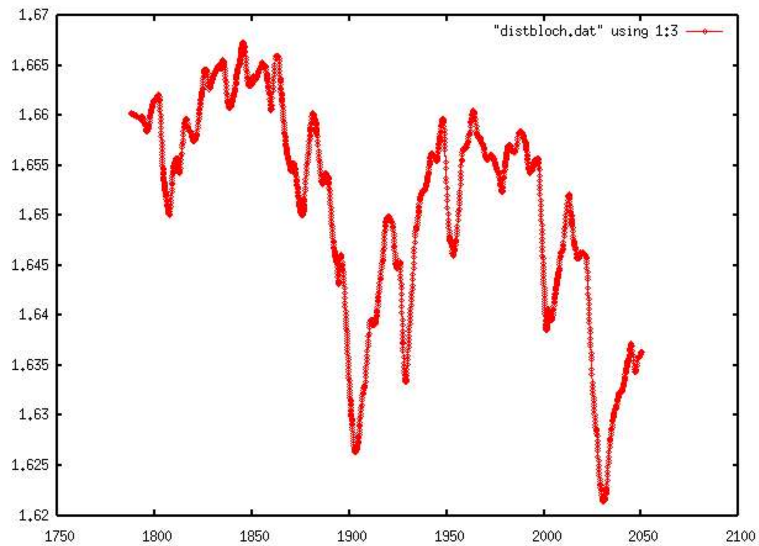
The vortices in the program are saved after a number of iterations and these files are used to analyze the length of the main vortex. When the program saves these files the vortices are rearranged into a more manageable order that can be read by the program again as a restart file. When an error occurs in the program and restarted from the last saved file this error does not occur again and so the error can not be found unless the program is started from its initial start.

Sometimes the errors occur after the program has been running for a few days and so starting the program from its initial conditions would mean it would take a few days to test for the error. I created a program that would rearrange the vortices in the restart file into the same arrangement from before the file save so that these errors would occur again without starting the program over from the beginning. This will help with error finding and checking.

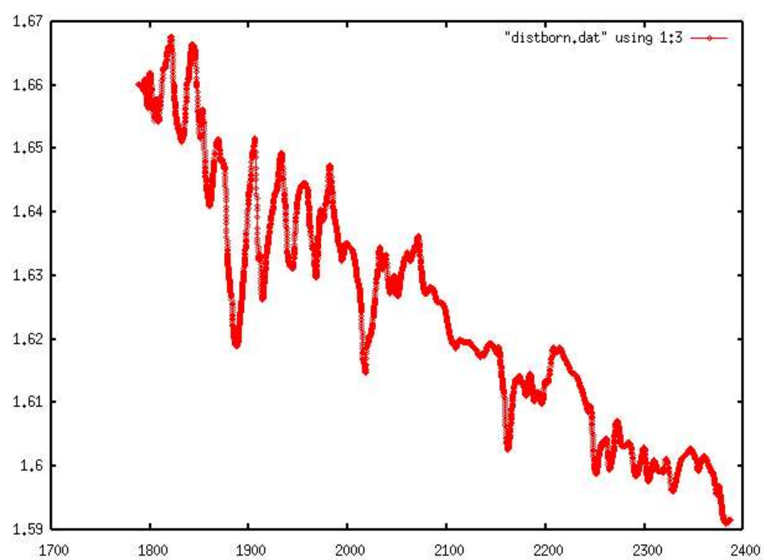
A couple of problems besides the program crashing are that the vortex could gain length and the main vortex could eat up all of the vortices on the wall. The latter would leave no vortices for the main vortex to reattach to and would not show much energy loss. When the program is run without a wall mesh, the length still decreases but not at the same rate as when there are vortices on the wall. It decreases at a slower rate. There should be a good number of vortices left on the wall for the length of the main vortex to be reliable in that it is interacting with the wall.



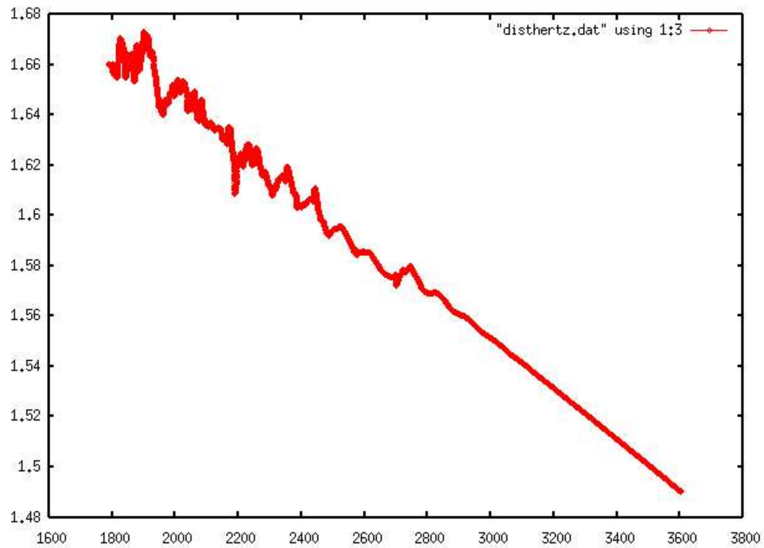
GRAPH 3: This was the first run where I used the parameters from Dr. Zieve. There were 80 vortices at the beginning and 41 at the end. For the first part of the run, the vortex is gaining length but near the end there does seem to be a negative slope but it is not that convincing.



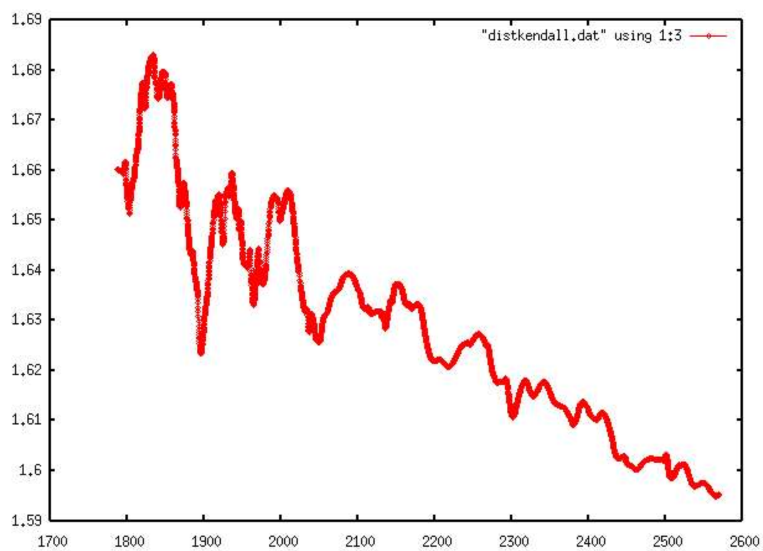
GRAPH 4: For this run, all of the loop orientations were between 1/4 and 3/4 so that all of the wall vortices were oriented vertical. This also does not seem convincing in its negative slope. This program ended with 56 vortices out of 80.



GRAPH 5: This graph is very convincing in its negative slope. And most of the vortices on the wall were left (45 out of 80). This run was were I varied the length of the wall vortices randomly between two values.



GRAPH 6: At first glance, this seems like a great slope. The only problem is that there is only one wall vortex left at the end. Halfway across, there are only 3 vortices left. This is not reliable and does not help any.



GRAPH 7: This graph also looks like it has a pretty good slope and there were 23 vortices left on the wall at the end. This run tested the orientation of vortices between 0 and .

GRAPH 8: This run changed the density of the vortex mesh by creating a larger area for the vortices to lie in. At the end of this run there were 65 vortices left in the mesh.

Note that these runs do not span the same amount of time. This means that the slopes cannot be compared as they are.

CONCLUSION/FUTURE WORK

The cell tested this summer supports the idea that the vortex tends to sit at saddle points and that this force is more than the extra energy needed for the vortex to attach at a point further away. However, more data on this needs to be collected before anything substantial can be said.

The computer simulations suggest that the vortices do want to be oriented in the same direction as the main vortex. Also, the lengths of the wall vortices are not the same but are more random. This should be investigated further by running more simulations. The slope of the graphs should also be figured out to see that the wall vortices are promoting energy loss.

REFERENCES

Donev, L. A. K. "Experimental Methods and Results on the Study of Superfluid Helium". UC Davis.