AC 2011-1819: RESURRECTING THE ELECTROLYTIC PLOTTING TANK

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Resurrecting the Electrolytic Plotting Tank

Abstract:

Before the advent of CFD software, electrolytic plotting tanks were used extensively to plot three-dimensional heat transfer and fluid flow fields. The theory behind these tanks is the well know electrical analogy between electrical fields and temperature or flow fields based on the Laplace equation. These tanks have been essentially replaced with modern computational methods.

As part of a student project, a set of small plotting tanks were designed and built to use as a heat transfer lab on two-dimensional conduction. These particular tanks have been designed to simulate a variety of boundary conditions. Readily available saline solution is used as the electrolyte. In order to simplify the plotting, and to reduce the over cost a modified common pencil is used as the probe, and the plot is made directly on a sheet of paper at the bottom of the container. Boundary conditions are simulated using up to 5 volts DC.

This paper describes the development of these devices and the test results. Results have been compared to finite difference plots and to ANSYS plots to verify that the tanks are working as intended, and these results are included in the paper. The simple tanks yield results very close to the analytical methods. Also included in the paper is a brief history of electrolytic plotting tanks, the relevant theory and a description of a potential lab exercise using these tanks.

Introduction:

Temperature fields are analogous to electrical potential fields. The theory behind this will be presented later in this paper. This concept leads to the idea that temperature fields can be simulated by using electrical potential fields. Before the appearance of digital computers and CFD software, various analogue devices were used for plotting fields in the areas of heat transfer and fluid flow, all based on this electrical analogy. This paper presents a brief history of such devices. Some of these were capable of plotting three dimensional fields, while some could only accommodate two dimensional fields. Once CFD software became commonly available for a reasonable cost the analogue devices were no longer needed. However, there are potential educational uses for such devices. This paper discusses one use for creating two dimensional temperature plots as part of a first course in heat transfer for mechanical engineering technology students.

At Penn State Erie, The Behrend College (PSB) an undergraduate research grant program encourages students to work on a project of their choosing for a semester. At the end of the semester the researchers present their findings at a regional undergraduate research conference held on campus. One of the authors, Tim Demetrio, decided to develop a small sized electrolytic plotting tank to use as a teaching tool in a heat transfer course for mechanical engineering technology students. One of the other authors, Bob Edwards was his faculty advisor on the project. The final author, Dave Johnson was the advisor on the finite element portion of the project.

There was an existing tank that had several problems that will be discussed below. The goal of this project was to develop a new design that solved the problems inherent in the original tank. The overall research plan called for the following steps:

- Become familiar with the existing tank,
- Design and build an improved model,
- Test the model for a variety of boundary conditions,
- Validate the results using both a finite difference analysis and an ANSYS analysis.

The remainder of this paper will consist of several sections. The theory that provides the basis for this analogue will be briefly presented. Both the old and the new designs will be discussed. Much of the paper will present the results of the testing and the validation of the results.

Brief History of Electrolytic Plotting Tanks

In 1845 Gustav Kirchhoff[1] proposed that equipotential lines in an irregularly shaped electric field could be plotted by using a sheet of metal cut to the desired shape and electrodes which are appropriately placed to simulate boundary conditions. He demonstrated this idea using a thin disc of copper. His early demonstration of this concept had several problems foremost of which was the high conductivity of the copper. This made it difficult to simulate boundary conditions. Nevertheless, the general concept survived and was improved during the early to mid 1900's. One improvement that was made to this method during the mid 1900's was to replace the metal sheet with a sheet of conductive paper with a lower conductivity[2]. This method is still in use today. In fact, several educational companies, including Pasco[3] sell equipment to run this kind of experiment. By using either metal or more recently paper, two-dimensional potential fields can be plotted. Advantages of using conductive paper include lower conductivity than metal and readily available supplies of the paper. A disadvantage is that the conductivity of the paper is often inconsistent causing errors in the field.

Another device that became popular for plotting equipotential lines in an electric field is known as an electrolytic plotting tank. This is a tank filled with an electrolytic solution. The electrolyte can be as simple as a saline solution, or even just water. These tanks make it possible to extend the field plotting capabilities from two to three dimensions. Any type of field that is analogous to an electric field can be simulated using this device. This concept was first used in 1924 by Ernest Relf[4].

During the mid 1900's many patents were issued relating to field plotting devices and accessories. For example, in 1949 B.D. Lee and G. Herzog[5] filed for a patent for an electrolytic tank to find solutions for electrical, magnetic, mechanical, hydraulic and thermal systems. Inventors began focusing on ways to automate the data collection, and many patents were issued for automated devices[6,7,8]. These devices were used for a wide range of applications in the thermal and fluid science fields. As CFD and heat transfer programs were developed the electrolytic plotting tank was pretty much phased out.

The Heat Transfer - Electrical Analogy

An analogy between heat conduction and electrical conduction problems is well known. In a two dimensional electrical problem a voltage field can be plotted. A similar temperature field is produced in a heat conduction problem. This analogy is based on the similarity between the governing differential equations for the two cases. Both are governed by a form of the LaPlace equation. In an electrical system the equation is:

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} = 0 \qquad \text{Equation 1}$$

For a thermal system the equation is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \qquad \text{Equation 2}$$

Since these two equations are similar, an analogue can be drawn between the electrical system and the thermal system. If the potential field in an electrical system where the conduction is taking place in a homogeneous material with constant resistivity it can be used to represent a temperature field in a thermal system where the heat conduction is taking place in a homogeneous material with constant conductivity, provided an appropriate scaling factor is used.

The device described in this paper uses a saline solution at the electrolyte, which approximates constant resistivity. The scaling factor is determined by simply looking at a ratio of the boundary condition temperature to the applied voltage on the device.

The Electrolytic Plotting Tank as a Teaching Tool

In a first course in heat transfer for mechanical engineering technology students there is often minimal treatment of multi-dimensional conduction. Several computational methods can be used to aid the students in visualizing the temperature distribution in a two-dimensional problem. Various CFD based programs can be used. Even Excel can be used by incorporating the finite difference method and plotting the results. An electrolytic tank gives the students an opportunity to do a physical experiment which can be used either as a stand-alone exercise to show the temperature field, or in a more integrated experiment to demonstrate that the results obtained from finite difference calculations do indeed make sense.

Electrolytic plotting tanks are capable of plotting three-dimensional fields. The tank that was developed for this project was purposely made shallow so that it could be used for two-dimensional simulation.

At the 1997 ASME National Heat Transfer Conference, Popiel and Bunt[9] presented a paper describing their experiences with a homemade device used to plot a two-dimensional temperature field. This paper gave very good information for building the device, and suggestions for its' application. The authors initially tried to replicate their device, with a few minor modifications. The results of this attempt will be discussed below.

The Existing Tank

The first tank that was built at PSB is shown in figure 1. The device consisted of a plastic tank to hold the electrolyte, a nonconductive base plate and a frame to simulate the boundary conditions. The frame is made of aluminum sections, to which a voltage is applied. Other sections are lexan to simulate insulated surfaces. The electrolyte that is used is a simple saline solution used for cleaning contact lenses. A sheet of paper is set

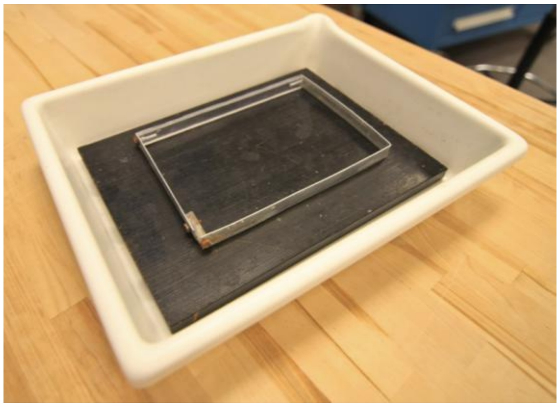

Figure 1 – First Plotting Tank

Figure 2 – Voltage Probe

on top of the base plate and below the frame. The tank is filled to just below the top of the frame with a saline solution. An electrode made from a simple pencil (figure 2) is used to probe for constant voltage lines. Points are plotted on the paper representing constant voltages, and later the points are connected by equipotential lines.

Problems with this device surfaced soon after students began using it during a lab. The main problem was the rapid deterioration of the aluminum used for the frame. Figures 3 and 4 show examples of this.

Figure 3 – Deterioration

Figure 4 – Deterioration

Designing a New Device

A new design was created by the student working on the undergraduate research project. The design is simple and sturdy with the potential for a variety of boundary condition simulations. The conduction plates are made of thicker gauge stainless steel to help prevent the corrosion problems encountered with the aluminum that was originally used. A single piece of Lexan is used as both the tank and the base plate. The material is machined to form a pocket for the solution and tracks in which to mount various boundary condition electrodes. Note: typical part drawings are shown in appendix 1. Figure 5 shows the new design.

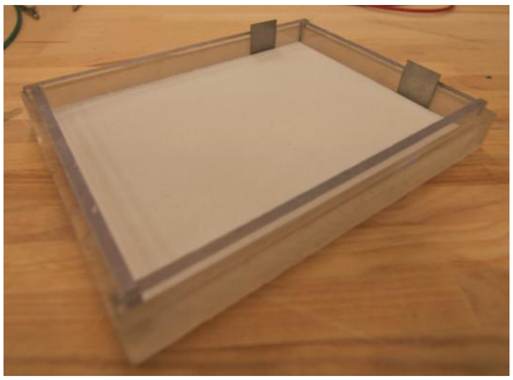

Figure 5 – New Design

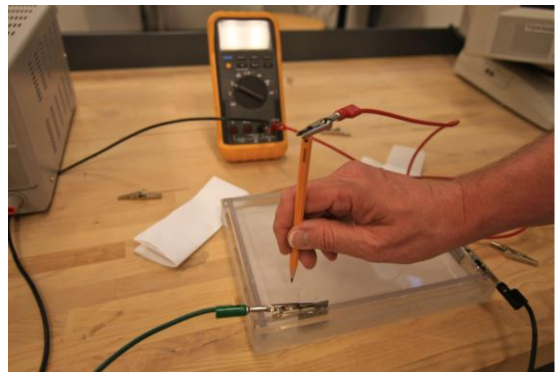

Figure 6 – Test in Progress

Once the design was built, tests were conducted and validated with both finite difference calculations and finite element calculations. Figure 6 shows a test being conducted.

Analysis of The Test Results

To determine if the device was producing good results, tests were run for a variety of boundary conditions. The results from the device were then compared to temperature field plots created in Excel using a finite difference analysis, and to a field plot generated using the finite element method incorporating the heat transfer capabilities of ANSYS software. All of the methods match very nicely. Figure 7 shows a comparisons of these methods.

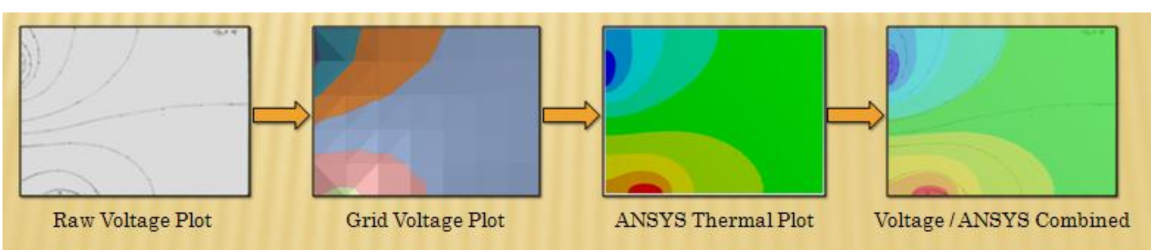

Figure 7 – Comparison of Results

Figure 8 show similar plots for a variety of boundary conditions. The electrodes have been superimposed to show how the test was run. In these plots the equipotential lines produced by the device are overlaid on the ANSYS test results. As you can see, the two methods match nicely.

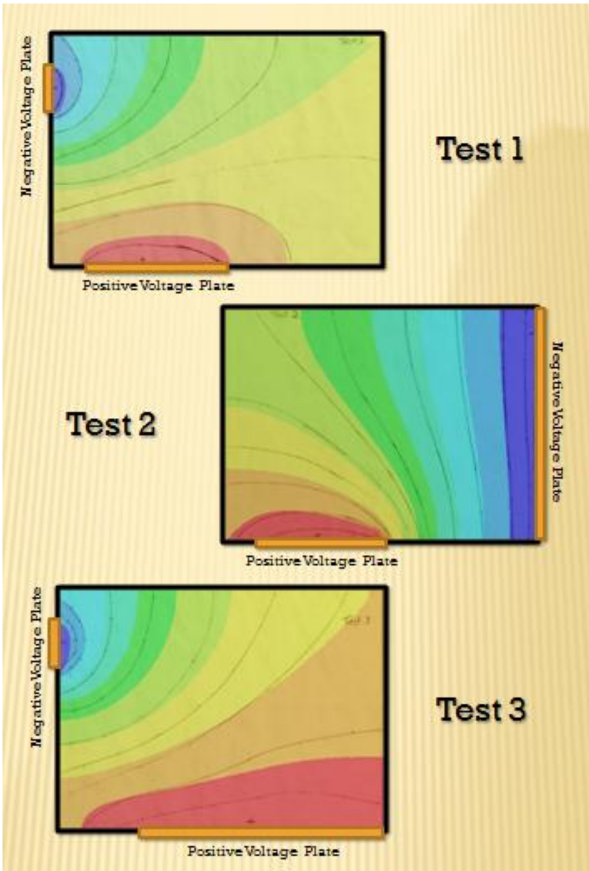

Figure 8 – Test Results

Recommendations For Use

Electrolytic plotting tanks are typically used to plot equipotential lines. However, It is possible to obtain good results using a different approach. This approach, which surfaced during the testing of this device, makes it much easier for a student to get good results. It will incorporated when this device is used for the first time in the spring, 2011 semester. Instead of probing for constant voltages, a grid can be drawn on the paper. Voltages are then measured and recorded at the grid intersections. This data can then be plotted using either Excel, MatLab or other similar plotting programs.

There are several primary advantages to this approach. First, a standard metal probe can be used to measure the voltages. Secondly, it is very difficult to get exactly equal voltages when trying to plot equipotential lines. The use of a grid eliminates the need for having to very carefully search for the constant voltages. Another related advantage is that the need for paper is eliminated. A grid can be drawn or etched onto the bottom of the tank, providing more consistency in the locations for the measurements.

When this is first used the students will be somewhat familiar with two dimensional heat conduction. They will all have conducted a prior lab using Excel to implement the finite difference method to determine temperature fields for two-dimensional conduction problems with a variety of boundary conditions. Some of them will have a background in using ANSYS for heat transfer problems, but some will not. Therefore, data taken from the device will be compared to the results from finite difference calculations. In a similar course designed for electrical engineering technology students the comparisons will be made using a resistance network that is solved using a PSpice program the students are already familiar with.

Bibliography

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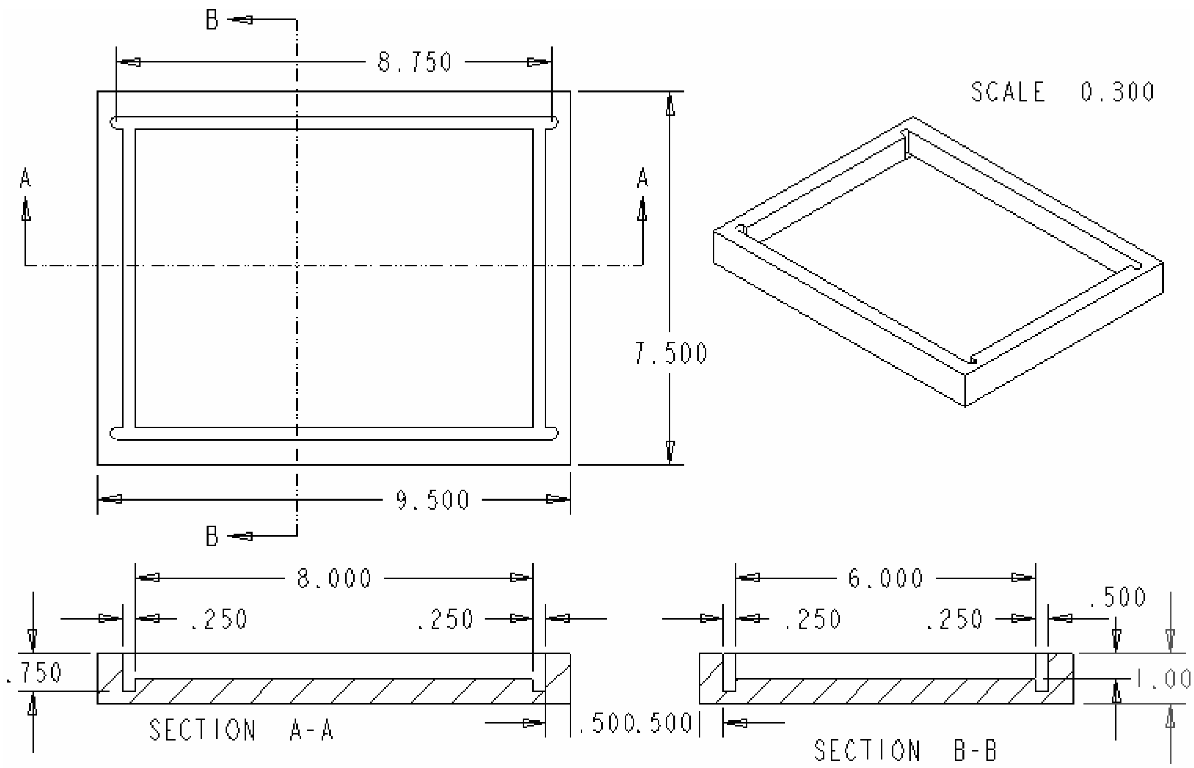
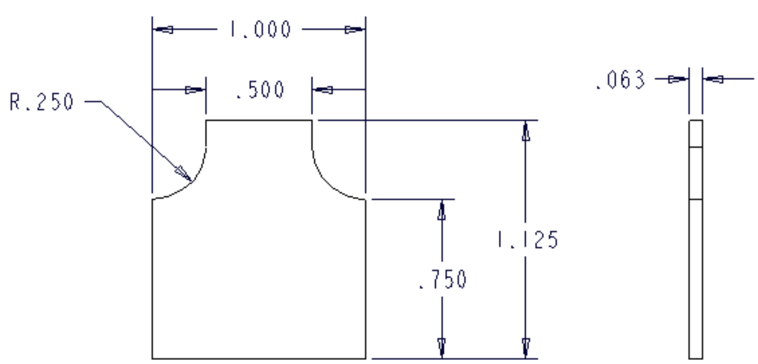
Appendix 1:

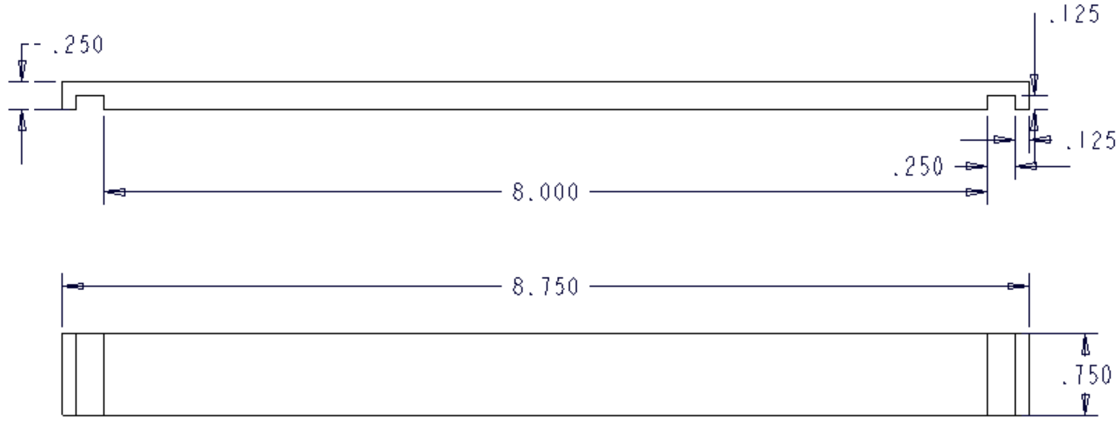
Appendix 1 shows typical drawings for the plotting tank described above.



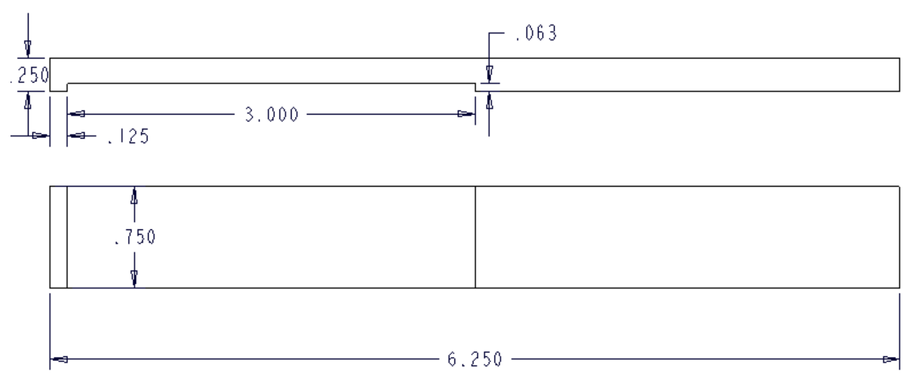
This drawing is for the body of the tank.



This drawing is for a 1” long boundary condition electrode.



This drawing is for the long side inserts. This particular one does not have a cut-out for a boundary condition electrode. Cut-outs can be made as required for the desired boundary conditions.



This drawing is for the short side inserts. This particular one shows a cut-out for a 3” long boundary condition electrode.