The Effects of Heating on the Pinning of Superfluid Vortices

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Abstract

This paper is the culmination of my summer research at UC Davis under the guidance of Professor Rena Zieve in the REU program funded by NSF. Basic background on superfluid helium, measuring vortices, and vortex motion will be covered before the results from this summer are relayed and discussed. The next steps in this research will also be explained.

Introduction

The study of vortices is significant to the study of fluid dynamics, which includes airflow, weather, and applications in superconductors and the study of neutron stars, among others. Studying vortices in superfluid, which has zero viscosity, greatly simplifies the problem so that basic properties can be established. Experiments of this kind are not new, but there are still many phenomenon left to be studied and discovered.

Our experiments study superfluid vortices in a cell, which is a tube about two inches long, with a thin wire down its center. The cell is surrounded by magnets and attached to the end of the cryostat used to cool the helium 4 used in the experiment down to superfluid temperatures. The magnetic field created by the magnets allows us to see what is going on in the cell when we vibrate the wire. Pinning occurs when the end of a vortex in the cell gets stuck on the wall of the cell.

Background

A superfluid is a fluid that has zero viscosity, much like a superconductor has zero resistance to the flow of current. Helium 4 is a liquid at 4.2K and can be made colder through evaporation by lowering the vapor pressure above the surface of the liquid through pumping. This causes boiling to occur because there is a temperature gradient between the top of the liquid that is being cooled and the bottom of the liquid. However, when the temperature is reduced to 2.17K, the bubbling stops, indicating that the thermal conductivity has become so great that there is no longer a difference in temperature between the top and the bottom of the liquid. This transition marks the difference between helium I and helium II. Experiments on the viscous resistance to flow of helium II have shown that in narrow channels the flow velocity of the liquid is almost independent of the pressure gradient along the channel, suggesting zero viscosity. However, experiments on moving bodies in helium II have shown that there can be viscous drag in the liquid, indicating that helium II can have both normal fluid and superfluid properties at the same time. These findings lead to the development of the two fluid model, in which helium II is made up of a fraction of superfluid and a fraction of normal fluid that each have their own density and velocity. However, this is just a model and the two fluids can never be separated. Below 1 Kelvin, helium II is nearly all superfluid.

A vortex is created by circulation in the cell. Circulation is given by $k = \oint u_s \cdot dl$, where u_s is the velocity of the superfluid and the integral is taken around a contour wholly within the liquid. Vortex circulation is quantized, and has the values $k = n\frac{h}{m_4}$, where n = 0, 1, 2, … and $\frac{h}{m_4}$ is called the quantum of circulation. A multiply connected region, such as the space between two concentric cylinders, is a sufficient condition for the quantization of circulation. Vortices form in helium II so that there is a ‘hole’ in the superfluid because the core of the vortex is best described as normal fluid, though it is only on the order of an angstrom thick.

A cryostat is used to get the helium 4 down to superfluid temperatures. First the cryostat, with the cell for the experiment on its end, is lowered into a large dewar full of liquid helium 4 at 4.2K. Next, pumping on a pot of helium 4 is used to cause evaporation, which cools this portion of the cryostat in much the same way that sweat cools your skin on a hot summer day. This brings the temperature down to about 1.5K. To lower the temperature even further, helium 3, the more rare isotope, is pumped on using charcoal. Since He 3 is lighter, it has a lower boiling point, so it reaches lower temperatures when it is used for evaporative cooling. Charcoal is used to pump on He 3 because charcoal powder has a very large surface area to volume ratio and atoms are likely to stick to its surface near their boiling point temperatures. Once the charcoal has absorbed all the atoms, it can be heated so that the He 3 is released and can be reused, which is important because it is very expensive. Pumping on the He 3 gets the He 4 in the experimental cell down to around .3K.

To trap circulation, the cryostat is rotated, which causes a matrix of vortices to form in the cell in order to make the fluid approximate solid body rotation. When the rotation stops, most of the vortices in the cell dissipate, but usually one will get caught on the wire down the center of the cell because it minimizes energy in two ways. The radial velocity of the fluid goes as the inverse of the radius from the core of the vortex. When the vortex is on the wire, its core has to be wider to fit around the larger diameter of the wire, so the fluid near the center doesn’t have to move as fast and kinetic energy is minimized. Secondly, the vortex does not have to use energy to force its core to be normal because the wire is already normal.

The motion of the vortex in the cell is observed by ‘plucking’ the wire down the center of the cell and observing how it vibrates. The magnets around the cell control a magnetic field that runs through it. The wire is plucked by running a short burst of current through it, which causes the magnetic field to exert a force on it in one direction. The wire then vibrates back and forth in the fluid. However, the movement of the wire through the fluid causes the circulation on one side of the wire to be in the direction of the fluid flowing past it as it moves and to be against the fluid flow on the other side [fig. 1]. This causes there to be lower pressure on one side of the wire due to Bernoulli’s Principle and a force to act on the wire in that direction [fig. 2]. This small force to the side while the wire is vibrating causes the wire to have spiral-graph motion, gradually moving to vibrate in and out of the plane of the magnetic field. Moving through the magnetic field causes a current to flow through the wire. The envelope of the voltage through the wire [fig. 3] can be used to find the circulation and observe the movement of the vortex in the cell. The normal fraction of the fluid causes damping on the motion of the vortex, so that eventually it decays.

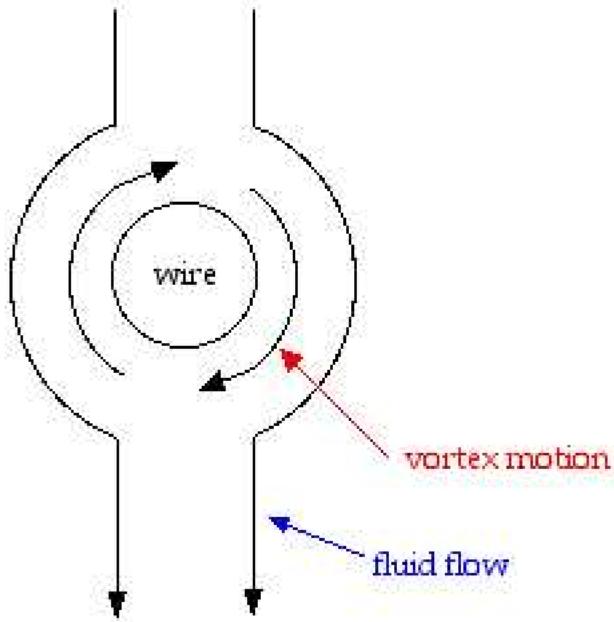

Fig. 1: The fluid flow around the wire as it moves

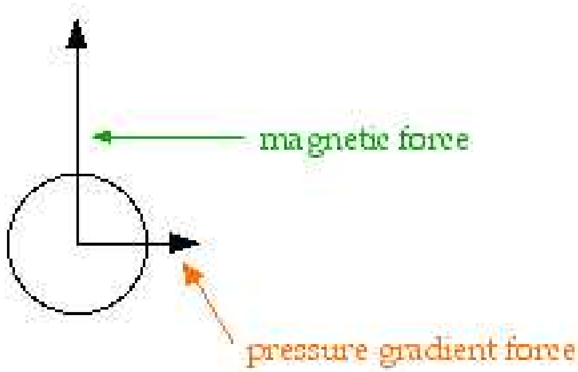

Fig. 2: The forces acting on the wire from the magnetic field and the fluid flow

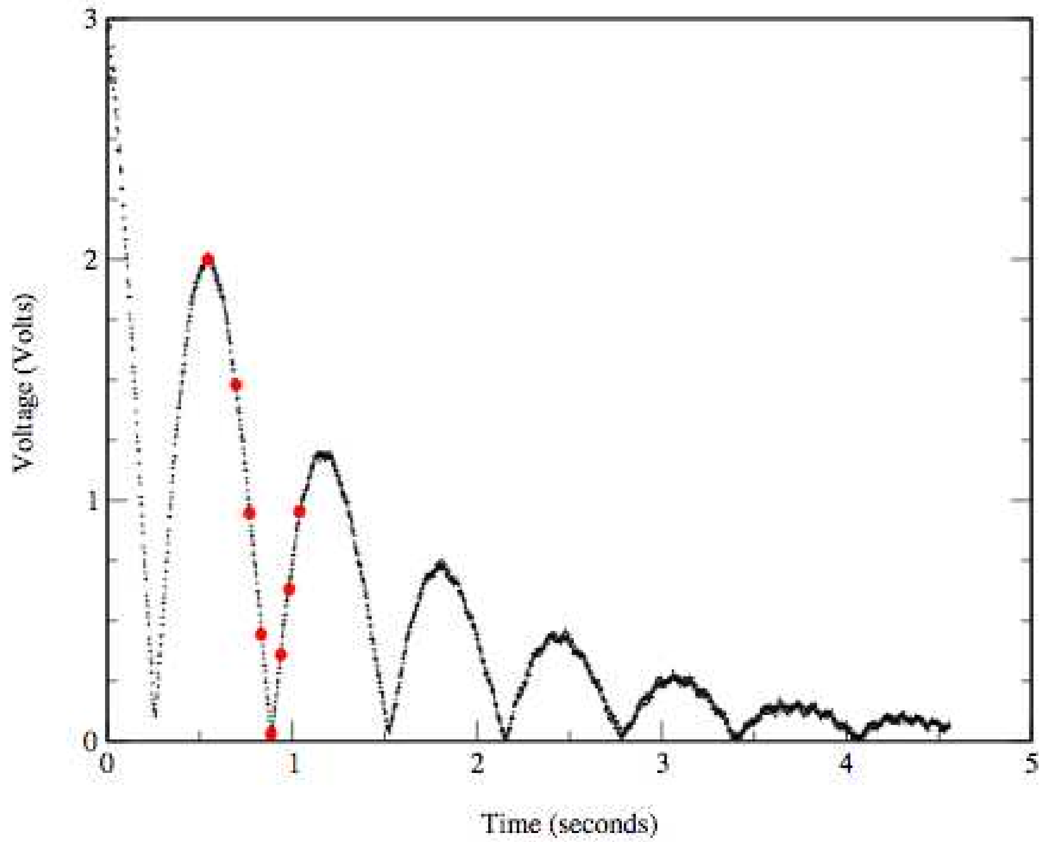

Fig. 3: The envelope of the voltage through the wire

A perturbation of some kind will cause a vortex end to come off of the wire and attach to the cell wall. This vortex end is then pushed around the cell wall by the circular flow of the fluid from the portion of the vortex that is still on the wire. The vortex gradually loses energy, so the attachment point moves down the wire as the end of the vortex precesses around on the cell wall. This precession is measured by the vibrating wire and can be approximately fit to a decaying sine wave [fig.4].

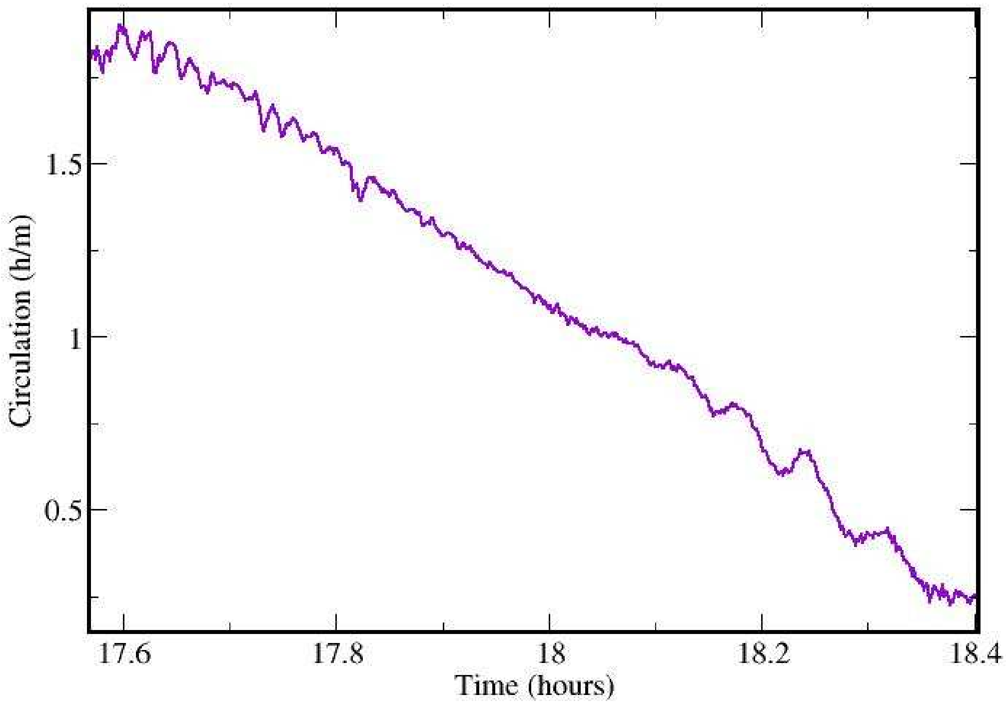

Fig. 4: The precession of the free end of the vortex around the cell wall. The numbers on the y-axis indicated the number N of full vortices on the wire. Note especially the beautiful precession below N=1.

The vortex movement phenomenon of most interest to this paper is the property of pinning. Occasionally the free end of the vortex will get stuck on the wall of the cell as it precesses around [fig. 5]. This is generally understood to be caused by a bump in the cell wall, which creates an energy minimum for the vortex because less of it has to reach from the wall to the wire, and the length of the vortex is proportional to its energy. In addition, the part of the vortex that is off of the wire has more energy than the vortex on the wire. A vortex is more likely to pin at higher temperatures, an effect that we wanted to study more this summer.

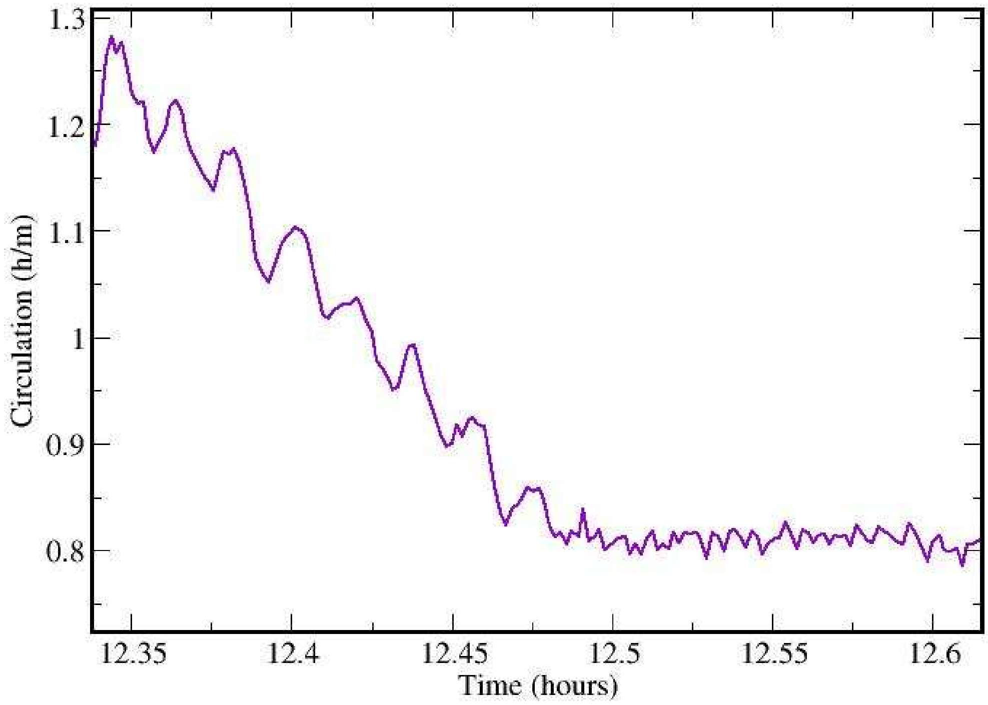

Fig. 5: Precession of the vortex into a pin. Note that the pin has some noise.

Last summer's REU project studied the effect of a smooth cell on the dissipation of the energy of the vortex. They found, as expected, that a polished cell wall causes the vortex to dissipate energy slower. However, they were not expecting to find that the vortex was more likely to pin on the smooth walled cells. This led to a new model for vortex pinning, in which the matrix of vortices created by rotating the cryostat do not completely dissipate when they disperse to the walls of the cell, but rather become caught on the bumps on the wall. This vortex 'mesh' creates a complex velocity field near the wall that pushes the free end of the vortex along as is precesses around the cell. When there are fewer bumps on the wall, there is less for the extra vortices to get caught on, the mesh is weaker, and pinning is more likely.

We worked with heating the cell this summer to test this new model. By heating the cell at the beginning of a rotation, we tried to see if it would make the mesh on the walls disperse and cause the vortex to pin as much as for a smooth cell. We also looked at the effect of heat on pinnings by annealing to successively higher temperatures when the vortex was pinned and observing when it came off. Finally, we rotated the cell at different base temperatures to see if it increased the probability of pinning.

Results and Discussion

Analysis of the first set of data gave some interesting results. A histogram of the unpin temperatures from the annealing of a pinned vortex shows that most vortices unpinned around 1.7 to 1.9K [fig. 6]. In addition, there appears to be no correlation between the unpin temperature and the base temperature of the rotation [fig.7]. When the number of pins for each base temperature was counted, it was found that pinning was most probable at the 400mK and 550mK base temperatures [fig. 8]. This was not expected, because pinning is usually more probable at higher temperatures. However, when the number of pins was compared to the amount of time that the motion of the vortex was eligible to pin, it was found that the number of pins over time increases for higher base temperatures [fig. 9].

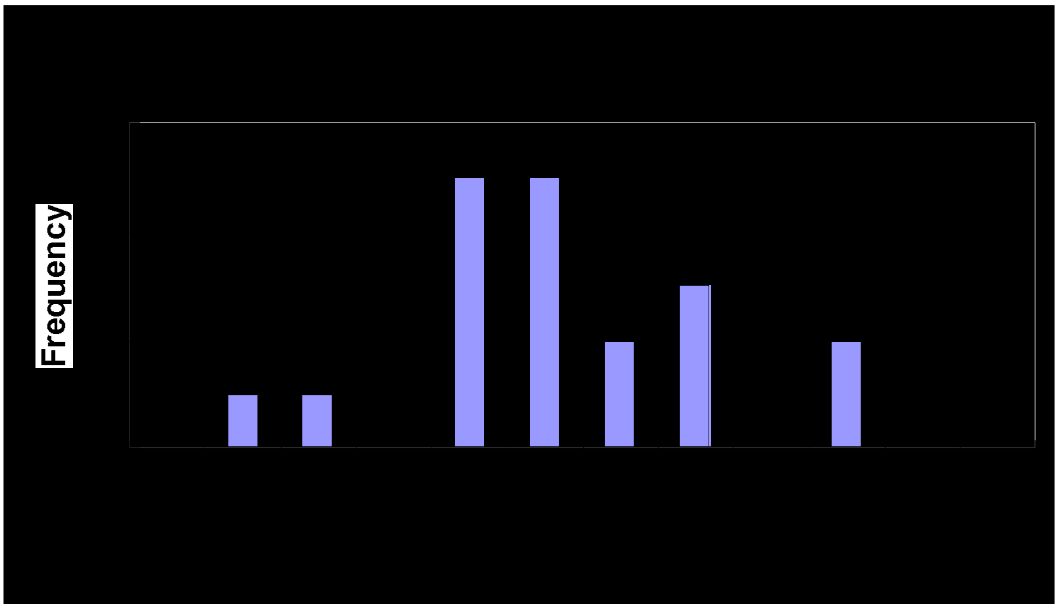

Fig. 6: Histogram of the frequency of each unpin temperature for annealing

Fig. 7: Unpin temperature vs. base temperature, which appears to have no correlation

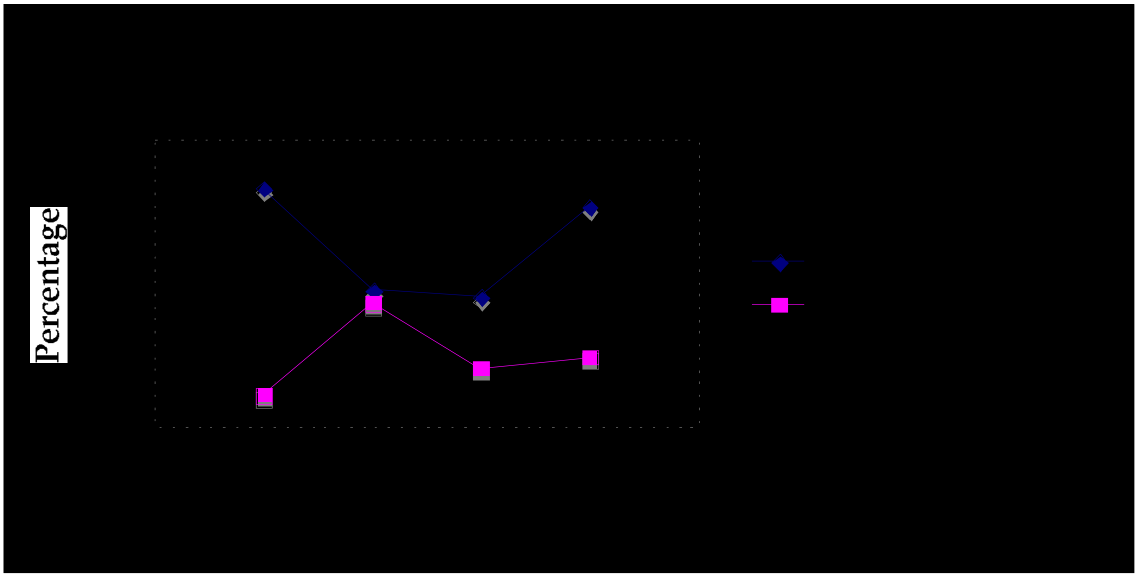

Fig. 8: Pinning percentage vs. base temperature, with the percentage of total runs for each base temperature included for perspective on accuracy and precision

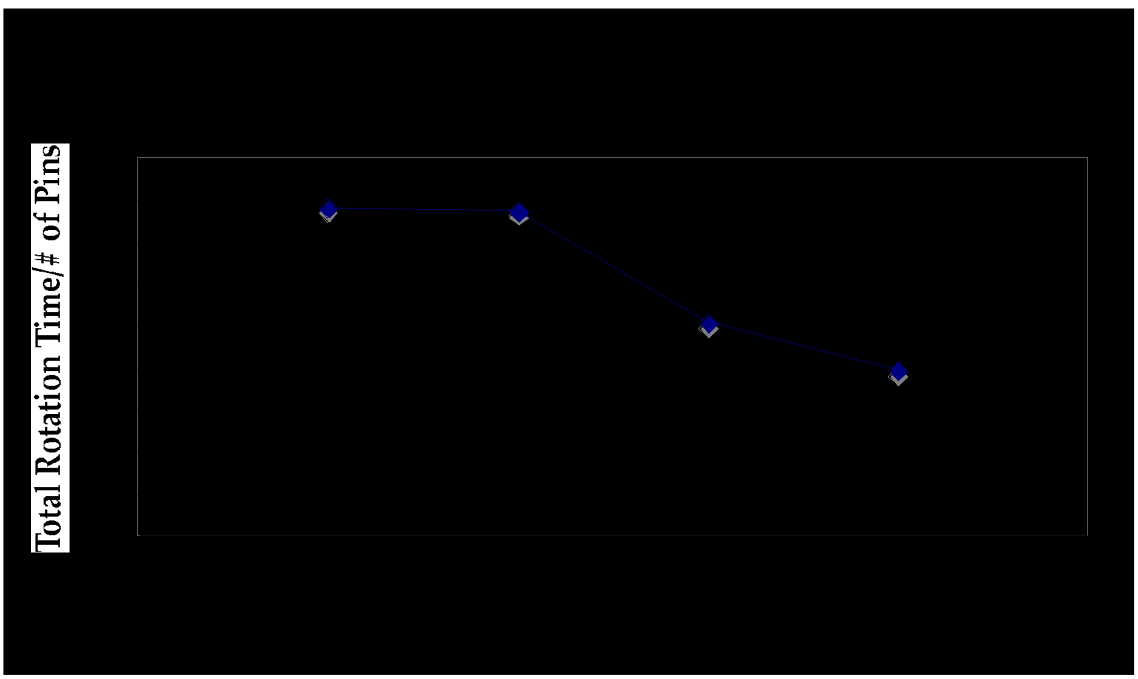

Fig. 9: Comparing the amount of rotation time for each pin at the different base temperatures. Notice the downward trend.

The results for heating the cell at the beginning of a rotation, or pre-heating, showed that the vortex was practically just as likely to pin on pre-heating rotations as other rotations. While 64% of the pre-heated rotations pinned, only 58% of the unheated rotations pinned. This is not a significant difference and suggests that pre-heating, or at least this method for it, is ineffective for causing pinning. However, only 27% of the total rotations were preheated and some of the preheated rotations came out of the heating noise below N=1, or below the circulation of one vortex, which meant that they had less of an opportunity to pin. We also usually only pre-heated for about five minutes, so a longer pre-heating time might have a different effect.

The fact that pre-heating does not seem to increase the likelihood of pinning suggests that heating the cell to temperatures below 2K does not cause the mesh on the walls to disperse. To further test this theory, we looked at what happened to the probability of pinning after the cell had been annealed to release an N=1 pin. It was found that 30% of rotations that had pinned at N=1 first pinned a second time between N=1 and N=0. In addition, 34% of rotations that didn't pin at N=1 did pin between N=1 and N=0, which suggests that pinning at N=1 does not affect the likelihood of the vortex pinning later on. This supports the results above that indicated that heating does not disperse the mesh on the walls, which would make pinning more likely.

Finally, the N=1 pinnings were compared to the pinnings between N=1 and N=0. It was found that the N=1 pinnings reached higher annealing temperatures than the pinnings between N=1 and N=0 [fig. 10], suggesting that the N=1 pinnings are stronger than those on the cell wall. This makes sense because the N=1 pinning is a stable state of one complete vortex on the wire, but a pin on the wall is not as stable and should be easily dislodged.

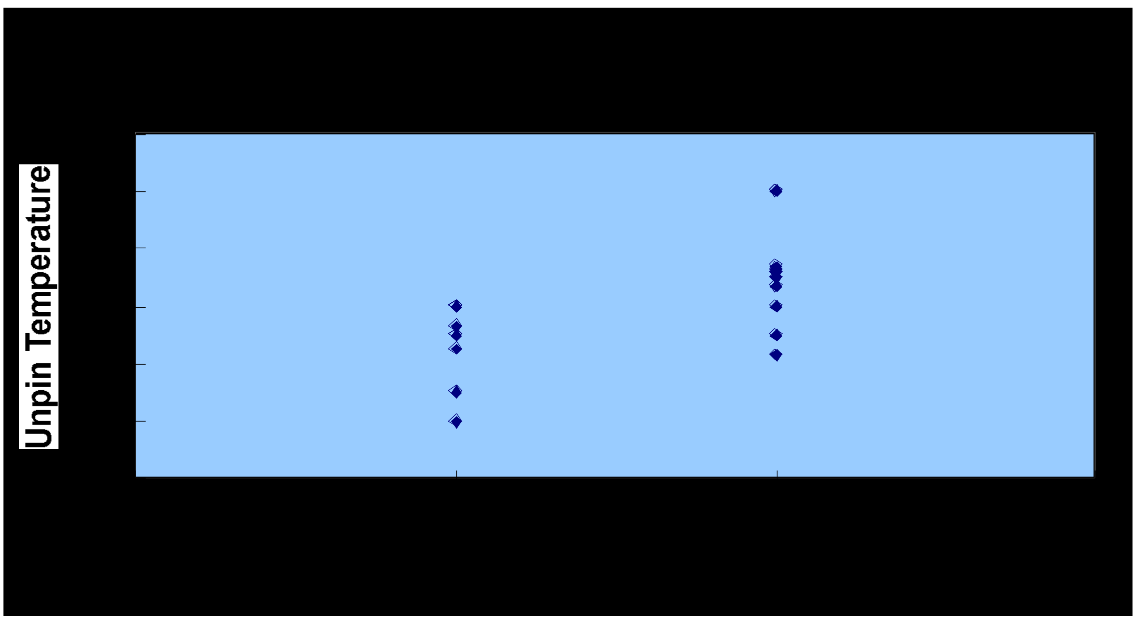

Fig. 10: Unpin temperatures for pins between N=1 and N=0 and pins at N=1. The N=1 unpin temperatures were higher, suggesting that those pins are stronger.

The results from the first data set lead to new questions and methods for the second data set. From the new data, we wanted to see if the temperature that the annealing reached or the number of annealings caused the vortex to unpin. We also wondered if the amount of time the cryostat had been in the dewar affected the probability of pinning. Though at first we wanted to collect more data for the 400mK base temperature, for consistency and speed we soon settled on a base temperature of

550mK.

I have only been able to analyze the first week's data for the new set so far. The results are a little confusing and look like they could be clarified by analyzing more of the data. All that can be learned for sure so far is that there are at least two kinds of pins, because some pins are definitely stronger than others. Some of our pins from the second set of data stayed annealing at 1.7 or 1.8K for extended periods of time, up to 24 hours. Other pins released after only one annealing, sometimes only up to 1.6K. However, there were also some that went through several annealings and then warmed up before pinning because the annealing temperature was low. So we don't know how strong many of the pins actually were. In addition, it appears that the weak pinnings and the strong pinnings were grouped together [fig. 11], which suggests that there may be some kind of cycle going on in which a mesh builds up on the walls and then disperses. This is further supported by the fact that the weak pinnings seem to occur when it is hard to get the vortex to pin and the strong pinnings happen when pinning is easy. However, much more data needs to be collected and analyzed before anything definitive about a cycle can be concluded.

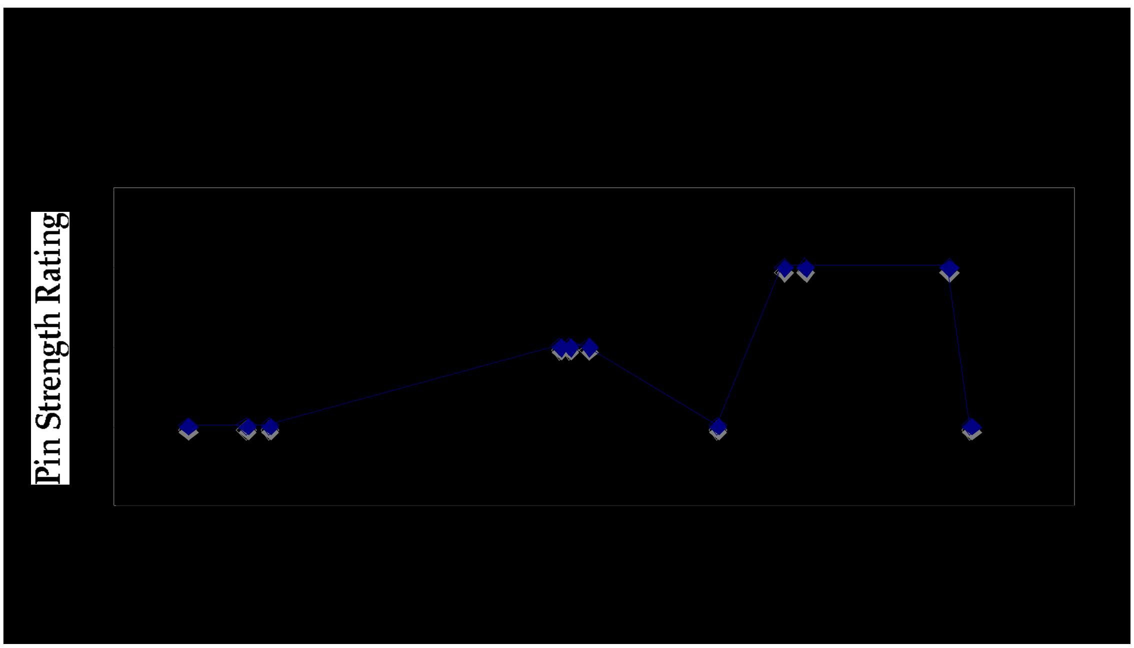

Fig. 11: Pin strength over time. Notice the group at strength three. Also, note that the strength 2 pins were ones that did not unpin before the fridge warmed up because their annealing temperatures were low, so we don't know how strong these pins really were.

Another aspect of the pinning that we want to look at is the amount of noise at a pin and the motion of the vortex before and after a pinning [fig. 12]. Some preliminary data on pinning noise width has been inconclusive about its effect on pin strength [fig. 13]. Further difficulties arise from the fact that noise at a pinning could be due to electrical factors, and not the motion of the vortex. Much more analysis of this aspect of the data will be useful.

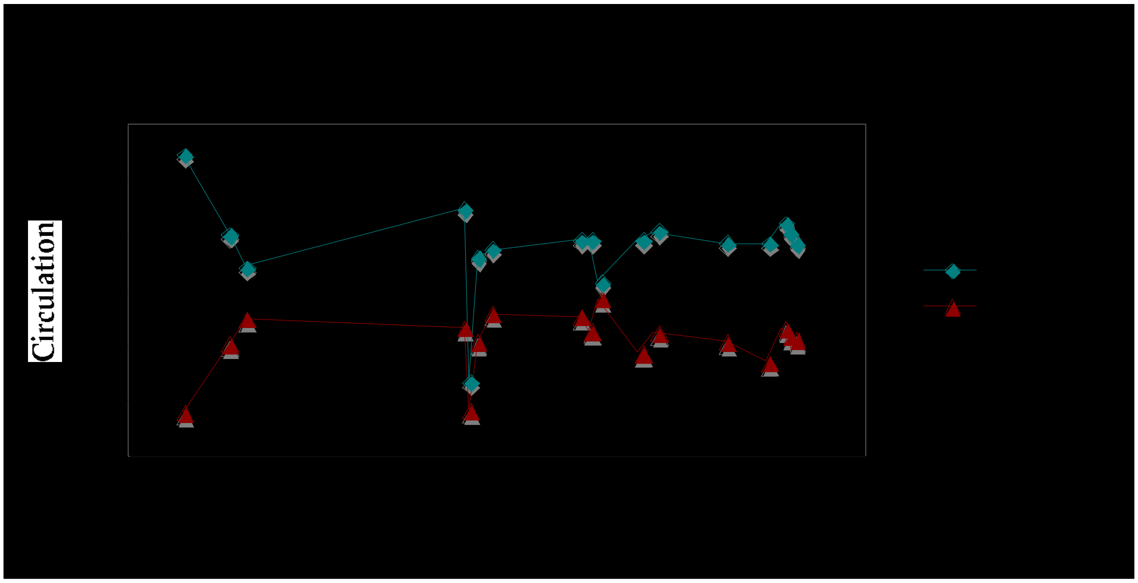

Fig. 12: Noise width over time. Notice the fact that the noise is centered around 700.

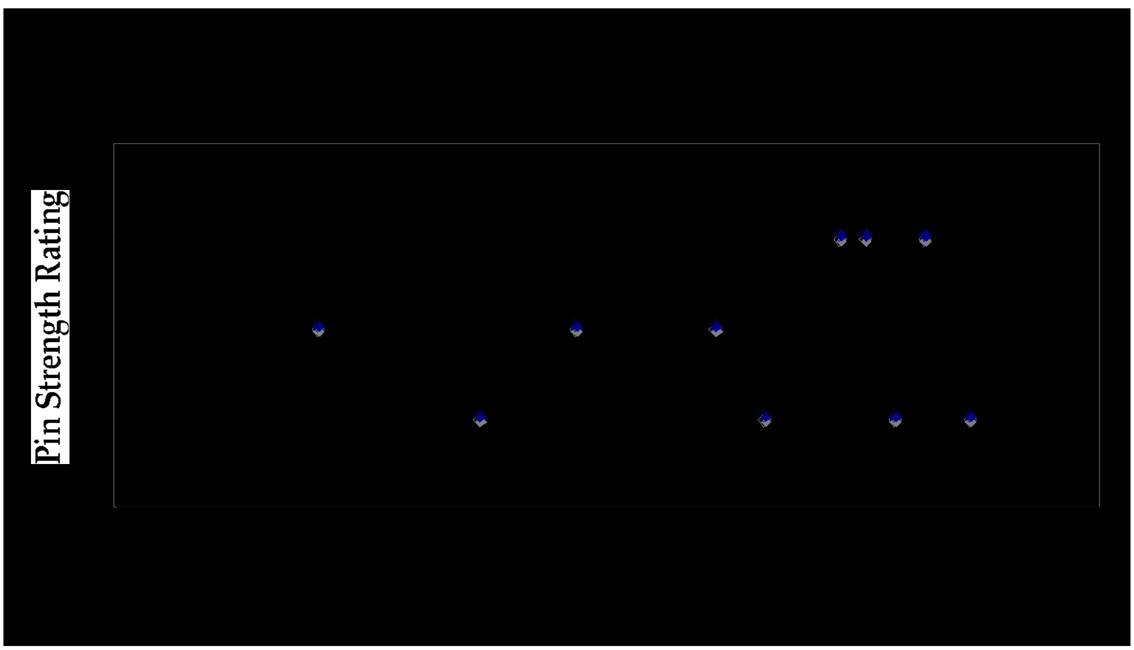

Fig. 13: Noise width compared to pin strength. See note on fig. 11 about the level 2 strength rating.

Conclusion

The experiments from this summer have given some very interesting results that cause many new questions to be asked. We have enough data to be confident that higher base temperatures cause more pinnings over time. We also know that heating the cell is a useful tool for releasing a vortex from a pin. However, it appears that heating the cell at any point in the rotation does not increase the probability of pinning later on. Finally, the last data set has made it clear that some pinnings are significantly stronger than others.

Our results, especially from the last data set, make it clear that pinning is not very well understood. Since there are so many different things that affect the cell at any one time, it is hard to figure out what is causing the pinning to behave the way it does. If the mesh in the walls exists, pinning would be a good way to study it. Further studies on the strength of pinning over time need to be made to understand the mesh and the mechanism for pinning better. A more complete analysis of existing data and reviewing old data from past experiments are the next steps for this particular investigation.

References

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