Jessica Sheehan
Advisor: Pamela Norris
University of Virginia

ABSTRACT

New devices are created everyday that have heat dissipation problems, such as computer components, satellites, certain car components, etc. In many cases the heat dissipation problem is so detrimental to the device that it becomes unusable. For example, production of Intel's newest computer chip called Prescott was abandoned due to heat dissipation problems that existed with the chip [1]. Since heat dissipation is a common problem, it has become necessary to look at devices that can quickly dissipate heat. Approaches using heat pipes are now often employed because of the efficacy of the technology. Research remains to devise large-scale devices that can dissipate an enormous (on the order of MW) amount of concentrated heat over short periods of time (on the order of 10 s). Large-scale heat pipes are one solution for effective rapid dissipation of a high concentration of thermal energy (heat). Thus, an experimental study of the efficiency of large-scale heat pipes that are cooled convectively was done to characterize the system to allow for proper implementation of the technology into the scientific world.

INTRODUCTION

A heat pipe is a vacuumed sealed device that efficiently transfers heat from the evaporator side to the condenser side of the device, as shown in Figure 1. The fluid is drawn to the evaporator side by a strong capillary force created by the wicking material that lines the pipe. The working fluid is then converted into vapor when heat is applied. The vapor travels rapidly toward the condenser side, thus transferring the heat. Once at the condenser side of the heat pipe, the vapor undergoes a phase change back to the liquid

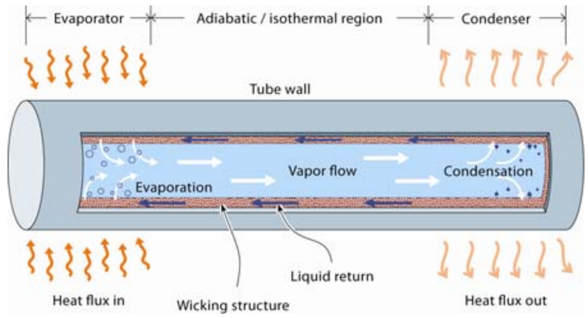

Figure 1: Diagram of a traditional heat pipe and its components [2].

phase and is drawn back to the evaporator side through the wicking structure again. This process is continually repeating while the vapor is removing thermal energy from the evaporator side and transferring the thermal energy to the condenser side. Once the heat has been transferred to the condenser side, it can be removed through convection. A heat spreader, another type of heat dissipation device, works under the same fundamental principles as heat pipes but differs since the wicking surface is distributed across a flat surface. Figure 2 shows the heat spreader that was examined in this study, and it can be seen that wicking inserted around the crosses will allow the plate to act as a heat pipe.

Figure 2: Digital picture of an opened heat spreader plate with nickel foam wicking visible on the cross structures [2].

The wicking material of a heat pipe greatly affects the efficacy of the heat pipes, and if the capillary force is not strong enough to fully wet the wicking material then the heat pipe will not function. A limitation of large-scale heat pipes is finding a material that will provide the wicking height necessary to make an operational heat pipe.

NEW HEAT PIPE CONFIGURATION

Two large-scale heat pipe configurations were tested: 1) a heat spreader plate (a type of heat pipe) with 2 inch dimensions and 2) an innovative combination of heat pipes. The new combination, depicted in Figure 3, uses both traditional heat pipes and heat spreader plates to dissipate a large concentrated heat flux on the front spreader plate and effectively cool the device. The innovative system consists of three major components: a front spreader plate, traditional heat pipes immersed in a flow, and a back spreader plate.

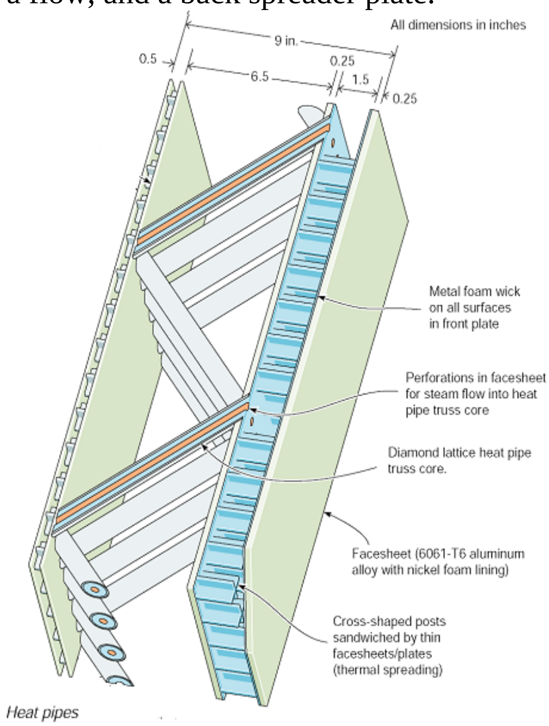

Figure 3: A cross-sectional view of the proposed geometry of the new heat pipe system [2]).

The test section is 9 inch deep with 2 inches devoted to the front spreader plate, 6.5 inches given to the core, and 0.5 inches allotted for the back spreader plate. The front heat spreader plate is utilized to dissipate the highly concentrated incident source of heat. Traditional heat pipes are employed to carry the heat to the core of the structure. A back spreader plate closes the circuit by spreading out the heat transferred to the traditional heat pipes, which increases the area being convectively cooled. The increased area allows the heat to be more effectively dissipated by the forced convection. This is analogous to the theory and implementation of heat sinks. A heat sink is placed on a device that generates heat. The heat sink cools the device by first spreading the heat through the base, and then the heat is drawn into the fins where is it is convectively cooled [3].

Both configurations use an innovative material, nickel-foam, as a wicking structure for the heat pipes. This material has not been widely used for this application; however it provides the force necessary to operate the large-scale heat pipes. Testing was conducted on the material to find the optimal thickness to produce the highest efficacy in a heat pipe. The thickness is directly related to the pore size, which governs the ability of a material to absorb a fluid. The experimental results for wicking behavior were also compared to a mathematical model developed to determine how well the model predicts the physical results.

LITERATURE REVIEW

Heat generation is a common problem among technical devices. It is becoming a limiting factor for advancements of technology since devices are impractical or unusable due to the large amount of heat created. For example, the release of the Pentium IV was postponed due to the large amount of detrimental heat melting other parts of the computer. It was later released only after the heat dissipation problems were solved [1]. Due to this cumbersome problem several devices have been invented to dissipate heat: heat sinks, heat pipes, heat spreader plates, fans, the use of cryogenics, and so forth. But, which devices are best suited for which problem?

CURRENT HEAT DISSIPATION PROBLEMS

Possible applications of heat dissipation devices, specifically large-scale heat pipe systems, include removal of heat from shuttle launch pads, diffusion of heat along the sides of space shuttles during take-off and reentry, and cooling of industrial machinery. In particular, large-scale heat pipe systems have been examined as part of a cellular lattice structure to both cool industrial machinery and to withstand the loading associated with such devices [4].

PREVIOUS RESEARCH

In the past, several different groups have tested various designs of large-scale heat pipes that relate to this work. For example, Hughes Aircraft conducted two distinct investigations on heat pipe structures. Hughes and NASA, in 1982, tested liquid metal heat pipe sandwich panels to determine their feasibility for scramjet engine coolers, radiators for space platforms, and electric and circuit board cooling devices [5]. In 1983, Hughes studied a honeycomb panel heat pipe structure for space radiators [6]. Another study of consequence was done on a flat heat pipe of similar size to the one investigated in this study (4’X 1’ X 0.5”) [7]. Although their application greatly differs from the desired uses of the new configurations examined here, the research provides examples of previous applicable experiments.

A review was also done of the research conducted through Generalized Extremal Optimization (GEO). GEO is an algorithm written to provide the optimization of a heat pipe. The algorithm is pertinent because it provides a modeling system that shows the optimization of heat pipes in space applications, which is one of the many applications that the new configurations are hoped to be utilized in [8].

Research has already been conducted on this project. Due to the unique geometry of the innovative design, several studies were conducted to examine the independent mechanisms that contribute to the overall operating principle of the proposed design. One of the first studies was a shear layer and induced flow analysis to ensure that the proper amount of forced convective cooling would occur despite the unique geometry. The idea behind a shear layer being created from the convective flow over the device was based on the research done on vortex development [9]. Next a study of friction factor for various core geometries was conducted. This research demonstrated the need for a corrugated core due to its low friction factor, high dissipation properties, and stability. Thus, while prior research has focused on the convective cooling expect, this research is focused on the heat dissipation by means of heat pipe/heat spreader plate technology.

The experiments with the heat pipe systems were designed to simulate a typical high heat flux impinging on a surface, such as might be associated with jet blasts, shuttle launches, or in some industrial machinery applications. Optimizing the use of heat spread plates and heat pipes inspired the design of the heat pipe system. Much like heat sinks, it was determined that the new heat dissipation mechanism would need to spread the heat, pull the heat away from the impingement point, and then remove the heat [10]. Due to the properties that heat spreader plates possess, it became apparent that the first device that should be utilized to spread the heat was a heat spreader plate [11]. Next, it was clear that heat pipes would be the proper devices to draw the heat away from the front spreader plate [12]. However, a combination of heat spreader plates and heat pipes of this type has not been tried before. Thus, this research is the first to fully demonstrate the feasibility of this hybrid system.

A large part of the ability of a heat pipe to function is determined by whether or not the capillary force is great enough to wick the entire height of the heat pipe to start the process that transfers the thermal energy. Studies of the wicking height versus the radius of the heat pipe have been done to reveal a correlation between the thickness of the wicking material and the maximum wicking height. In the study done of liquid transport properties of wicking materials, the Young-Laplace's equation below is used to predict the trend by which the compression relates to

$$h = \frac{4 g_0 \sigma \cos\theta}{g d(\rho_l - \rho_v)}$$

the wicking height, h [13]. In this equation g_o is the gravitational constant, σ is the surface tension of the liquid, theta is the contact angle, g is gravity, d is pore diameter, and ρ_v and ρ_l are the densities of the vapor and liquid phases. For the purposes of this thesis, the equation was modified slightly by using the radius, r, instead of diameter and working in international scientific units.

$$h = \frac{2\sigma \cos\theta}{g r(\rho_l - \rho_v)}$$

In this equation, *g* is the acceleration due to gravity (9.8 m/s^2), σ = 0.061 N/m, ρ_l = 958.3 kg/m^3, ρ_v = 0.597 kg/m^3 and good wetability is assumed, thus $\cos\theta$ = 1. This equation is derived from a force balance in the vertical direction on a single capillary tube. The force balance can be represented by the Young-Laplace equation:

$$P_v - P_l = \frac{2\sigma \cos\theta}{r}$$

where r is the radius of the capillary tube. If equilibrium conditions are assumed, the wicking height equation above can be above. To relate the capillary tube radius to the pore size of the various nickel-foam samples, effective pore diameter, d, of the compressed foam was determined using:

$$d = d_o \frac{t}{t_o}$$

where d_o is the initial average pore size of the nickel-foam from the manufacturer (~600 µm), t the thickness of the compressed foam and t_o the original thickness.

MATERIAL AND METHODS

Three experiments were designed in order to characterize the new system to determine if the novel combination of heat dissipation devices works as predicted. The first experiment was designed to ensure the efficacy of the heat spreader plate's performance in rapidly spreading out the heat (thermal energy), and thus quickly becoming isothermal. The second experiment was designed to test if the combination of a front spreader plate, traditional heat pipes, and a back spreader plate would function as a heat pipe (similiar to the configuration depicted in Figure 1). The third experiment was aimed at an increased understanding of the wicking characteristics of the material used in the heat pipe systems, nickel foam.

FRONT SPREADER PLATE EXPERIMENTS

To test if the front spreader plate operates as expected the experimental setup shown in Figure 4 was designed and constructed. The torch is a Red Dragon Torch produced by Flame Engineering, which uses a simple nozzle with lead hose to generate a concentrated amount of propane to be ignited. The Red Dragon Torch is placed 18" from the test sample. The test section shown in the picture is a 2’X2’ front spreader plate, and it is 2”

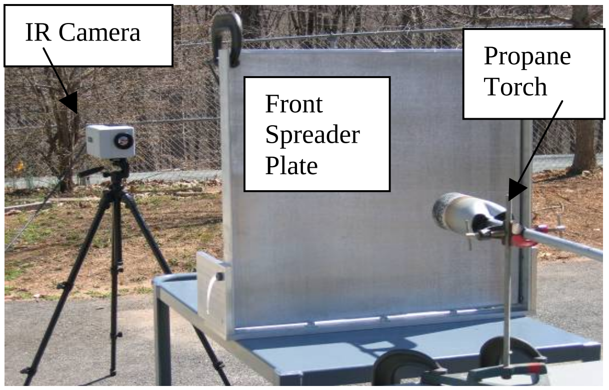

Figure 4: The experimental setup for the heat dissipation research [2].

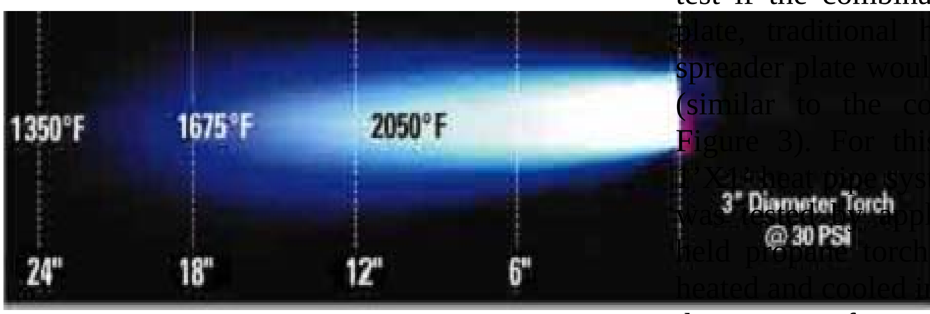

Figure 5: Diagram of the temperature of the flame at different distances [2].

thick. Figure 5 shows the approximate breakdown of the flame temperatures at different distances from the nozzle; however, due to the varying pressure of the tank these are not completely accurate. The propane torch at 18” will heat the plate to a maximum 1675˚F (the temperature is variable because of the pressure of the propane tank). An infrared (IR) camera is utilized to image the backside of the sample being tested. The camera is placed behind the plate to avoid images of the actual flame being in the camera’s line of sight. When the flame is imaged it completely blocks out any other object in the picture due to the high temperature and distribution of the flame. In addition, the back of the front spreader plate is painted with black heat resistant paint (thermal resistant paint) to create a uniform and known emissivity. The emissivity, which is a non-dimensional quantity, with a maximum value of one, describes the ability of the plate to reflect light and is given by the equation, e= 1-reflectivity. The emissivity was determined experimentally to be 0.95 by imaging the plate and taking temperature readings of the surface using a thermocouple. The value of the emissivity was then adjusted until the IR temperature matched that of the thermocouple reading.

TESTING OF INNOVATIVE HEAT PIPE SYSTEM

The second experiment was designed to test if the combination of a front spreader plate, traditional heat pipes, and a back spreader plate would function as a lead pipe (similar to the configuration depicted in Figure 3). For this experimental study, a 1’X1’ heat pipe system was constructed, and was tested by applying heat using a hand held propane torch. The configuration was heated and cooled in cycles to gain insight to the amount of energy that needs to be added to cause this configuration to work optimally. For the second experiment, the desired outcome was to determine if the configuration was plausible, and thus little regard was given to the specific characteristics of the heating element. A small handle held propane torch was used to impinge concentrated heat at one end of the heat pipe system. Again, the IR camera was used to image the system as heat was applied to determine the transient behavior of the heat pipe configuration.

WICKING EXPERIMENTS

The third experiment examined the wicking properties of the nickel-foam used to create the necessary capillary forces to make large-scale heat pipes feasible. For this study, varying thicknesses of the nickel-foam were tested to determine the relationship between wicking height and pore size. The very simple experimental setup is shown in Figure 6. One end of the prepared nickel-foam is placed in de-ionized water and the capillary forces created along the radius of curvature of the open-celled foam structure results in wicking of the material. Once steady state has been reached and the maximum wicking height had been obtained, a measurement is taken to determine the height of the water. This experiment was repeated with ten samples of nickel-foam, with thicknesses varying from 1X the manufacturing thickness to 0.1X the manufacturing thickness. Each sample, after being compressed to the proper thickness, is placed in a furnace at 900 C for two hours. This is to remove any contaminates, but more importantly to evaporate any water vapor that the material has absorbed from the air.

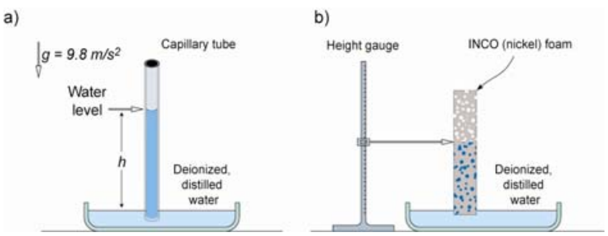

Figure 6: a) shows a capillary tube of comparable radius to the pore size of the nickel-foam sample b) a nickel-foam sample placed in deionized distilled water.

RESULTS AND ANALYSIS

RESULTS AND ANALYSIS OF FRONT SPREADER PLATES

From the experimentation described earlier, several results interesting results were obtained. From the tests that were conducted it was determined that the front spreader plate became isothermal extremely quickly as desired. Figure 7, demonstrates the efficacy of the heat spreader plate. On the left is an IR image of an aluminum plate, where it can clearly be seen that there exists a hot spot. On the right, a heat spreader plate is imaged, it can be seen that even in the early stages of use the impinging concentrated heat has been spread out. Both the aluminum plate and the front heat spreader plate were subjected to the same heating conditions. A curve that shows the temperature distribution on the dashed

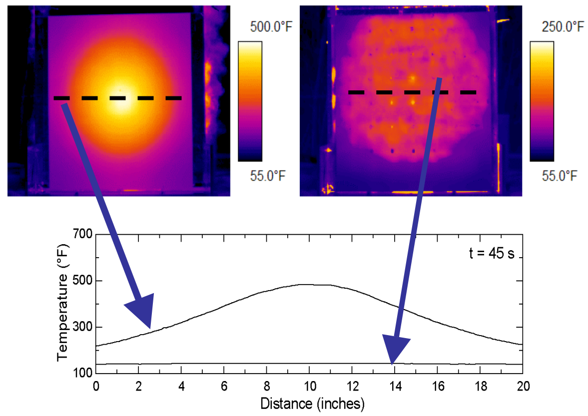

Figure 7: IR images of an aluminum plate after heating (left) and a heat spread plate after heating (right) [2].

line in each IR image is presented on the graph below the IR image. This further demonstrates the magnitude to which the aluminum plate has a high concentration of thermal energy at the center of the heated area, while the heat spreader plate becomes isothermal. Figure 7 shows the front spreader plate in its initial stages of operation after 45 seconds of heating. Figure 8 shows the front heat spreader plate after 90 s of heating. Again an aluminum plate is imaged on the left, showing a hot spot; and on the right a front heat spreader plate is imaged, demonstrating an isothermal system. It is even more apparent that the heat spreader plate effectively becomes isothermal after a slightly longer exposure to the propane torch.

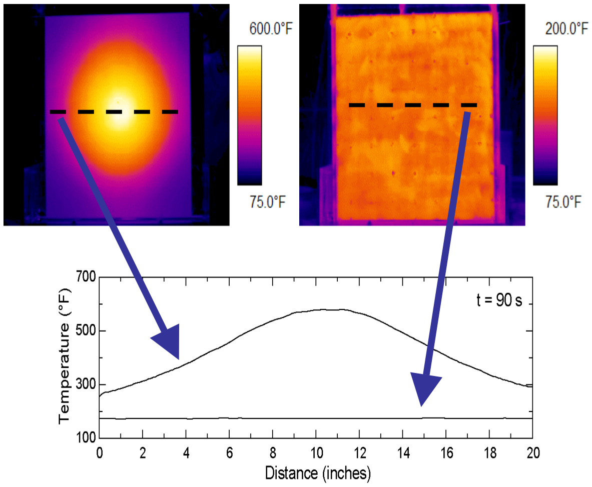

Figure 8: On the left is an aluminum plate that has been heated for 90 seconds and on the right is a heat spreader plate that has been heated for 90 seconds [2].

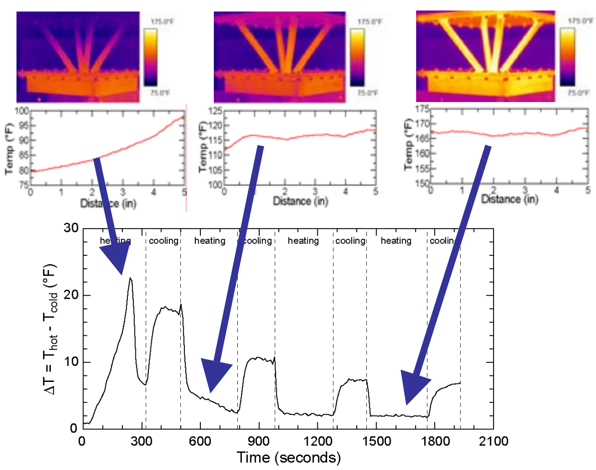

Figure 9: IR imaging and graphical results from testing done on a 1'X1' cell of the innovative combination design [2].

RESULTS AND ANALYSIS OF INNOVATIVE HEAT PIPE

The second series of experiments were designed to determine if the innovative configuration would function. Due to the complex structure some questions were raised about the feasibility of the design. Figure 9 shows the results for this experiment, which verifies that the configuration functions efficiently as a heat pipe. On the left side of the figure, the IR images show the response of the system to the heat applied over a period of time. It is evident that the IR image to the far left is not isothermal, but that the IR image of the system to the far right has become isothermal. To better represent and quantify the findings, graphs were generated that correspond to the temperature over the length of the heat pipe being tested. The graphs just below each IR image are the temperature gradients from the top to the bottom of the heat pipe. This quantifies the difference between the configuration when heat is applied, and when enough heat/energy is added to turn the entire system into a functioning heat pipe. The graph at the bottom of the figure shows the heating and cooling cycles, and graphically represents the gradual transition from an element being heated to an isothermal heat pipe.

WICKING RESULTS AND ANALYSIS

The third in the series of experiments was aimed at experimentally determining the maximum wicking height of the varying thicknesses of the nickel-foam wicking material. One of the first things examined was if uniform compression of the wicking foam had occurred during processing (where the samples are compressed and baked described earlier). Figure 10 shows the graphical representation of the sample
that were not compressed, but simply had variation due to shipping or manufacturing error. This shows that the samples had inherent variations in thicknesses before processing, and that the processing was not the only cause of the non-uniform compression.

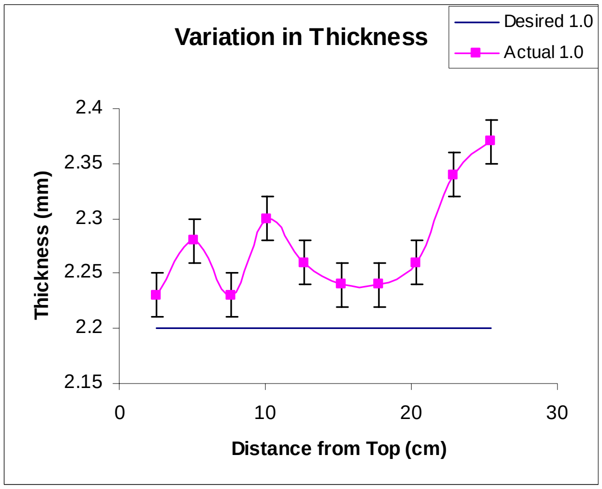

Figure 10: Graphical representation of the varying thicknesses in the unprocessed sample (Sheehan).

These wicking experiments also confirmed the theoretical predictions made. Figure 11 shows the wicking height versus

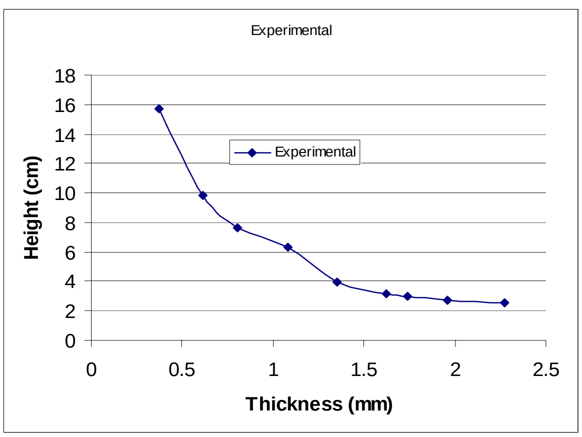

Figure 11: A graphical representation of the wicking heights collected through experimentation (Sheehan).

the compression thickness of the wicking material. The graph follows the general trend of the mathematical Young-Laplace model that is used to predict the behavior of a single heat pipe. Figure 12 shows the mathematical model presented in the literature review section graphed along with the experimental results. This demonstrates how closely the data follows the trend predicted by the wicking model.. The experimental results consistently fail below the theoretical prediction, and this is most likely due to an assumption made to fit the mathematical model to the experiment. (if you give a derivation of the model then you can speculate as to the causes)

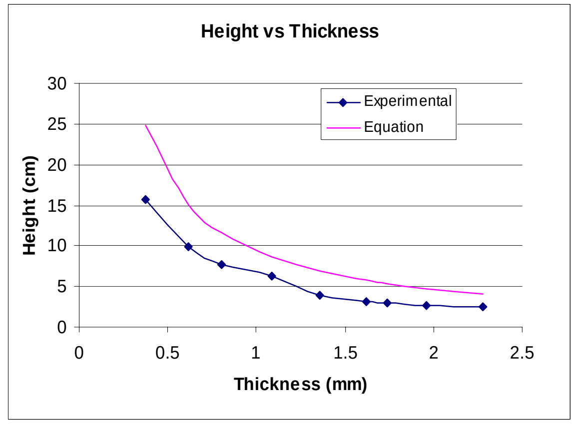

Figure 12: Theoretical model and experimental data plotted together to demonstrate the accuracy to which the mathematical model predicts the experimental trend.

CONCLUSIONS

Due to the need for heat dissipation devices that can handle both today's and tomorrow's heat dissipation problems, two heat pipe configurations were tested. From the experiments done to characterize these configurations, it has become clear that under applied intense heat the front spreader plate becomes isothermal rapidly. Since this configuration becomes isothermal, it demonstrates that this large-scale heat pipe effectively dissipates large amounts of concentrated heat by spreading it out effectively, providing more area to be cooled by convection. Furthermore, from the 1'X1' model of the innovative heat pipe configuration it was determined that this unique system does work as a heat pipe. Due to the positive results of these experiments, large-scale heat pipes could potentially be implemented to solve problems in aerospace, mechanical, and civil engineering fields. Further testing will be conducted to determine the limits of the system, the best applications, and ways to optimize the system.

The wicking experiments on compressed nickel foam also generated outcomes that make this material highly attractive as a wicking material. Tests will continue to determine the optimal thickness of the wicking material to create the most efficient heat pipe. Although a correction factor will have to be generated to account for the slight discrepancy between the theoretical prediction and the experimental results, the general trend is accuracy predicted. The discrepancy can be due to the variation in thickness along the length of the sample. Further tests should be done to determine if the variation of thickness significantly affects the overall wicking height, and at what tolerances this affect is negligible. In addition, due to the material it became increasingly harder to determine the wicking height as the thickness decreased. A study should be done that proves a better visual of drawn liquid. It is possible to die the liquid, or use something that would illuminate under black light for example. Lastly, the discrepancy could be due to several factors. One of which is the assumption that a single heat pipe with wicking has the same capillary forces as just the wicking material. This assumption is based on the fact that the wicking forces due to the sides of the capillary tube are equivalent to the multiple pores of the nickel-foam. In addition, the prediction of the pore diameter of the crushed foam is based on uniform deformation and circular pores. However, due to the compression process it is unlikely that the deformation was uniform and the pores more likely resembled elliptical shapes. A study should be done to examine the affects the wall has on the overall capillary force of the heat pipe.

ANKOWLEDGEMENTS

I would like to thank the Virginia Space Grant committee for selecting my proposal and affording this amazing opportunity. Special recognition to my advisor Pamela Norris for all her help, and I am extremely grateful for all the research assistance I obtained from my fellow staff members.

REFERENCES

[1] Wikipedia. “Pentium 5.” Online 23 May 2005. Internet. <http://72.14.207.104/search?q=cache:C0rySBCLEdoJ:en.wikipedia.org/wiki/Pentium_+pentium+5+chip+heat&hl=en&client=firefox-a>

[2] J. Sheehan, D. Jordan, D.T. Queheillalt, and P.M. Norris, “Innovative Configurations of Large Scale Heat Pipes.” *Proceedings of 2005 International Mechanical Engineering Congress & Exposition*, IMECE2005-83004, 2005.

[3] Incropera, F. and DeWitt, D. (1996). Fundamentals of Heat and Mass Transfer. New York: John Wiley and Sons.

[4] Valkavitch, G., “Determination of Friction Factor and Heat Transfer Coefficient for Passive Jet Blast Deflectors,” Master's Thesis, University of Virginia, 2005

[5] Basiulis, A. and Camarda, C.J., 1983, “Design, Fabrication and Test of Liquid Metal Heat-Pipe Sandwich Panels.” *3rd ASME-AIAA Thermophyics, Fluids, Plasma and Heat Transfer Conference*, 1983STIN...8322541B.

[6] Tanzer, H.J., 1983, “High-capacity honeycomb panel heat pipes for space radiators.” *18th AIAA Thermophysics Conference*, 1983thph.confQ…T.

[7] Cerza, M., Boughey, B., Lindler, K.W., 2000, "A Flat Heat Pipe for Use as a Cold Side Heat Sink." *35th IECEC Conference*, AIAA-2000-3054.

[8] Sousa, F., Vlassov, V., Ramos, F., 2004, "Heat Pipe Design Through Generalized Extremal Optimization." *Heat Transfer Engineering*, 25(7), pp. 34-45.

[9] Ho, C.M., Huerre, P. (1984). Perturbed Free Shear Layers. Annual Review of Fluid Mechanics, 16, 365-424.

[10] "Heatsinks and Heat pipes." Online 20 June 2004. Internet. <http://www.heatsinkguide.com/content.php?content=heatpipes.shtml>

[11] Tien, Chang L. (1935). Heat Pipes. New York: American Institute of Aeronautics and Astronautics.

[12] Chi, S.W. (1931). Heat pipe theory and practice: a sourcebook. Washington: Hemisphere Publishing Corporation.

[13] Langston, L.S., and Kunz, H.R., "Liquid Transport Properties of Some Heat Pipe Wicking Materials," ASME Paper No. 69-HT-19, August 1969.