# Heat Pipe Cooling of Concentrating Photovoltaic (CPV) Systems

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**Concentrating photovoltaic systems (CPV) utilize low cost optical elements such as Fresnel lens or mini-reflecting mirrors to concentrate the solar intensity to 200 to 1000 suns. The concentrated solar energy is delivered to the solar cell at up to 20 to 100 W/cm$^2$. A portion of the energy is converted to electricity, while the remainder must be removed as waste heat. Solar cell cooling must be an integral part of the CPV design, since lower cell temperatures result in higher conversion efficiencies. A heat pipe cooling system was developed to passively remove the high heat flux waste heat at the CPV cell, and reject the heat to ambient through natural convection. With a heat flux of 40 W/cm$^2$, the heat pipe heat sink rejected the heat to the environment by natural convection, with a total cell-to-ambient temperature rise of only 40°C. In contrast, the $\Delta$T between the cell and ambient would be over 110°C using natural convection from the backplate.**

## I. Introduction

Conventional photovoltaic (PV) systems operate at one sun illumination intensity, with the entire surface of the PV system covered with solar cells. The PV material is expensive, leading to intrinsically high costs. As an alternative, concentrating photovoltaic (CPV) systems utilize low cost optical elements like Fresnel lens or mini-reflecting mirrors to concentrate the suns intensity to 200 to 1000 suns, resulting in a photovoltaic system that uses 200 to 1000 times less silicon semiconductor material. Square meters of silicon are replaced with square meters of low cost lenses or reflectors. Moreover, the multi-junction solar cells are significantly more efficient than conventional silicon solar cells.

The concentrated solar energy is delivered to the solar cell at 20 to 75 W/cm$^2$. The energy that is not converted to electricity must be dissipated to prevent excessive cell heating and to maximize efficiency. Therefore, solar cell cooling is an integral part of the CPV design. First, the solar cell efficiency is a function of cell operating temperature and lower temperatures result in higher efficiencies. Second, the solar cell must be kept below the melting point of the die and interconnect attach materials that are used to manufacture the multi-junction cell receiver package to prevent immediate cell failure. And third, the reliability of the receiver is a function of the number of thermal cycles and the magnitude of the thermal excursion. Some experts claim that reliability or life expectancy is doubled for every ten-degree reduction in thermal excursion.

### A. CPV System

A schematic of the CPV system with a heat pipe heat sink is shown in Figure 1. The solar cell is mounted on a back plate. The incoming solar flux (1X) is concentrated roughly 500 times by a Fresnel lens. The concentrated flux strikes the solar cell, producing electricity. The waste thermal energy passes from the cell through the saddle,

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and into the heat pipe. The heat is distributed by the heat pipe to a series of fins, where it is removed by natural convection.

Figure 2 shows details of the EMCORE Gen 1 CPV modules. As shown in the left picture, the EMCORE design has multiple modules, each containing a 1 $cm^2$ cell. Each cell is sealed in a box and mounted on a 3/16th inch thick aluminum plate. As shown in the right picture in Figure 2, the cells are mounted in a two axis system that is always pointed toward the sun. The solar panels track the sun by rotating around a vertical axis. The cells rotate around a second axis. This is helpful for the heat pipe design, since the heat pipe is horizontal under all operating conditions, simplifying the heat pipe design.

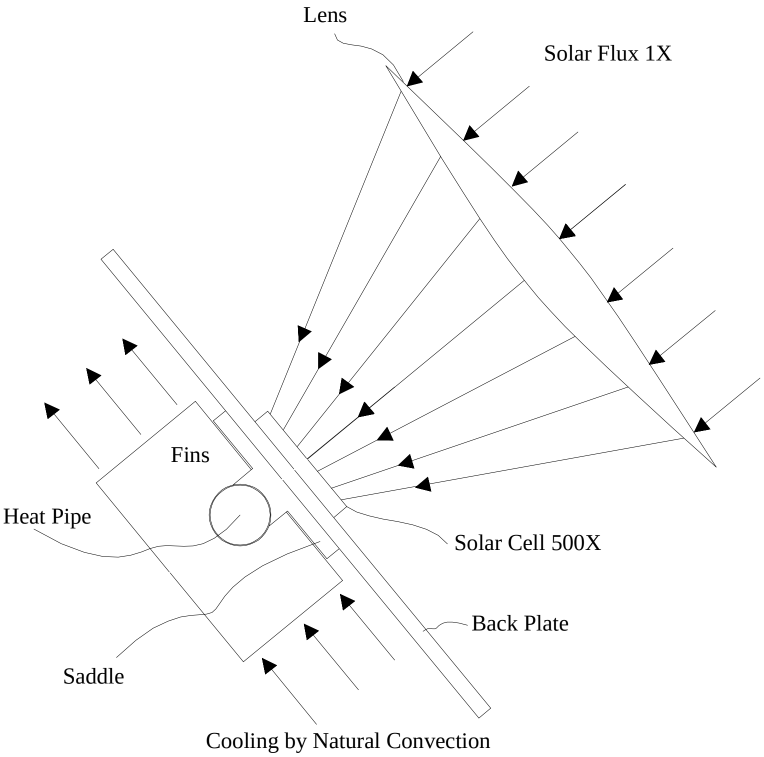

**Figure 1. A lens concentrates solar energy roughly 500 times before it strikes the cell. The fraction of the solar energy not converted to electricity is heat that must be removed from the CPV cell (not to scale).**

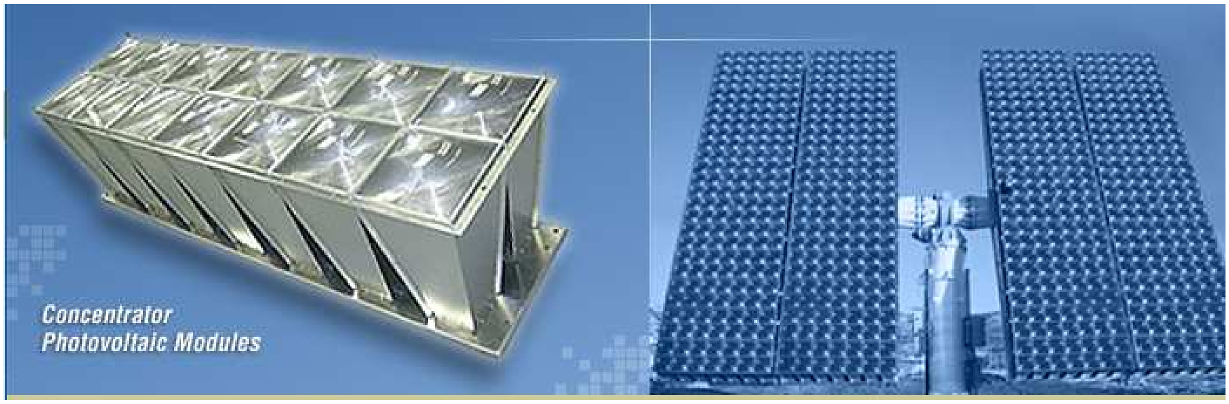

**Figure 2. CPV Modules developed by EMCORE.**

The cell cooling requirements are given in Table 1. Cooling is by natural convection, since forced convection requires a fan, and the power used to run the fan lowers the overall system efficiency. While natural convection allows for the passive removal of heat, typical natural convection coefficients are 10 to 100 times lower than forced convection coefficients. As the heat sink size is increased, conduction losses through the heat sink further reduce the heat sink efficiency. Because natural convection requires a large heat sink, efficient heat spreading is important. Heat pipes provide a method to isothermally deliver the heat to all of the fins, increasing the system efficiency.

**Table 1. CPV Cell Cooling Requirements.**

| | |
|---|---|
| Cell Size | 1 cm x 1 cm |
| Solar Concentration | ~500 Suns |
| Heat Removal During Normal Operation | ~ 40 W |
| Rise above Ambient, Normal Operation (Heat Pipe to Air) | 25°C |
| Design Life | 20 to 30 years |
| Cooling Method | Passive |

### B. Heat Pipes

Heat pipes transport heat by two-phase flow of a working fluid. Shown in Figure 3, a heat pipe is a vacuum tight device consisting of a working fluid and a wick structure. The heat input vaporizes the liquid working fluid inside the wick in the evaporator section. The vapor, carrying the latent heat of vaporization, flows towards the cooler condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The phase change processes and two-phase flow circulation continue as long as the temperature gradients between the evaporator and condenser are maintained.

Heat pipes are an ideal device for cooling CPV systems. Heat pipes are passive thermal devices that transfer heat across long distances with a very low drop in temperature. Heat pipes are also heat flux transformers. They can accept heat at very high heat fluxes (at the backside of the CPV solar cell) and transfer the heat to a significantly lower heat flux heat sink (natural convection to the ambient air). Because the heat pipe operates nearly isothermally, the heat sink portion is also very effective. The typical heat sink spreading resistance is eliminated; and therefore, the heat sink portion can often be significantly smaller and less expensive.

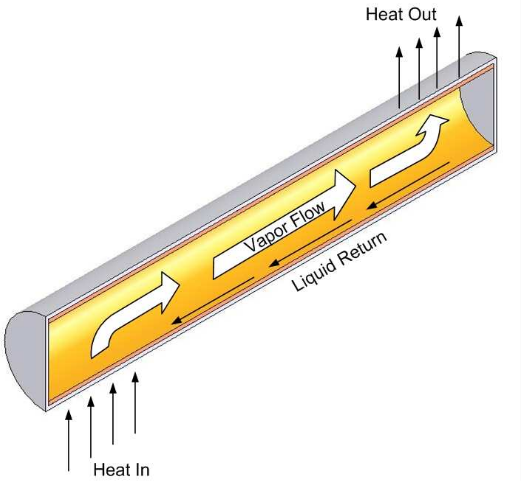

**Figure 3. Heat Pipe Cross Section.**

## II. Previous Work

As discussed in Royne, Dey, and Mills [2005], there are three basic CPV cell arrangements: 1. Single Cell, 2. Linear Concentrator, and 3. High Density Arrays. Heat pipe cooling is suitable for single cell arrays at high concentration ratios, e.g., 1,000 suns, and linear concentrators at lower concentration ratios, on the order of 30 suns. Table 2 below summarizes the previous work done on CPV cooling using heat pipes.

**Single Cells**: Beach and White [1981] used a copper heat pipe with soldered longitudinal copper fins to remove heat at roughly 700 suns, using water or acetone as the working fluid. The system was a thermosyphon pool boiler, and was only tested when oriented vertically. Heat removal was by natural convection. The ΔT between the cell and the ambient air was roughly 30°C. Farahat [2004] conducted a study comparing heat pipe and forced convection water cooling for single cell systems, and concluded that the heat pipe cooling system was superior.

**Linear Concentrator**: Feldman, Kenney, and Edenburn [1981] examined heat pipe cooling for a linear concentrator with about 24 suns incident on the cell. The heat pipe was a "kite-shaped" thermosyphon, with benzene as the working fluid. Heat was rejected from two aluminum plates with perpendicular extruded fins. The evaporator temperature exceeded the design temperature of 140°C for wind speeds of less than 1 m/s. Akbarzadeh and Wadowski [1996] cooled a linear concentrator with a copper thermosyphon, with 20 suns incident on the cell. The working fluid was refrigerant R-11, due to the relatively low operating temperature of 40°C. Heat removal was by natural convection. The fin material, size, and orientation were not specified.

**Table 2. Previous work on CPV cooling using Heat Pipes for Passive Cooling.**

| Work done by | Heat pipe material | Working Fluid | Insolation | Type | Results |
|---|---|---|---|---|---|
| Akbarzadeh and Wadowski (1996) | Copper | Refrigerant, R-11 | 20 suns | Line Concentrator | Thermosyphon, Kept temperature below 46°C |
| Feldman, Kenney, and Edenburn (1981) | Aluminum Heat Pipe and Integral Fins | Benzene | 24 suns | Line Concentrator | Thermosyphon, requires 1 m/s or higher wind |
| Beach and White (1981) | Copper Heat Pipe, Soldered Copper Fins | Acetone or Water | Up to 700 suns | Single Cell | Thermosyphon, vertical testing only, ~30°C rise above ambient |

## III. Heat Pipe System Design

Heat pipes are manufactured using a wide variety of envelope and wick materials as well as working fluids. The envelope material, working fluid and wick material must be compatible. Compatibility means that the working fluid does not attack or corrode the envelope or wick and that there is no chemical reaction between the working fluid and the envelope or wick structure that liberates non-condensable gas (NCG). If NCG is generated, a portion of the condenser section will be blocked off and the performance of the heat pipe will degrade over time.

### C. Potential Heat Pipe Wick/Wall Materials

For the temperature range of interest (roughly -20 to 100°C), the two potential heat pipe wick and wall materials are copper and aluminum. Copper has a higher thermal conductivity, but is more expensive and has a higher density than aluminum. An advantage of copper is that copper screen and sintered powder wicks are both well developed, and have exhibited high reliability. Aluminum heat pipes have the potential for lower cost heat pipes. An advantage of aluminum is that it is easily extrudable: Grooved wicks on the inside of the heat pipe and planar fins on the outside of the heat pipe can easily be extruded at low cost in production quantities.

### D. Heat Pipe Compatibility – Potential Working Fluids

The selection of a working fluid goes hand-in-hand with the selection of the wall and wick material. A fluid must be compatible with the heat pipe envelope and wick for the potentially long operating life of a heat pipe. The heat pipes for CPV cooling will be expected to operate for roughly 30 years. The two major consequences of incompatibility are internal corrosion and the generation of non-condensable gas, or both. The resulting corrosion products can block portions of the wick, preventing the heat pipe from operating properly. In more extreme cases, the heat pipe can leak.

For the operating temperature range, the following combinations give the best results:

- Copper/water
- Aluminum/ammonia

However, both of these fluids have potential problems. Water freezes at 0°C, and water heat pipes carry very little power at temperatures roughly below 30°C. Copper/water heat pipes must be designed to minimize damage when the water freezes. The fact that water heat pipes operate at temperatures above 30°C is not necessarily a problem, since the system could warm up until the water heat pipe begins to operate. Ammonia has a high vapor pressure. Ammonia heat pipes do not perform well at temperatures above 80°C.

### E. Heat Pipe System Design

For this reason, copper water heat pipes were chosen. A schematic of the design is shown in Figure 4, while Table 3 gives a summary of the system. The solar cell is mounted on an aluminum mounting saddle. Heat is transmitted from the cell through the saddle to a copper water heat pipe. The heat pipes isothermally supplies heat to a series of aluminum fins. The heat is transferred from the fins to the air by natural convection.

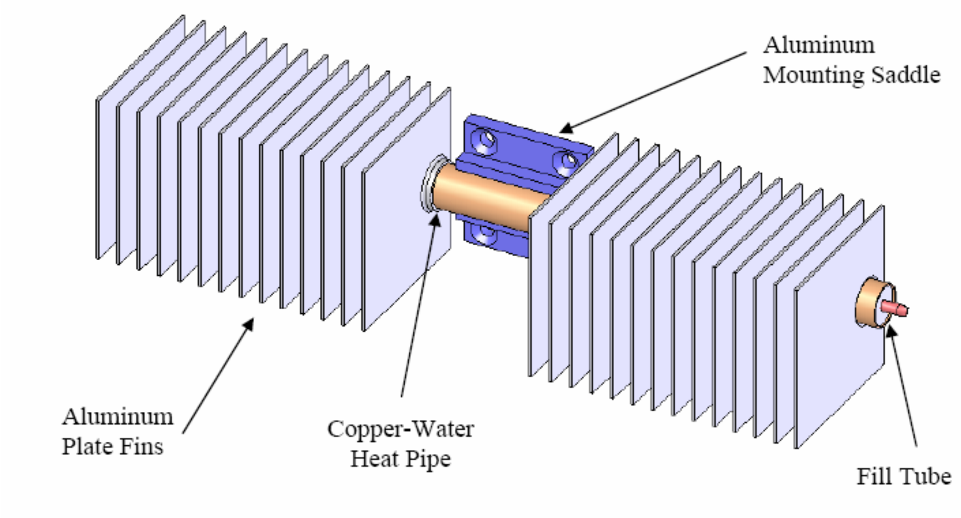

**Figure 4. Heat pipe cooling system schematic with a copper saddle for the CPV cell, a copper/water heat pipe, and aluminum fins.**

**Table 3. Heat Pipe System Summary**

| **Parameter** | **Value** |
|---|---|
| Assembly | |
| Overall Dimensions | 22.9 cm x 5.1 cm x 5.1 cm (9” x 2” x 2”) |
| Finish | Nickel plate |
| Heat Pipe | |
| Envelope | Copper |
| Working fluid | Water |
| Heat Input Saddle | |
| Material | 6061-T6 Aluminum |
| Dimensions | 3.8 cm x 3.8 cm (1.5” x 1.5”) |
| Fins | |
| Material | 1100-H14 Aluminum |
| Quantity | 24 |
| Pitch | 7.94 mm (0.3125 inch) |

The fin dimensions and pitch in Table 3 were selected based on multiple CFD analyses of heat pipe assemblies in free air. The heat pipe assembly was evaluated in a large control volume whose outer surfaces were fixed at 20°C and zero pressure. The direction of the gravity vector was set to be parallel to the mounting flange surface.

SolidsWorks was used for the 3D modeling, and CFDesign for the computational fluid dynamics (CFD) analysis.  A typical result is shown below in Figure 5.

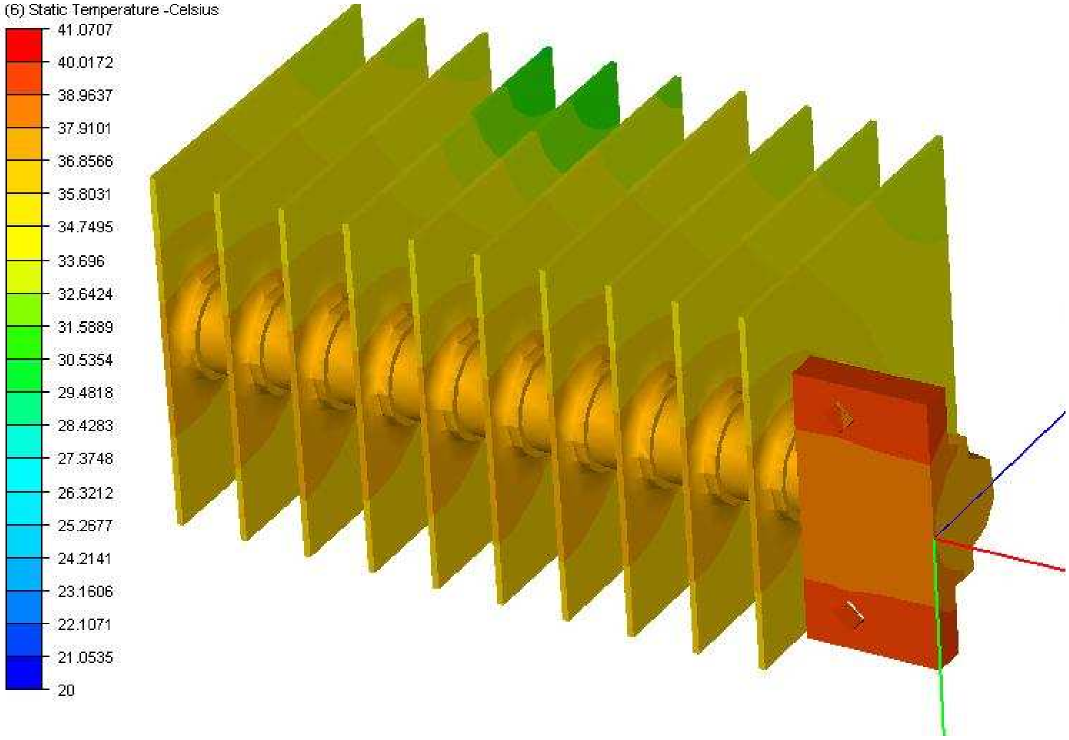

**Figure 5.  CFD analysis was used to select the optimum fin pitch.**

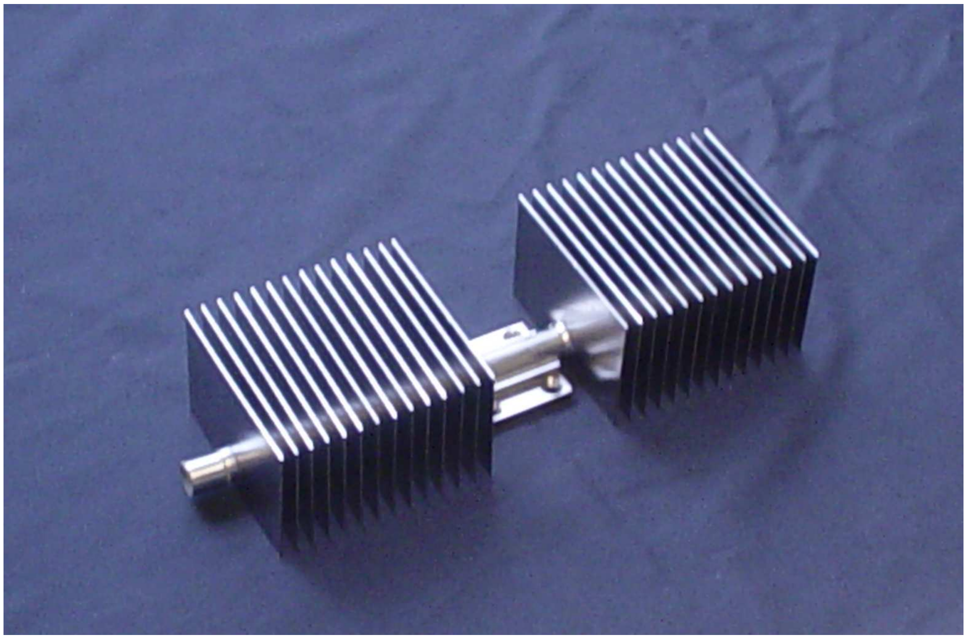

**Figure 6.  Final Heat Pipe Cooling System.**

The cases modeled and the predicted results are summarized in Table 4 below.  The optimum fin pitch was 7.94mm (0.3125”).  While the finer fin pitch design has more surface area the air cannot circulate through the fins as easily. Conversely, air can flow freely through the coarse-pitch fins but the assembly has less surface area. Figure 6 is a photo of the final heat pipe cooling system.

**Table 4. Summary of Fin Performance Predictions.**

| Fin Pitch | Number of fins | Rise over Ambient | Thermal Resistance |
|---|---|---|---|
| 9.53 mm (0.375”) | 20 | 42.4°C | 1.12 K/Watt |
| 7.94 mm (0.3125”) | 24 | 42.3°C | 1.12 K/Watt |
| 6.35 mm (0.250”) | 28 | 45.8°C | 1.12 K/Watt |

## IV. Experimental Apparatus

Figure 7 is a schematic of the experimental apparatus, while figure 8 shows the test setup with an elevation of 60°. A copper heater block with cartridge heaters was used to simulate the waste heat from the CPV cell; see Figure 7. The heater block had a square boss that fit into the location where the cell would be mounted. A plunger thermocouple hole is used to measure the temperature where the CPV cell would be located.

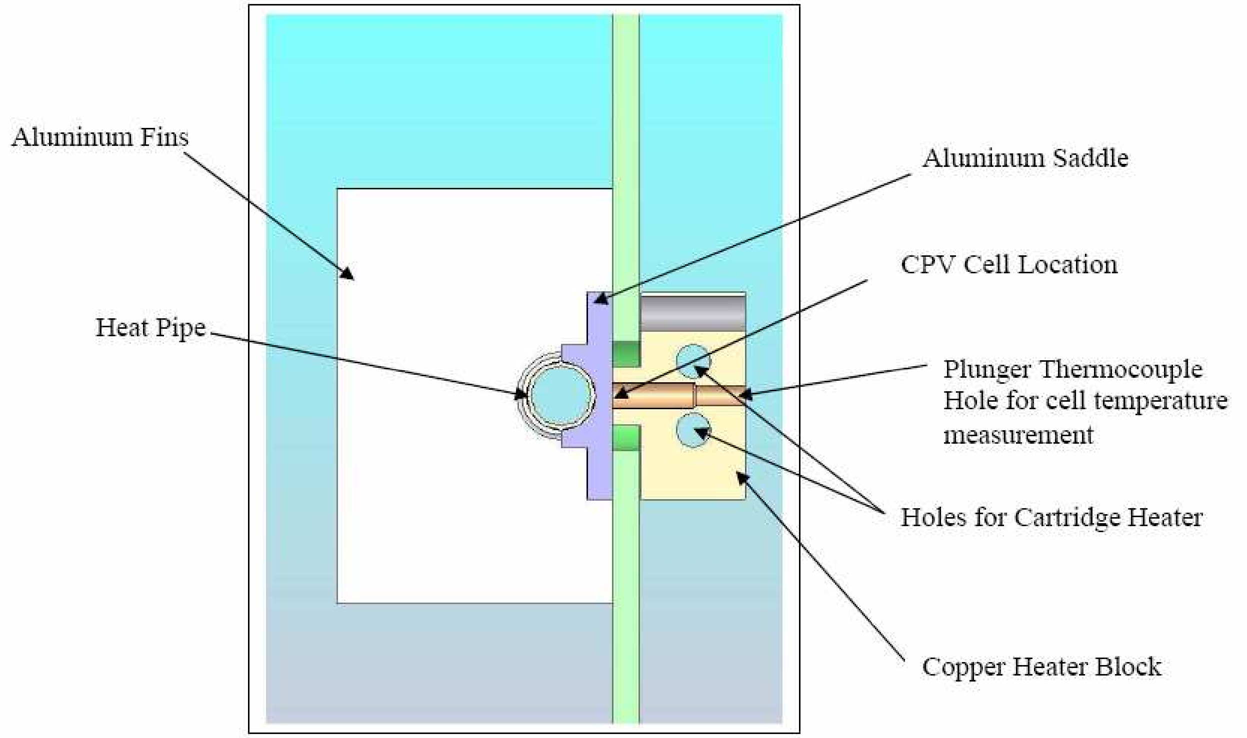

**Figure 7. Heat pipe test setup, with a copper heater block simulating the CPV cell waste heat.**

As shown in Figures 1 and 2, the heat pipe/fin assembly mounts to an aluminum plate. During operation, the heat pipe is located beneath the plate. The elevation of the plate changes from dawn to dusk. In the field, the CPV modules are mounted on a two-axis assembly. The entire assembly turns from East to West during the day, while each module is oriented towards the sun. With this setup, the heat pipe is always horizontal.

During the tests, the heat pipe was instrumented with thermocouples on the copper saddle, heat pipe, and fins. The simulated CPV cell temperature was measured with a plunger thermocouple as shown in Figure 7, while an additional thermocouple measured the ambient air temperature.

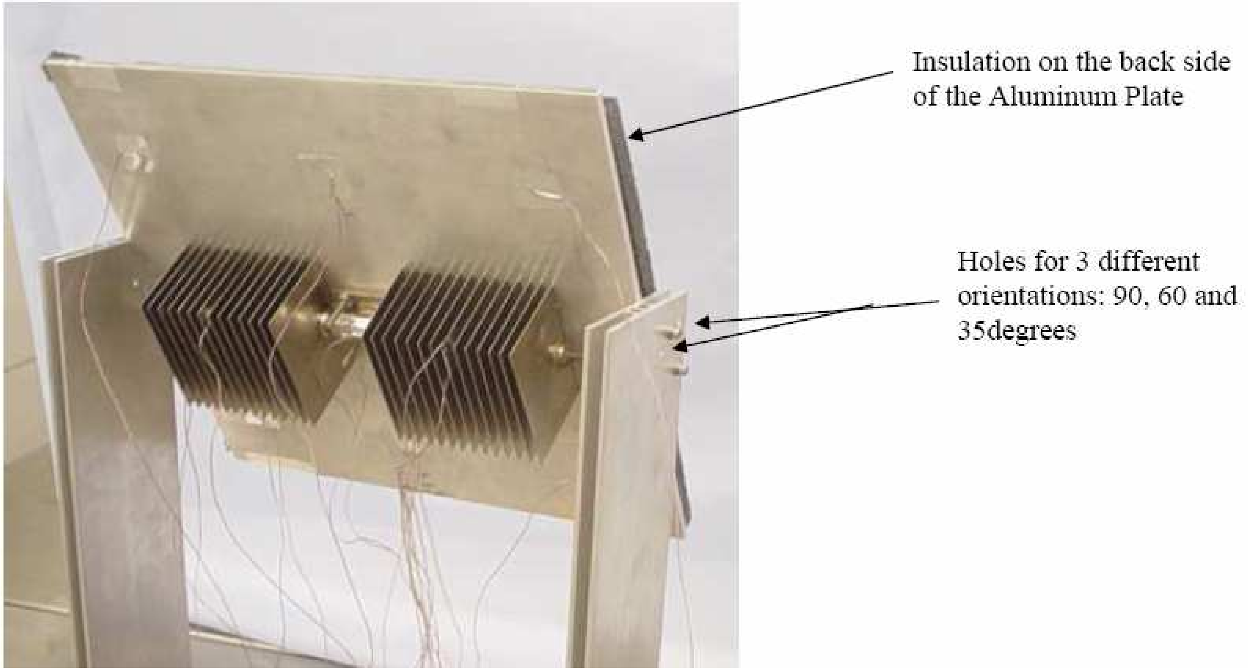

**Figure 8. Test Setup with the plate at 60 Degrees.**

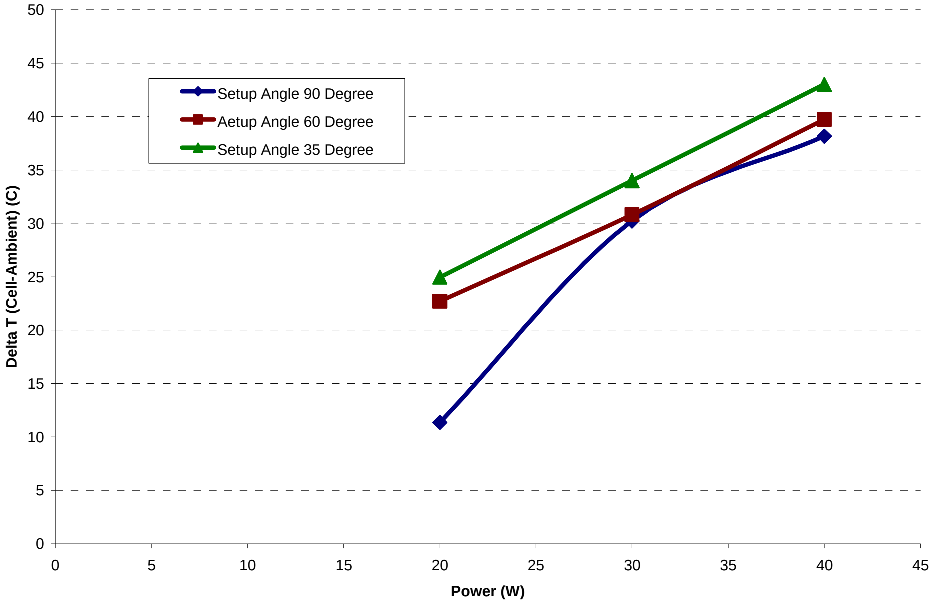

**Figure 9. Plot of cell temperature rise above ambient at various powers, and three different orientations.**

## V. Experimental Results

Measurements were made for three different setups:

- 35° Orientation (High Noon)
- 60° (Morning or Evening)
- 90° (Dawn or Dusk)

The results are shown in Figure 9. Since the simulated cell (and copper boss) had an area of 1 $cm^2$, a power of 40 W is equivalent to a heat flux of 40 $W/cm^2$. As expected, the ΔT is highest for the 35° orientation (high noon), where the plate is most nearly horizontal, giving a longer path for the natural convection. The maximum ΔT from the cell to ambient was about 43°C. The ΔT from the heat pipe to ambient was less than 25°C, meeting the design requirements in Table 1.

The temperature of the cell without the heat pipe and fins was estimated using a CFD program, CFDesign. In contrast to the 40°C experimental temperature rise with the heat pipe heat sink, the calculated ΔT between the cell and ambient was 110°C, if only the flat plate was available to reject the heat

## VI. Conclusions

This work successfully demonstrated the feasibility of a heat pipe cooling solution for concentrating photovoltaic cells. Heat pipes can be used to passively remove the heat, accepting a high heat flux at the CPV cell, and rejecting the heat to fins by natural convection, at a much lower heat flux.

A copper/water heat pipe was selected, with an aluminum saddle, and aluminum fins. A series of CFD analyses were run to determine the optimum fin size and spacing for rejecting heat by natural convection.

A prototype heat pipe heat sink was designed, fabricated, and tested. With a input heat flux of 40 $W/cm^2$, the heat pipe rejected the heat to the environment by natural convection, with a ΔT of only 43°C. This exceeded the design requirements of the application. In contrast, a system rejecting the heat to the aluminum plate would have a ΔT of 110°C.

The next step is to conduct tests with a series of CPV modules on sun.

## Acknowledgements

This program was sponsored under a DOE Phase I SBIR program, Grant No. DE-FG02-07ER84847. Alec Bulawka of DOE was the technical monitor. The heat pipes and experimental test setup were fabricated by Rod McClellan of Advanced Cooling Technologies, Inc. Calin Tarau of ACT drew some of the schematics.

## References

Akbarzadeh, A., and Wadowski, T., “Heat Pipe-Based Cooling Systems for Photovoltaic Cells Under Concentrated Solar Radiation,” Applied Thermal Engineering, 16(1), pp. 81-87, 1996.

Beach, R. T., and White, R. M.., “Heat Pipe for Passive Cooling of Concentrator Solar Cells,” Proceedings of the 15th IEEE Photovoltaic Specialists Conference, pp. 75-80, Kissimmee, FL, May 12-15, 1981.

Farahat, M. A., “Improvement in the Thermal Electric Performance of a Photovoltaic Cells by Cooling and Concentration Techniques,” proceeding of the 39th International Universities Power Engineering Conference (UPEC 2004), IEEE, New York, New York, ISBN: 1-86043-365-0, pp. 623-628, September 6-8, 2004.

Feldman, K. T., Kenney, D. D., and Edenburn, M. W., “A Passive Heat Pipe Cooled Photovoltaic Receiver,” Proceedings of the 15th IEEE Photovoltaic Specialists Conference, pp. 165-172, Kissimmee, FL, May 12-15, 1981.

Royne, A., Dey, C. J., and Mills, D. R., “Cooling of Photovoltaic Cells Under Concentrated Illumination: A Critical Review,” Solar Energy Materials and Solar Cells, 86(4), pp. 451-483, April 2005.