Heat Pipe Cooling of Concentrating Photovoltaic Cells

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ABSTRACT

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 portion that is not converted to electricity must be dissipated as waste heat. Solar cell cooling must be an integral part of the CPV design, since lower cell temperatures result in higher conversion efficiencies. Heat pipes can be used to passively remove the high heat flux waste heat at the CPV cell level, and reject the heat to ambient through natural convection. This paper discusses a cooling design that uses a copper/water heat pipe with aluminum fins to cool a CPV cell by natural convection. With a cell level waste 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℃.

INTRODUCTION

Conventional photovoltaic (PV) systems operate at one sun illumination intensity and the entire surface of the PV system is covered with solar cells. Solar cells are made of semiconductors, typically silicon. The silicon material is expensive and this leads to inherently 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. Recently developed, high efficiency, multi-junction cells are placed at the focal point of the reflector and the result is 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 cell overheating 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 solder that is used to manufacture the multi-junction cells to prevent immediate cell failure. And third, the reliability of the solar cell 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.

Heat Pipes

Heat pipes transport heat by two-phase flow of a working fluid. Shown in Figure 1, 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 also heat flux transformers. They can accept heat at very high heat fluxes (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.

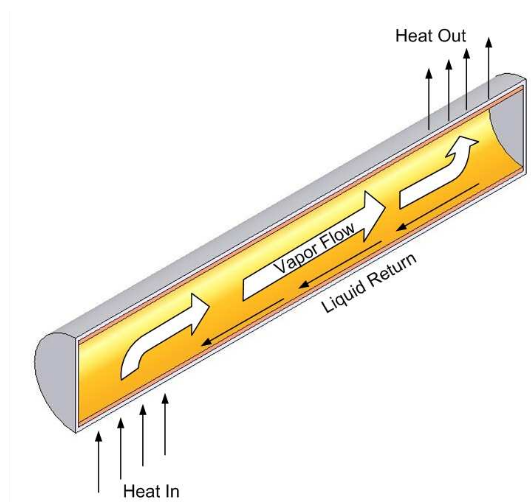

Figure 1. Heat Pipe Cross Section.

A schematic of the heat pipe cooling system is shown in Figure 2. Sunlight enters a CPV module, where it is concentrated, then reflected unto the CPV cell. The waste heat is conducted from the heat acquisition block into the

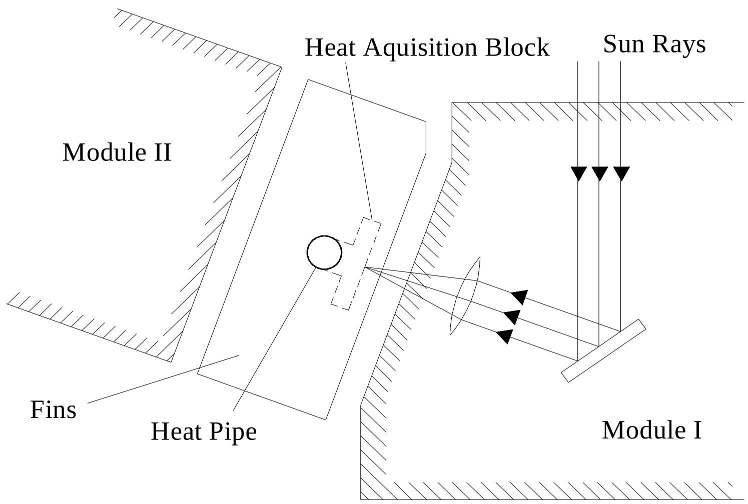

Figure 2. Heat pipe cooling system fits between two CPV modules.

heat pipe, at a high heat flux. The heat pipe than transmits the energy to the radiator fins, where it is rejected by natural convection.

The CPV modules are arranged like stadium seating. Module II in Figure 2 is located behind Module 1, at a slightly higher elevation, so that the sun rays are not blocked by Module 1.

Previous Work

As discussed in Royne, Dey, and Mills [1], 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.

Single Cells: Beach and White [2] 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℃. Farahat [3] 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 [4] 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 [5] 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℃. Heat removal was by natural convection. The fin material, size, and orientation were not specified.

HEAT PIPE DESIGN

There two major decisions for the heat pipe design are: 1. Selection of the heat pipe envelope/wick materials, and the working fluid to give a compatible heat pipe, and 2. Wick design to reliably cool the CPV under any orientation and environmental conditions. The envelope, working fluid and wick structure 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). For the temperature range of interest (roughly -20 to 100℃), 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.

Compatible working fluids for copper and aluminum are shown in Table 1, based on surveys by Brennan and Kroliczek [7], Dunn and Reay [8], and Anderson [9].

Table 1. Fluids Compatible with Copper and Aluminum, based on heat pipe life tests.

Copper	
Compatible	Incompatible/Unsuitable
Water	Ammonia
Methanol, Ethanol	Acetone
Aluminum	
Compatible	Incompatible
Ammonia	Water
Acetone (possible problems)	Methanol, other alcohols
Toluene	Benzene (carcinogen)
n-Butane, n-pentane, n-heptane	Naphthalene (Higher Melting Temperature)

The heat pipe cooling system must satisfy the following requirements:

- Ambient -20 to 50℃
- Heat Flux of 40 W/cm^2
- Freeze Tolerant
- Reject Heat by Natural Convection at minimal ΔT

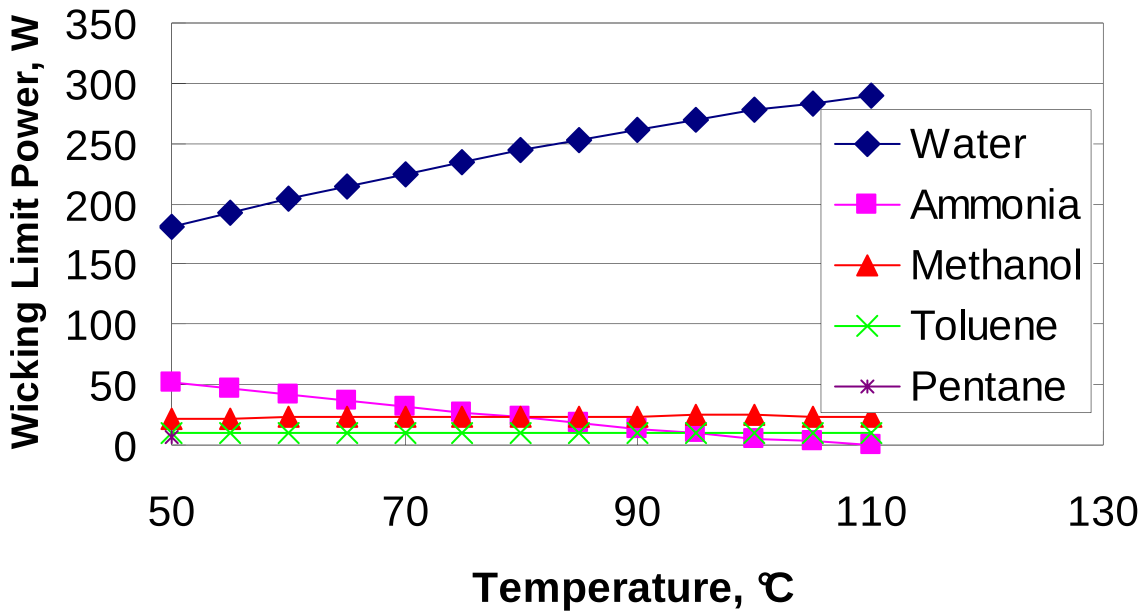

Figure 3. Heat pipe wicking limit, three wraps of 150 Mesh Screen, 0.25 inch Adverse Elevation. The copper/water heat pipe power is more than six times greater than the other fluids.

Heat pipe designs with different working fluids compatible with either copper or aluminum were examined. Typical results are shown in Figure 3. Water is the best working fluid. A water heat pipe with three wraps of 150 mesh screen can carry more than six times the power of alternate working fluids. For this reason, a copper/water heat pipe with a copper screen wick was selected.

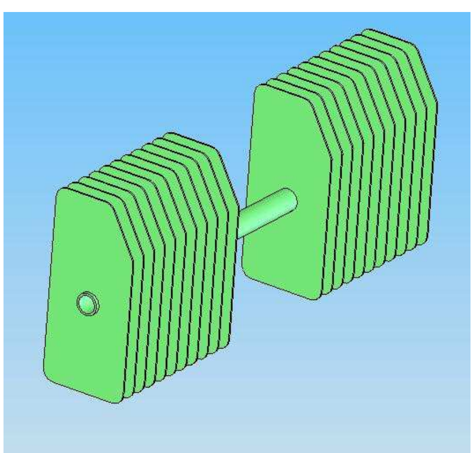

Figure 4. Fin design that rejected the waste heat by natural convection while minimizing ΔT.

FIN DESIGN

After designing the heat pipe, the next step was to design the fins. As shown in Figure 2, the fins in this case were constrained by the need to fit between the module to be cooled and the module behind it, while minimizing the the temperature drop between the CPV cell and the ambient air. A series of CFD analyses were run to determine the fin shape that minimized the temperature drop. The final shape is shown in Figure 4, while the fin properties are given in Table 2. As shown in Figure 5, there is good flow between the fins during natural convection.

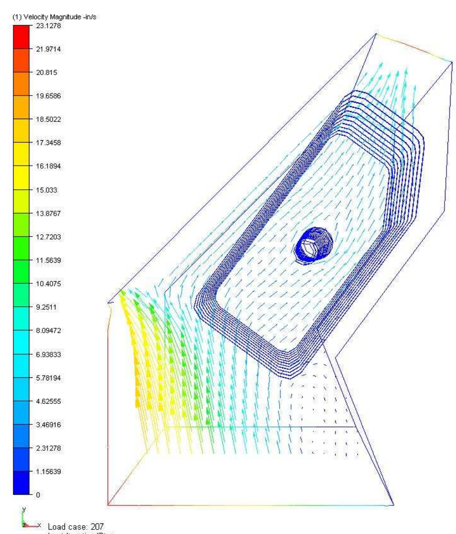

Figure 5. CFD analysis of the velocity distribution on a cross sectional plane shows good flow during natural convection.

Table 2. Fin Properties

Fin Material	Aluminum
Quantity	22 (11 on each side of the saddle)
Total fin area	0.23 m^2
Spacing	0.34 inch

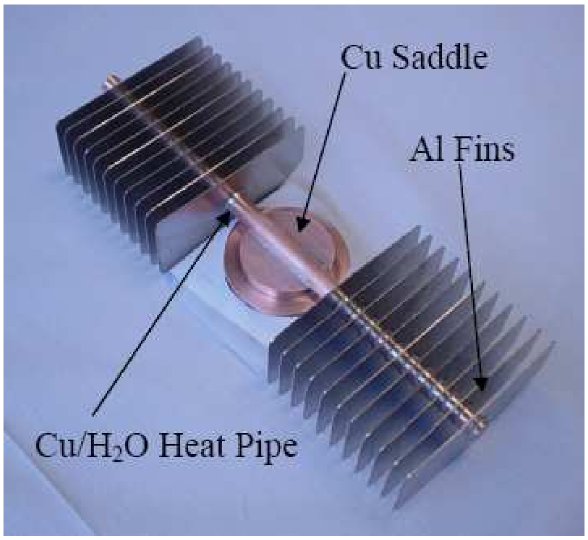

Figure 6. Heat pipe cooling system with a copper saddle for the CPV cell, a copper/water heat pipe, and aluminum fins.

The final heat pipe heat sink is shown in Figure 6. The copper water heat pipe was fabricated, then attached to the copper saddle. The CPV cell to be cooled sits on the bottom of the copper saddle. Next, the aluminum fins were attached.

Experimental Apparatus

A copper heater block with cartridge heaters was used to simulate the waste heat from the CPV cell, as shown in Figure 7. The heater block had a square boss that fit into the location where the cell would be mounted.

As shown in Figure 2, the heat pipe/fin assembly fits between the module that the heat pipe is mounted to, and the module to its rear. This provides a chimney through with the air must flow to remove the heat by natural convection. 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.

Tests were conducted in two orientations, using the test setup shown in Figures 8 and 9. Insulation panels were used to simulate the module and adjacent module.. Figure 8 shows the test setup corresponding to high noon Test Setup 1).

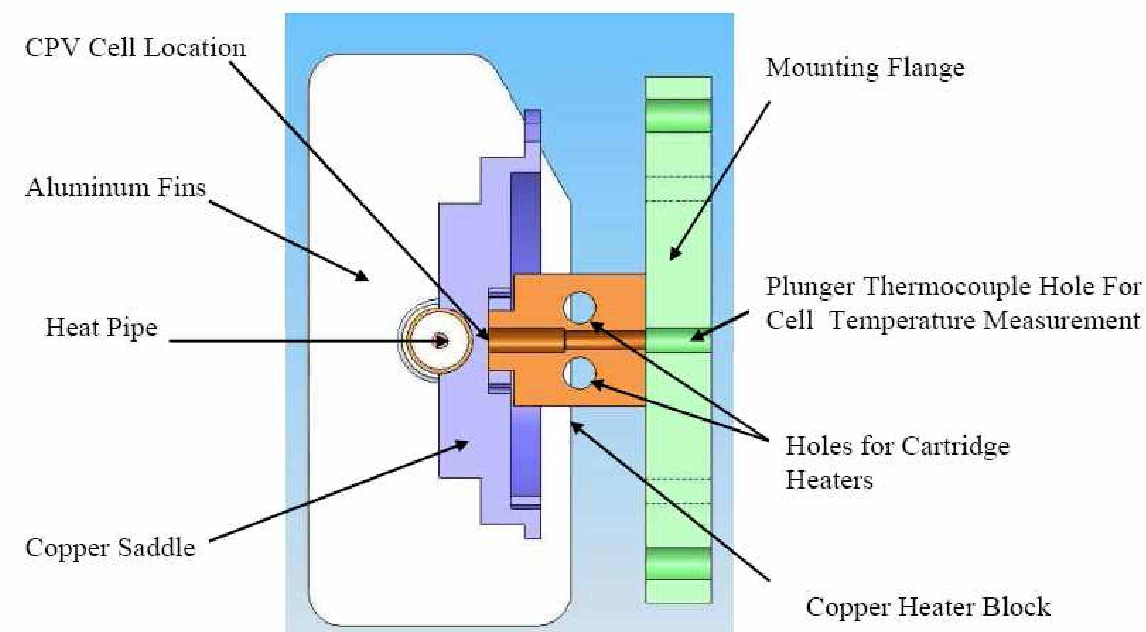

Figure 7. Heat pipe test setup, with a copper heat pipe simulating the CPV cell waste heat.

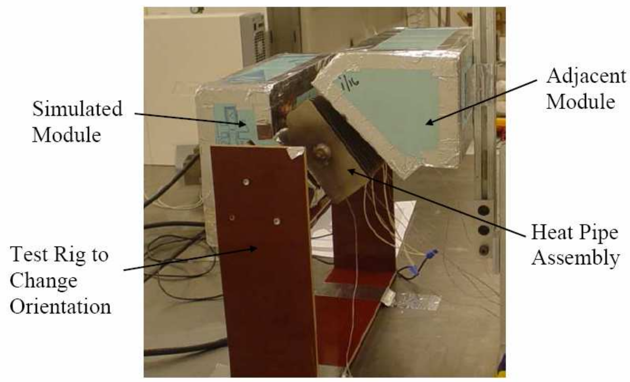

Figure 8. Heat pipe test setup #1. Orientation at high noon.

The heat pipe was also tested in the orientation corresponding to late morning and early afternoon, as shown in Figure 9.

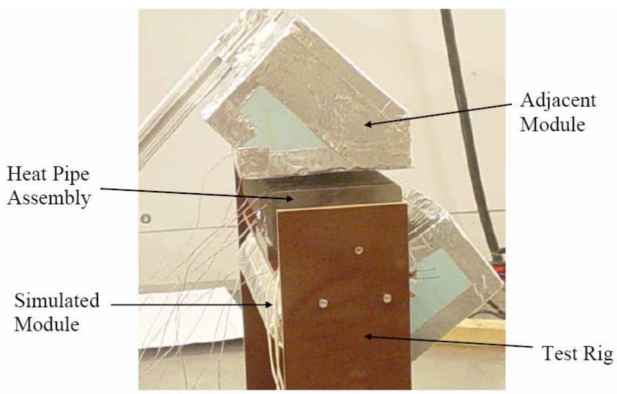

Figure 9. Heat pipe test setup #2. Orientation for morning and evening.

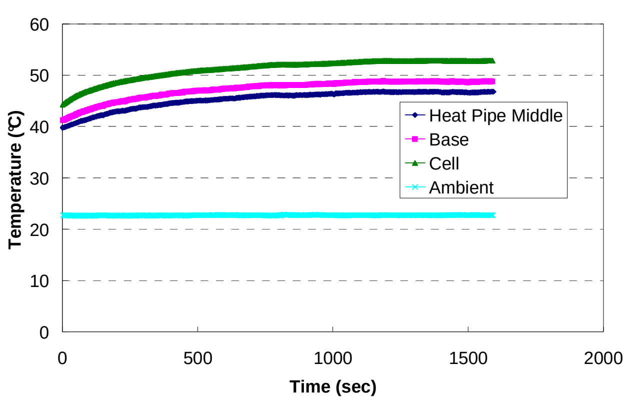

Figure 10. Time vs. temperature, test setup #1 (High Noon), 30 W.

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.

Typical results are shown in Figure 10 for a 30 W heat input. Since the simulated cell (and copper boss) had an area of 1 cm^2, the heat flux was 30 W/cm^2. The system approached equilibrium relatively slowly, which is typical or natural convection systems.

Measurements were made for three different setups:

- Setup 1 (High Noon)
- Setup 2 (Morning or Evening)
- Setup 3 (Open air, with no flow constraints on the natural convection.

The ΔT between the saddle and ambient air was measured for three different powers: 20, 30, and 40 Watts, which corresponds to 20, 30 and 40 W/cm^2, respectively.

The results are summarized in Figure 11. The maximum ΔT for both high noon and early morning orientations was roughly 40℃ for the 40 W/cm^2 heat input. The orientation had only a slight effect on the ΔT.

The temperature of the cell without the heat pipe and fins was estimated using a CFD program, CFDesign. In contrast to the 40℃ experimental temperature rise with the heat pipe heat sink, the calculated ΔT between the cell and ambient was 210℃, if only the saddle was avail able to reject the heat.

Confining the assembly between the two boxes increases the ΔT by roughly 12℃, when compared with the same system operating in the open air.

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.

Copper and aluminum heat pipes with various working fluids were examined, and a copper heat pipe was chosen, with water as the working fluid. 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 40℃. This exceeded the design requirements of the application and the current standard cooling design. In contrast, a system with only a copper block would have a ΔT of 210℃.

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. We would like to thank Bruce Drolen, John Hall, Russ Jones, Qiong (Joan) Li, and Adam Plesniak for their many helpful suggestions.

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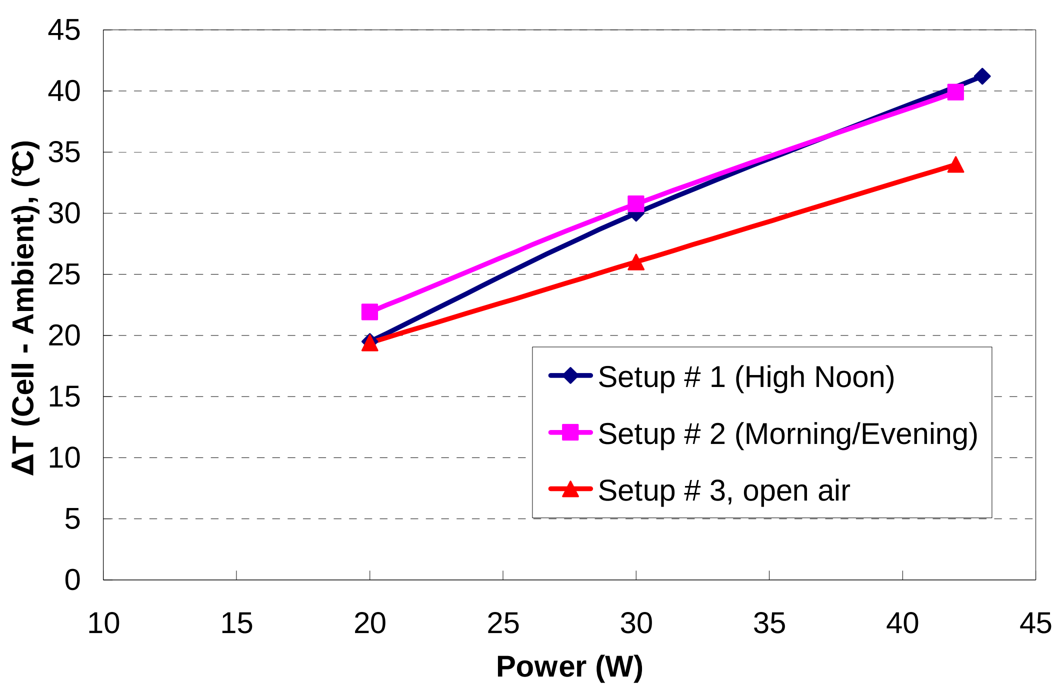

Figure 11. Power versus ΔT, different orientations.