ASSESSMENT OF THE EFFECTIVENESS OF HEAT PIPES IN COOLING PHOTOVOLTAIC CELLS IN SOLAR CARS

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Abstract: The efficiency of photovoltaic cells depends on its temperature which is why stationary arrays are often designed with a cooling system. However, in the development of solar cars where weight and aerodynamics are the major constraints, providing a means to cool the photovoltaic cells are not yet prioritized. By designing a passive cooling system, the energy load of the solar car is left unaffected, and by finding a good balance between cooling capabilities and weight, the possibility of using cooling systems in solar cars can also be developed. In this study, the use of heat pipes for cooling the solar array of a solar car was evaluated.

The results of the evaluation show that the heat pipes would be able to reduce the PV Cell surface temperature by at least 14^{o}C. From this, the assembly is expected to be able to provide an additional 60W gained from sustained higher efficiency. All of the configurations considered required an additional 26W-43W at 70 kph due to the additional rolling resistance on an average of 22.5 kg additional weight. Thus, the range of the net power benefit is from 17W – 34W. This confirms that heat pipes can be effective in cooling photovoltaic cells on a solar car.

The downsides on the use of heat pipes, however, aside from high costs, are the constraints on shell design, aerodynamics, and total body weight.

Key Words: heat pipes; PVC cooling; solar cars

1. INTRODUCTION

One of the performance issues in the design of solar cars is maintaining the photovoltaic cells at low temperatures. At higher temperatures, the efficiency of photovoltaic cells (PVC) drops considerably, limiting its capability of providing high power output to the motor. Cooling systems can be implemented but in doing so, one must avoid drawing energy from the main power source as much as possible.

One example of a passive cooling technology that can be implemented is the use of heat pipes. Heat pipes are commonly seen nowadays in laptops and new generation cooling systems for computers. They have already been used to cool PVC but only for stationary systems. So far they have not been applied cool PVC in solar cars where in order to be practicable, the heat pipe cooling system should sufficiently reduce the temperature without having considerable effects on the weight and aerodynamics of the vehicle.

2. METHODOLOGY

2.1 Estimation of required heat dissipation

The data on the solar array and motor used by SIKAT2 are shown in Table 1 and Table 2. For the determination of the heat dissipation required for the cooling system, the data in Table 1 for the SIKAT2 solar array using SunPower C60 Solar Cells were used.

Table 1. SIKAT2 Solar Array using SunPower C60 PV Cells

Number of Cells		391
Rea		5.998 m2
Encapsulation		Gocherman
Peak Power (+5/-3%)	P_{MAX} (reported)	1300 W/m^2
Efficiency		22 %
Per cell		
Rated Voltage	Vmpp	0.577
Rated Current	Impp	5.87 A
Open Circuit Voltage	Voc	0.684 V
Short Circuit Current	Isc	6.26 A
Temperature Coefficients	Power (P) Voltage (Voc)	-0.38%/K -1.8 mV/K

Table 2. Data on CSIRO In-wheel Motor used in SIKAT2

Nominal Speed	111 rad/s
Nominal Torque	16.2 Nm
Nominal Power	1800 W
Efficiency at Nominal	97.4%
Maximum Speed	250 rad/s
Maximum Continuous Torque	31 Nm
Maximum Tested Torque	50.2 Nm
Winding Temperature rise at Nominal	22 K
Maximum Winding Temperature	110^{o}C

The required heat dissipation was determined with the assumption that all the energy not converted to power will have to be dissipated by the heat pipe. At 1 sun (1000W/m^2) level, as per den Haan (2009), the calculations are as follows:

$$Q_{sun\,per\,cell} = \frac{(1000W/m^2)(5.998m^2)}{391cells} = 15.34W$$

$$\eta = 0.22\left[1-\left(T_{cell}-25^oC\right)\left(0.0038K^{-1}\right)\right] \quad \text{where } \eta \text{ is the efficiency of the PV cells at any cell temperature}$$

$$Q_{dissipation} = 15.34\left\{1-0.22\left[1-\left(T_{cell}-25^oC\right)\left(0.0038K^{-1}\right)\right]\right\}$$

For instance, at 50°C, the required heat dissipation is:

$$Q_{dissipation\ at\ 50^o C} = 15.34\left\{1-0.22\left[1-(50-25)\left(0.0038K^{-1}\right)\right]\right\} = 12.29W$$

For a temperature reduction of 20^{0}C, the estimated additional power from the solar panels is:

$$P_{solar\,add} = 1300W(0.0038)(20) = 98.8W$$

For an electrical efficiency of 90%, with motor efficiency of 97.4%, from Table 2, the additional power that can be supplied to the wheels is:

$$P_{benefit} = 98.8W(0.974)(0.9) = 86.61W$$

Table 3. Heat dissipation per cell, efficiency vs temperature

Temperature, °C	Efficiency, %	Required Heat dissipation for constant temperature, W
30	21.58	12.03
40	20.75	12.16
50	19.91	12.29
60	19.07	12.41
70	18.24	12.54
80	17.40	12.67
90	16.57	12.80
100	15.73	12.93

This value would be further reduced by additional rolling resistance due to increased weight and additional drag should shell aerodynamics be affected by heat pipes configuration.

The different efficiencies of a SunPower C60 solar cell and the necessary heat dissipation are shown in Table 3. It can be seen that the required heat dissipation is 12-13W per cell across the temperature range. From this, the design of the cooling system should handle 15-20W of heat per cell.

2.2 Heat Pipe Characterization

The heat sink setup (see Figure 1) was mounted on a tripod allowing the heat pipe to be tested at varying angles (0^{o}, 30°, 45°, 60° and 90° angle with respect to the horizontal). A heat source rated at 70W was attached at the evaporator side of the heat sink setup. A fan is attached to the fins included in the heat sink setup to provide air flow for cooling. LM35 temperature sensors were used to monitor the heat produced by the heat source and the temperatures of the inlet and outlet air going through the fins.

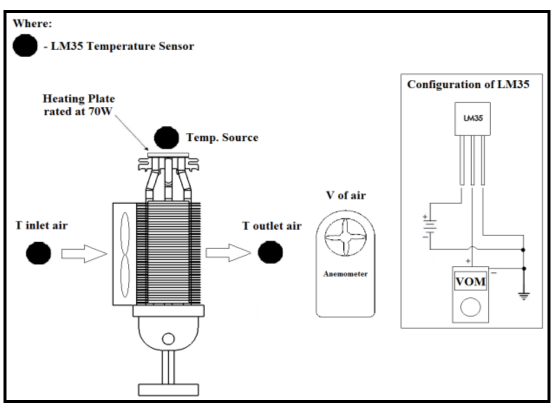


Figure 1 Test Setup Schematic

Weight: 415g (with fins and fans)
Cost: P 800 (approx.)

Figure 2 DEEPCOOL Ice Edge 300

For the heat pipes, a Deepcool Ice Edge 300 (Figure 2) was considered. It is a desktop CPU heat sink which features three 6mmØ sintered powder heat pipes. Loh, et al (2005) established that a 6mmØ sintered powder heat pipe was able to dissipate 15W of heat at an angle of 90° against gravity with a ΔT of only 11.5°C and 20W at an angle of 60° against gravity with a ΔT of 37°. Since the requirement for the solar car is a heat dissipation of 15W per cell, the heat pipe would be sufficient assuming similar performance for the heat pipe is obtained.

A heating plate with a heating capacity of 70W was used to simulate the heat from the solar cell. The heating plate is composed of coiled nichrome wires sandwiched between two metal plates.

2.3 Determination of the Heat Pipe Conductivity

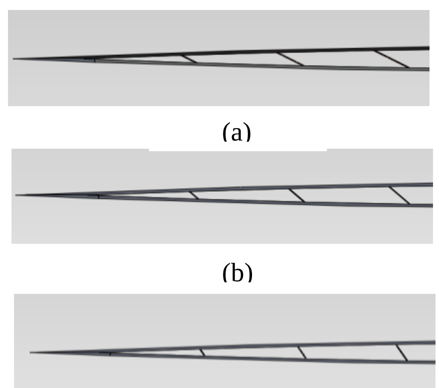
The values for the heat pipe conductivity obtained for the various angles were tested on a computer model simulation with conditions same to that of the actual setup. A similar CFD simulation for heat pipes by Yalcin (2008) reveals that little to no difference can be observed in simulations using heat pipe conductivity as the varying parameter as shown in Table 4. These data would imply that there would be little to no effect to temperatures at very high thermal conductivities – in heat pipes, as long as the heat pipe is within its operating capacities.

2.4 Simulation

The obtained thermal conductivity from the test was then used in the simulation of 8 different heat pipe configurations. The model used for the solar car is the basic air foil of Sikat2.

Table 4. Temperatures of Computer Components vs k value of Heat Pipes (Yalcin, 2008)

Components	Heat Pipe 1 T(°C) k = 20000 W/mK	Heat Pipe 2 T(°C) k = 40000 W/mK	Heat Pipe 3 T(°C) k = 60000 W/mK
CPU	50.6	49.5	49
HDD	46.4	46.2	46.1
BATTERY	34.3	34.3	34.2
GC	43.1	42.8	42.8
SB	42.1	41.8	41.7
RAM	41.7	41.4	41.3
PCMCIA	39.5	39.3	39.3
PCB	41.6	41.3	41.1
DVD	34.8	34.7	34.7



(a) (b) (c)

Figure 3. Side profiles (a) 30^o (b) 45^o (c) 60^o

Two heat pipe arrangements for each angle were considered– one with 9 long heat pipes across the cells and another with 18 shorter ones. From Armstrong and Hurley (2010), PV cell material properties k = 148 W/m·K, c = 677 J/kg·K were used in the simulation.

3. RESULTS AND DISCUSSION

Tests for heat pipe conductivity with respect to angular orientation (Fig. 4 and Fig. 5) show a thermal conductivity of 47.9 kW/m K at 0^o decreasing to 20.3 kW/ m K at 90^o almost linearly.

The comparison between test data on the heat pipe and the simulation results (Fig. 6 and Fig. 7) show minimal difference at 0^o increasing slightly at 90^o. Considering these differences as acceptable, the analysis and computations based on them are also considered as acceptable.

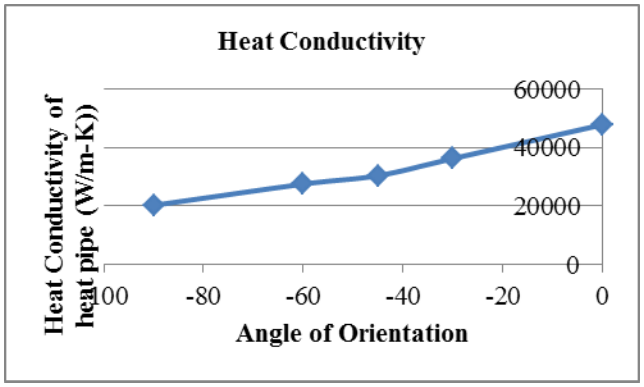


Figure 4. Heat Conductivity of the heat pipe with respect to orientation

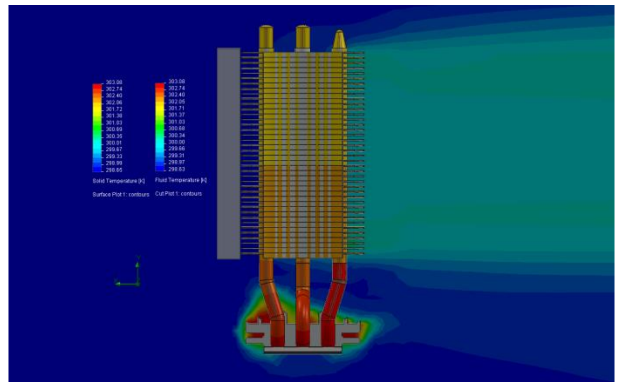


Figure 5. Sample Simulation Result for horizontal orientation

Table 5 outlines the results of the simulations for the temperature distribution on the solar array. It is noted that there is very little difference between average temperatures for the different test angles. Figure 8 shows the temperature profile in one of the simulations.

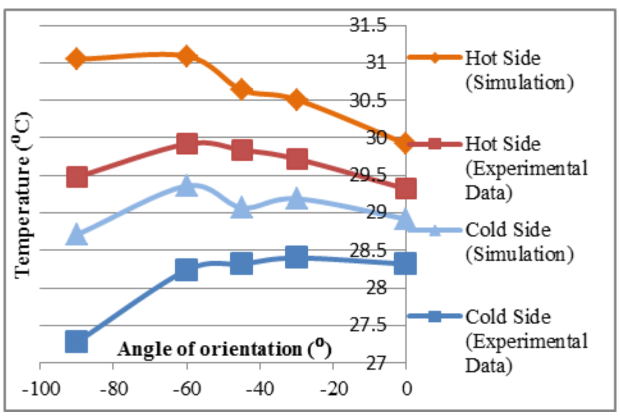


Figure 6. Heat Pipe Temperatures on Finned Surface

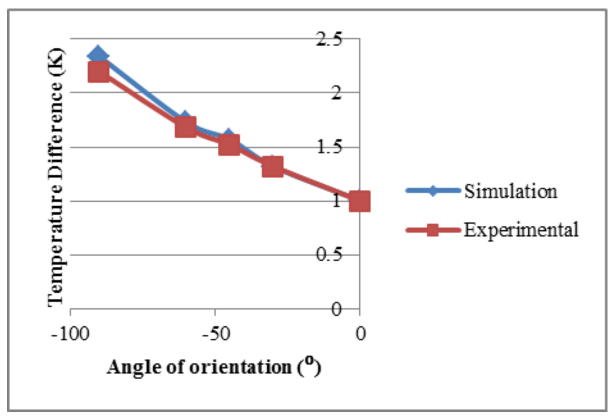


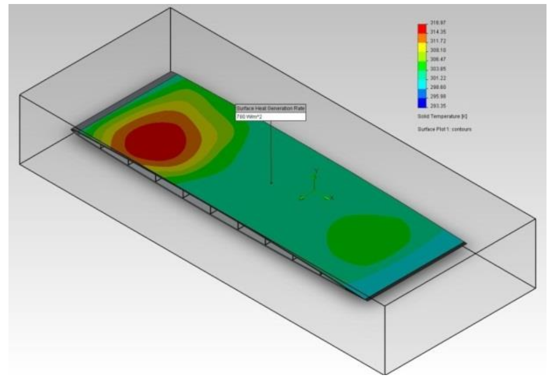
Figure 7. Difference in Temperature Between Cold and Hot Side

Table 5. Summary of solar cell temperature

Setting	Temperatures of PV Cell (K)		
	Min	Max	Ave
No Heat Pipe	305.77	345.89	319.22
30^0 Long	298.90	316.24	305.33
30^0 Short	298.88	316.13	305.29
45^0 Long	298.78	313.33	305.02
45^0 Short	298.75	316.91	305.34
60^0 Long	298.93	316.05	305.12
60^0 Short	298.92	316.71	305.54
90^0 Long	298.98	312.49	305.02

Figure 8. Sample temperature profile on solar car array

90^0 Short	298.86	316.97	305.23



From Table 6, though slightly, the settings using shorter heat pipes show less weight. Focusing on these shorter heat pipes, Table 7 summarized the computed additional power gained.

Table 6. Computed additional weight per configuration

Setting	Total Heat Pipe L, m M	Heat pipe weight kg	Aluminum Wt, kg	Total Added Wt, kg
90^0 long	27.6	2.46	20.57	23.03
60^0 long	27.77	2.47	20.57	23.05
45^0 long	27.99	2.49	20.57	23.07
30^0 long	28.51	2.54	20.57	23.11
90^0 short	19.41	1.73	20.57	22.30
60^0 short	19.69	1.75	20.57	22.33
45^0 short	20.17	1.80	20.57	22.37
30^0 short	21.22	1.89	20.57	22.46

Table 7. Additional Power Absorbed

Setting	Temperatures of PV Cell, K			Total Add'l Power W	Add'l Power on wheel W
	Min	Max	Ave		
No Heat Pipes	305.8	345.9	319.2		
90 Short	298.9	316.9	305.2	69.11	60.58
60 Short	298.9	316.7	305.5	67.58	59.24
45 Short	298.8	316.9	305.3	68.57	60.11
30 Short	298.9	316.1	305.3	68.81	60.32

From Table 8, considering a range of coefficient of rolling resistance, C_{rr}, from 0.0062 to 0.01, it is seen that at best, about 34 W will be the net power gain, while a marginal 17 W is gained in the least.

Table 8. Net Power Benefit at 70 kph

Crr = 0.01			
	Added Required Power W	Added Power from the solar panel W	Net Power Benefit W
90 short	42.54	60.95	18.41
60 short	42.59	59.60	17.01
45 short	42.67	60.47	17.80
30 short	42.85	60.69	17.84

Crr = 0.0062			
	Added Required Power W	Added Power from the solar panel W	Net Power Benefit W
90 short	26.37	60.58	34.20
60 short	26.40	59.23	32.83
45 short	26.45	60.10	33.64
30 short	26.56	60.32	33.75

4. CONCLUSIONS

The results of the evaluation show that the heat pipes would be able to reduce the PV Cell surface temperature by at least 14^{o}C. From this, the assembly is expected to be able to provide an additional 60W gained from sustained higher efficiency. All of the configurations considered required an additional 26W-43W at 70 kph due to the additional rolling resistance on an average of 22.5 kg additional weight. Thus, the range of the net power benefit is from 17W – 34W. This confirms that heat pipes can be effective in cooling photovoltaic cells on a solar car.

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5. REFERENCES

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