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Heat-Pipe Wick Characterization

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Abstract

The development of liquid metal heat-pipes for use in solar powered Stirling engines has led to an in-depth analysis of heat-pipe wick properties. To model the flow of liquid sodium through the wick its two-phase permeability measurement is of interest. The permeability will be measured by constructing a test cell made up of a wick sample sintered to a manifold. Measuring the volumetric flow rate through the wick will allow for a determination of the wick's permeability as a function of pressure. Currently, simple estimates of permeability as a function of vapor fraction of a porous media are being used as a model to calculate the two-phase permeability. The above mentioned experiment will be used to test the existing formulas validity. The plan is to make use of a known procedure for testing permeability and apply those techniques to a felt-metal wick. The results will be used to verify and/or modify the two-phase permeability estimates. With the increasing desire to replace directly illuminated engines with the much more efficient heat-pipe apparatus it is inherently clear that the usefulness of known wick properties will make wick permeability design a simpler process.

Heat-Pipe Wick Characterization: Summary

This report will give the experimental values for the two-phase permeability of felt-metal wicks used in heat-pipes and will model the results.

- Heat-pipes will replace the less efficient method of direct illumination.

- The transport properties, namely the permeability, of felt-metal wicks used in heat-pipes have been determined.

- The use of heat-pipe technology will increase the efficiency of the remote dish up to 20%.

- Once testing is complete continued application of heat-pipe technology used in solar engine systems is recommended.

For more information on the uses and current research of heat-pipe technology as applied to remote dish systems see the reference section at the end of this report.

The Sun and Heat-Pipes

The National Solar Thermal Test Facility (NSTTF) located in Albuquerque, New Mexico, is a center for the research and development of concentrated solar energy. Operated by Sandia National Laboratories the NSTTF is on the cutting edge of solar energy technology.

To apply this technology the NSTTF has made use of the Stirling 161 Solo engine. The process involves the design and building of a remote reflective dish, the mounting of a Stirling engine onto the framework, and the proper control system to operate the dish. The technique then used is referred to as Direct Illumination. Direct Illumination focuses and concentrates sunlight into an aperture mounted to the engine. The concentrated sunlight then heats small tubes filled with helium therein causing the helium to cycle through the engine and provide a means of cyclic rotation thereby producing power by means of a generator.

While Direct Illumination is effective it does have its negatives. The major disadvantage of Direct Illumination is the variation of heat flux across the helium tubes. Variations in heat flux may result in a drop in engine efficiency. Another possibility of variations in heat flux is the development of hot spots. Hot spots may destroy or damage the helium tubes, aperture, or components of the engine. Variations in dish movements and inclement weather may also result in an unbalanced heat flux.

The problems associated with Direct Illumination do have a solution. Instead of Direct Illumination the addition of a heat-pipe will greatly increase the efficiency of the engine and solve some of the problems caused by Direct Illumination. A heat-pipe is a metal tube designed to heat a substance, in this case sodium, at one surface resulting in evaporation of the sodium from that heated surface. The evaporated sodium then condenses onto the helium filled tubes where the heat transfer occurs. The sodium then drips off of the helium tubes and onto a wick. The wick then redistributes sodium over the heated surface where the process repeats itself.

The heat-pipe is mounted onto the engine in such a way that the concentrated sunlight directly illuminates the dome shaped end. Figure 1 illustrates the operation of the device. Even though there may be variations in the heat flux on the absorber surface what's going on inside of the heat-pipe is nearly isothermal.

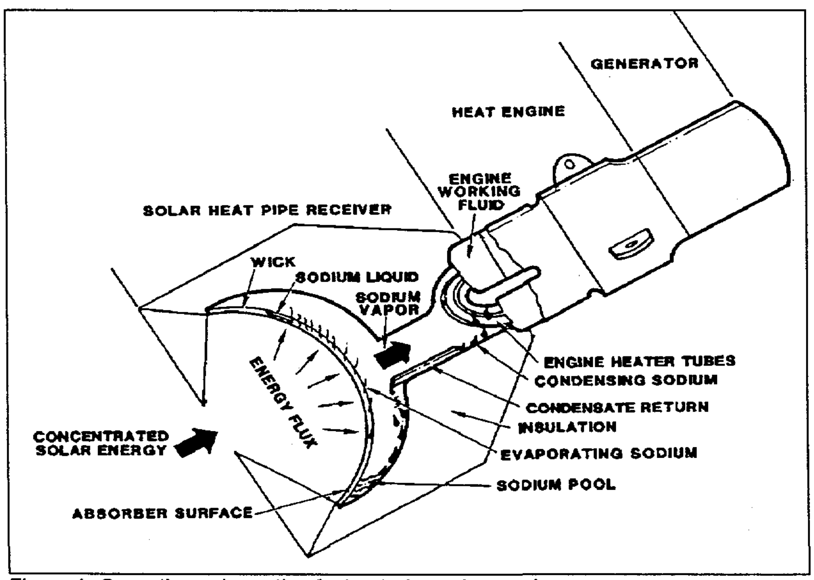

Figure 1. Operating schematic of a heat-pipe solar receiver.

This solves the problem of hot spots and changing to the heat-pipe rather than using Direct Illumination has increased the efficiency of the operation by 20%.

This paper will focus on the heat-pipe wick and its transport properties. The wick itself is made-up of millions of metal fibers that measure in the microns in diameter. The wick is sintered to the inside of the heat-pipe and will act as the transport mechanism for the liquid sodium. In order to be able to predict these transport properties the wick permeability as a function of vapor fraction will be measured. Vapor fraction is the vapor phase volume in a substance divided by the total volume. Since the wick is a felt-like material the radii of the wick's pores differ throughout the wick itself. Therefor, within the wick there will be areas of liquid sodium and vapor sodium existing simultaneously. This is referred to as two-phase permeability.

To determine the permeability of the wick a horizontal test cell is constructed. To solve for the permeability it is necessary to begin with Darcy's law for the viscous flow of fluids through permeable media stated in general terms as

$$v_s = -(k/\mu)[(\mathbf{dp/ds}) - \rho g(\mathbf{dz/ds})] \qquad (1)$$

Where v_s is the volume flux across a unit area of the porous media over time. k is the permeability of the media. μ is the viscosity of the fluid. **dp/ds** is the pressure gradient along s. ρ is the density of the fluid. z is the vertical coordinate directed downward. It is also useful to note that

$$v_s = Q/A \qquad (2)$$

Where **Q** is the volume rate of flow and A is the cross-sectional flow area of the sample. For the experiment described in this paper Methanol flows horizontally through the wick. The governing equations for this type of flow are

$$\mathbf{dz/ds} = o \qquad (3)$$

$$v = -(k/\mu)\ (\mathbf{dp/dx}) \qquad (4)$$

$$k = -\ \mu v/\ (\mathbf{dp/dx}) \qquad (5)$$

For laboratory experiments in the case of horizontal flow, equation 5 becomes

$$k = \mu QL/\ A(p_1-p_2) \qquad (6)$$

Where L is the length of the sample and p1 and p2 refer to the inlet and outlet pressures, respectively. Equation six will serve as the permeability measurement for each wick tested. Once the permeability is known the next step is to calculate the vapor fraction. In the future the vapor fraction results will serve to test the two-phase liquid permeability formulas. These simple estimation formulas are as follows:

$$k_L = k_{1\text{-}Ph}\ (1-\alpha)^3 \qquad (7)$$

$$k_V = k_{1\text{-}ph}\ (\alpha)^2 \qquad (8)$$

Where k_L is the liquid phase permeability, k_V is the vapor phase permeability, and α is the vapor fraction. If the permeability calculations from equation 7 are similar to the permeability measurements observed in the laboratory, using equation 6, then equation 7 will serve as the model for wick permeability estimates in the liquid phase. A brief overview of that modeling will be presented later in the report.

Felt-Metal Wicks

The wick material used in the heat-pipe is a porous metal product that has been developed by Bekaert Fiber Technologies. The metal fibers are extracted from stainless steel or other metals and alloys. For use in the heat-pipe processed mats or sheets of the interconnected fibers are constructed. Bekaert can produce fibers in the range of 1 to 80 microns in diameter. A human hair is 50 microns in diameter for comparison. The fibers high resistance to both heat and corrosion make their application to a heat-pipe a good choice. The fibers will have to withstand temperatures up to 750 degrees Celsius and will have to resist corrosion due to unforeseen oxygen or other contamination not previously removed.

Once the metal fibers have been cut from the bulk material they are randomly laid upon one another to form a porous mat. When the process is complete the mat looks and feels like felt. Hence the name felt-metal wick. The varying pore size throughout the felt-metal wick is desirable so that a dry spot inside the heat-pipe does not occur. Dry spots can occur due to pressure changes and the accompanying breakage of liquid menisci. A varying pore size means that larger pore menisci will rupture first while smaller pores will stay saturated. The previous use of metal-screen wicks in heat-pipes, all of which have the same size pores, included the possibility that when a pressure change or another unforeseen event occurs all menisci break. Hot spots due to dry spots may irrevocably damage the heat-pipe and/or cause a decrease in efficiency.

Experimental Setup and Expectations

Before any construction of an apparatus or measurements of the permeability were taken a concise literature review was conducted and a number of informal meetings were attended. Literature on the subject matter was readily available from the Sandia National Laboratories technical library as were papers written by engineers currently working on the many aspects of the heat-pipe. Past experiments using metal-screen wicks were studied and discussed with those individuals who had been directly involved with those experiments. This knowledge made measuring the permeability of the felt-metal wick a clearer process.

The next step in the experiment was to design the apparatus that would be used to measure the permeability of the felt-metal wick. Initial drawings and ideas were developed with the help of the project leader. It was decided that a simple horizontal flow manifold could be built to house a 2.75" X 5" piece of felt-metal wick. A mariott bottle filled with Methanol was attached to the inlet side of the manifold while a collection beaker was attached to the outlet side of the manifold. Methanol is then allowed to flow through the wick. The viscosity of Methanol at various temperatures are known and are used directly in equation 6. The inlet and outlet pressures are calculated by measuring the height of the fluid levels multiplied by the specific weight of Methanol. Therefor, knowing the length and cross-sectional area of the wick sample, the viscosity of Methanol, the volumetric flow rate of the Methanol through the wick, and the pressure at the inlet and outlet will allow for calculations of the wick permeability by way of equation 6. Throughout the experiment the inlet pressure will be held constant using a mariott bottle. The outlet container will be stationary and will allow for the incoming Methanol to spill over and into a collection pan. This will keep the outlet pressure constant and will make the procedure much simpler.

Successful application of the above mentioned procedure led to a table of permeability measurements. The vapor fraction is then obtained from previously determined values of mercury porisimetry readings. The vapor fraction is represented as a function of pressure.

Then it will be possible to generate a number of data tables and graphs. Once the vapor fraction is known a table comparing the permeability measurements from the experiment can be compared to those of permeability as a function of vapor fraction. This will make clear whether the estimates of permeability as a function of vapor fraction were initially correct. Knowing the permeability of the felt-metal wick will conclude the experiment. Before conducting the experiment it was useful to gain an idea of how changing pore radii would affect the pressure at the inlet and outlet of the manifold. Figure 2 shows the expected flow of Methanol through the wick vs. the expected permeability.

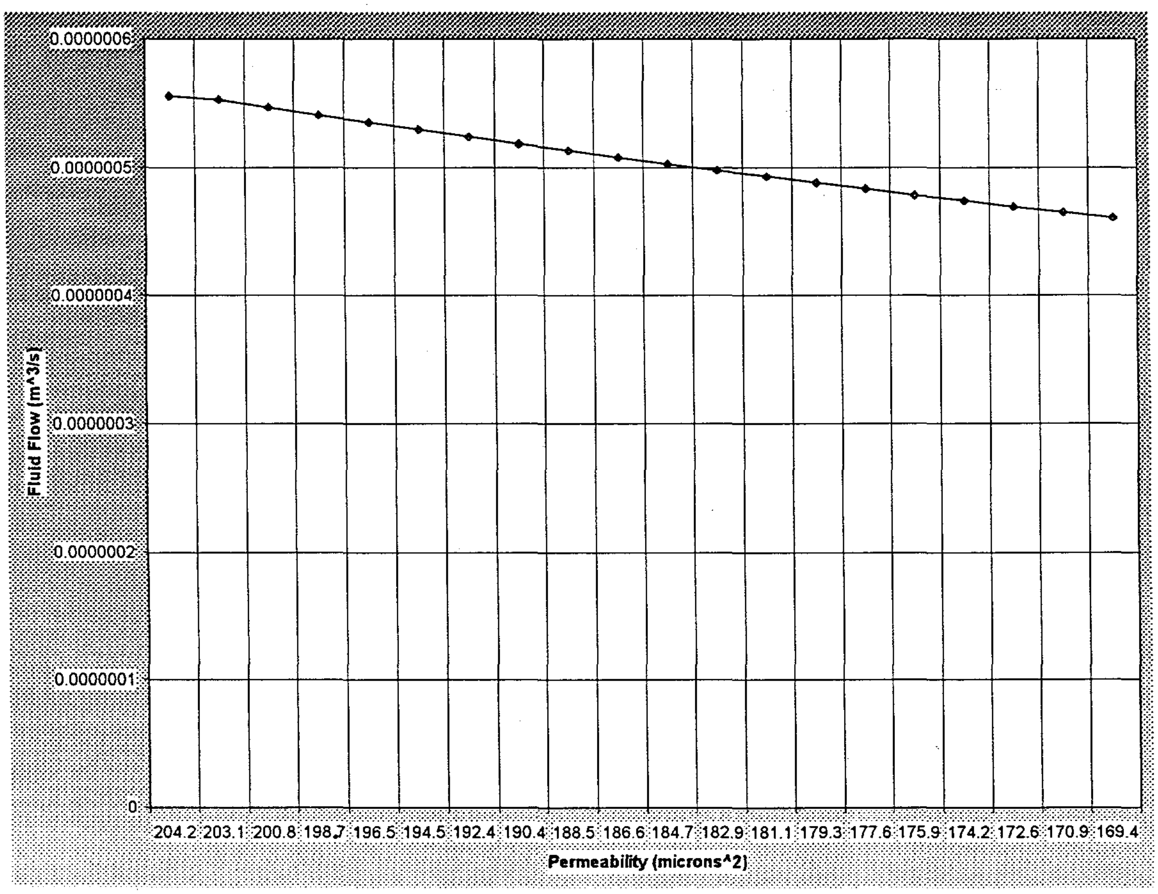

Figure 2. Expected Volumetric Flow rate of Methanol through an 8-300 Bekaert felt-metal wick vs. Permeability.

This chart suggests a permeability that will be compared to the final results obtained in the experiment stage. The wick is fully saturated and the pressure here is assumed to be constant throughout the experiment and can be calculated beforehand.

Finally, expected permeability values should be close to 200 μm^2. Obviously a more precise model will be available once data values are collected from the running of the experiment.

Experimental Results

Technically, determining the permeability of the felt-metal wick was a very clear scientific task. Of course there were a number of variables to account for such as stopwatch time variations due to human starting and stopping.

To determine the volumetric flow of the Methanol through the felt-metal wick multiple time trials were conducted to determine how much fluid was exiting the manifold over time. An average of the times was recorded and thereby using the volume of Methanol collected divided by its average time to reach that volume a flow number was acquired. Table 1 shows the value of the calculated permeability.

Viscosity (kg/m*s):	0.000598				
Pressure (Pa):	1281.128		Wick Thickness:		0.00127
Wick Width (m):	0.06985		Wick Length (m):		0.127
Wick Area (m^2):	0.00016129	Cross sectional			
Volumetric Flow (m^3/s):	0.000000503				
Permeability (microns^2):	184				

Table 1. Final recorded values of Methanol constants, wick dimensions, and the measured permeability of an 8-300 felt-metal wick.

Using equation 6 directly the permeability, k, is close to the estimate of 200 μm^2. Now it is possible to construct a relationship between the simple estimates for the two-phase permeability, equation 7, and equation 6 after determining the vapor fraction.

A brief overview of the expected modeling is presented here to show where this research is heading. Equation 7 is restated here in slightly different terms from its original and will serve as the model.

$$(K_L / K_{1\text{-}ph}) = (1-\alpha)^3 \qquad \text{(7) (restated)}$$

From this the model will be compared to this experiment by plotting the following:

$$(1-\alpha)^3 / [K_L(\alpha) / K_L(0)] \text{ versus } \alpha$$

This is the ratio of the theoretical to the experimental functional dependence and states that if the model is perfect the plot will be a straight line. Otherwise, the plot will fall away from the ideal curve and a percent error can be calculated.

Conclusions

The experiment to determine the permeability of an 8-300 Bekaert felt-metal wick was an exercise in fluid mechanics, basic design, and data acquisition. The confidence in procedure and results obtained are high. Some error does exists and could possibly be in the form of channel flow, human time measurements, and/or slight variations in pressure. Future experiments on wick permeability can be conducted in similar fashions and the results can be made to increase the efficiency of heat-pipe operations.

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