ALAMO COLLEGES
SAN ANTONIO COLLEGE

Spring Solar Undergraduate Research Program

Project 3 – Intermittent Mist Cooling

Final Research Project Report

July 3, 2012

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Student Research Participant: Ram Bhattarai

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Table of Contents

ABSTRACT

The purpose of this research project was to acquire data to investigate the effects of cooling on the output power/efficiency of solar (photovoltaic) modules* using an intermittent water misting system. Based on significant output power gain from previous research with a continuous misting system completed by Adam Boehm in summer 2011[1], additional research was warranted. Information gained from this previous research allowed for modification of Mr. Boehm's design to a more efficient system design that uses less water. We attempted to incorporate a water chiller, cooler, and a thermostat. Test duration was extended from three to four hours per day covering the period from 11:00 a.m. to 3:00 p.m. This project used two solar modules and collected data within one 5 day period. Measurements were made of each solar module's surface temperature, output voltage, and output current, as well as the ambient temperature and ambient solar illumination. Data was collected at 30 samples per minute for 1 minute every 5 minutes during the test period. One of the modules served as a control unit; i.e., without any cooling. For the other panel, initially, it was supposed to be operated by a thermostat that would be programmed to turn on and off at a predetermined temperature. That would minimize the water usage used to cool the module. Also, we wanted the water to be stored in a cooler with a water chiller inside, hoping that the cooler water would result in a cooler module. Due to technical difficulties and lack of time, we were unable to use the extra components that would make that design possible. Our final design consisted of a simple manual control to operate the misting system. The surface of the modules remained perpendicular to the sun throughout the test period by using a manual tracking system. Two different misting intervals were analyzed; i.e., misting for one minute then off for five minutes (water on 14.3% of the time), and misting for one minute then off for 10 minutes (water on 9.1% of the time). The one minute misting every six minutes proved to be the more electrically efficient of the two. Overall, it had a 20.7% average output power gain over the uncooled module while the one minute misting every eleven minutes had a 15.2% average power gain. The 20.8% power gain is slightly less than achieved with continuous water misting by Mr. Boehm in summer, 2011 (22.7%) and by the Project 1 Team in spring, 2012[2] (23.8%). However, the significant power output gain coupled with the approximately 86% reduction in water usage makes the intermittent misting cooling system more practical and economical than a continuous mist cooling system.

* Commonly known as solar or photovoltaic (PV) panels

RESEARCH PROJECT DESIGN

1.) Equipment List

A. Vernier Technology and Software Equipment

i. Labpro Interface [LABPRO] (4)
ii. Surface Temperature Sensor [STS-BTA] (4)
iii. 30-Volt Voltage Probe [30V-BTA] (2)
iv. High Current Sensor [HCS-BTA] (2)
v. Light Sensor [LS-BTA] (2)

B. Yingli Solar, Solar Module [YL235P-29b] (2)

C. Laptops for data acquisition (2)

D. Wooden mounts for solar module (1 set per solar module)

E. Intermittent Misting Cooling System

i. Drip Irrigation Poly Tubing [T007] (50 ft)
ii. Adjustable Misting Jet; Quarter Circle [MAJ90] (4)
iii. Metal Strapping Kit [85390] and hardware(1) (Replaced by zip ties (4) and corner brackets (4))
iv. Drip Irrigation Fittings for poly tubing (1 set)
v. Rainbird Electric Valve [100DVFMB] (1)
vi. Hose thread and filter [784204] (1)

F. Power resistors [8 ohm, 200 watts] (4)

G. Wooden mount for resistors (2, one mount for two resistors)

H. Cables and connectors for data collection and system control

2.) Test Configuration:

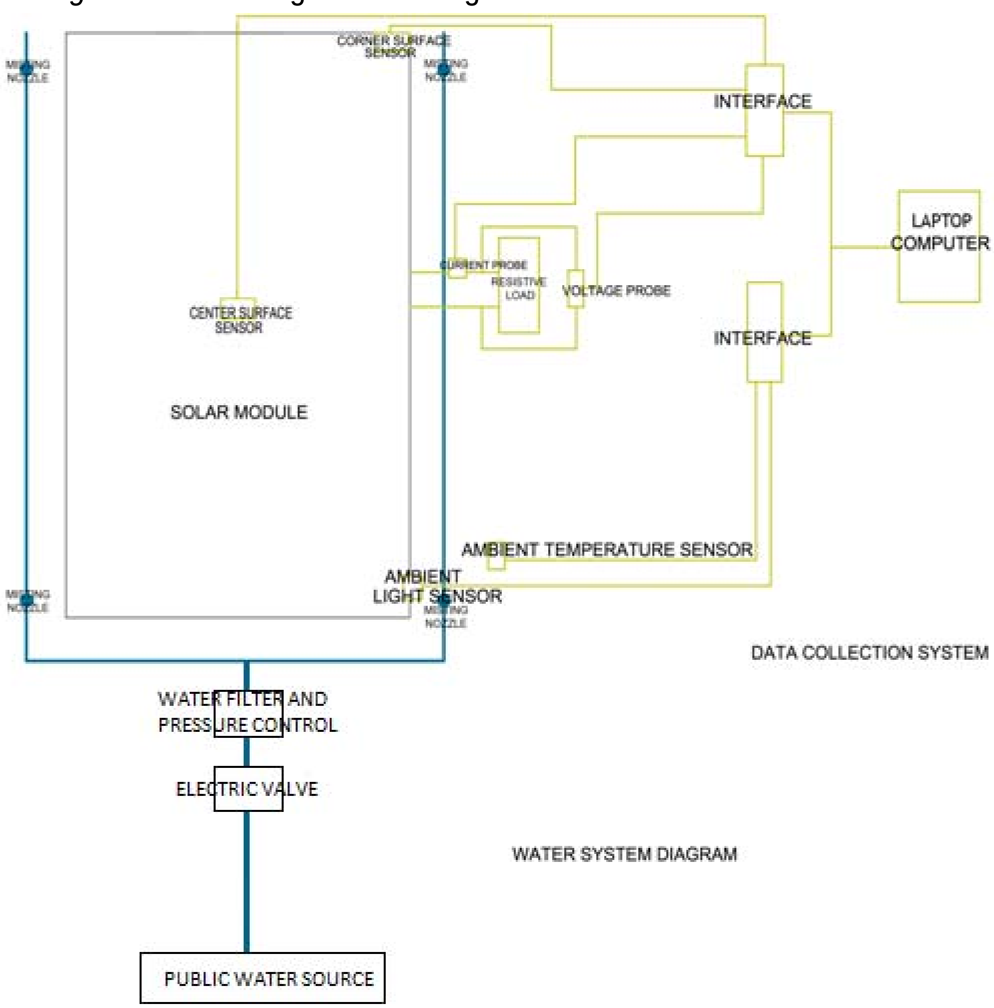
A. Module without cooling system (Connected as in Figure 1, pg.7, but without the water misting system)

B. Module with intermittent misting system (Figure 1)

i. A drip irrigation tubing system mounted to the solar module frame. The system is operated by operating the valve by hand.

ii. The water in the misting system is from the public water supply (in San Antonio, this is SAWS or San Antonio Water System), and flows from the supply, through a standard garden hose, into the tubing system, and onto the module.

3.) *Fig 1* – Test Configuration Diagram



4.) General Test Procedures:

The following applies to all solar modules during testing.

A. Modules were at a steady-condition (i.e., temperature, solar illumination and output loading) when testing began, after which measurements were taken every five minutes for four hours, from 11:00 am to 3:00 pm CST.

B. Two different test configurations were tested at the same time; i.e., one without any cooling (control module) and one with intermittent water mist cooling.

C. Ambient light intensity was measured using the light sensor connected to the Labpro interface and laptop computer to record the data. The light sensor was mounted to the control module frame, such that the sensor was pointed in the same direction as the photovoltaic layer of the solar module (perpendicular to the Sun).

D. Ambient temperature was measured using a surface temperature sensor which is connected to a Labpro interface and laptop to record the data. The ambient temperature sensor was mounted to the control solar module mount and far enough away from the module to ensure results were untainted by misting system or module temperature.

E. Surface temperature was measured using surface temperature sensors connected to a Labpro interface and a laptop computer to record data. One sensor was placed at the photovoltaic cell near the edge of each module, and another was placed near the center of each module. The temperature sensors were secured to the module using electrical tape without covering or affecting the sensors' thermocouple.

F. Measurements of solar module output voltage and current were taken using a voltage probe and a high current sensor, which was connected to a Labpro interface and laptop computer to record the data. Two 8-ohm power resistors were connected in parallel to the output of each solar module, providing an equivalent load resistance of 4 ohms to each solar module. This load will result in a maximum solar module power output of approximately 217 watts, which is 92.5% of the rated full power output of 235 watts under maximum solar illumination and full loading of 3.7 ohms[1]. Power output will be calculated from voltage and current measurements.

G. The misting system was controlled manually. Two misting intervals (6 minutes and 11 minutes) were used; i.e., one minute on, five minutes off (water mist on 14.3% of the time) and one minute on, ten minutes off (water mist on 9.1% of the time).

5.) Test Times and Dates:

A. Testing occurred from 11:00 a.m. to 3:00 p.m. CST, for five days.

B. Testing began on Sunday, April 22nd, 2012 and ended on Wednesday, May 16th, 2012

6.) Test Data:

A. Test data that was collected includes ambient and module surface temperatures (C°), light intensity (lux), voltage (V), and current (A).

B. Data was collected for one minute every five minutes.C. Power output was calculated by multiplying output voltage by output current.

D. Without volume measurement equipment, the amount of water used was measured.

E. Data is presented in the form of charts and graphs.

F. Comparative analysis of the test data obtained from the different test configurations was performed.

RESULTS – 6-MINUTE MISTING INTERVAL (1 MIN ON, 5 MIN OFF)

The raw testing data for the two days that were averaged to represent the 6-minute interval results are featured in Appendix II.

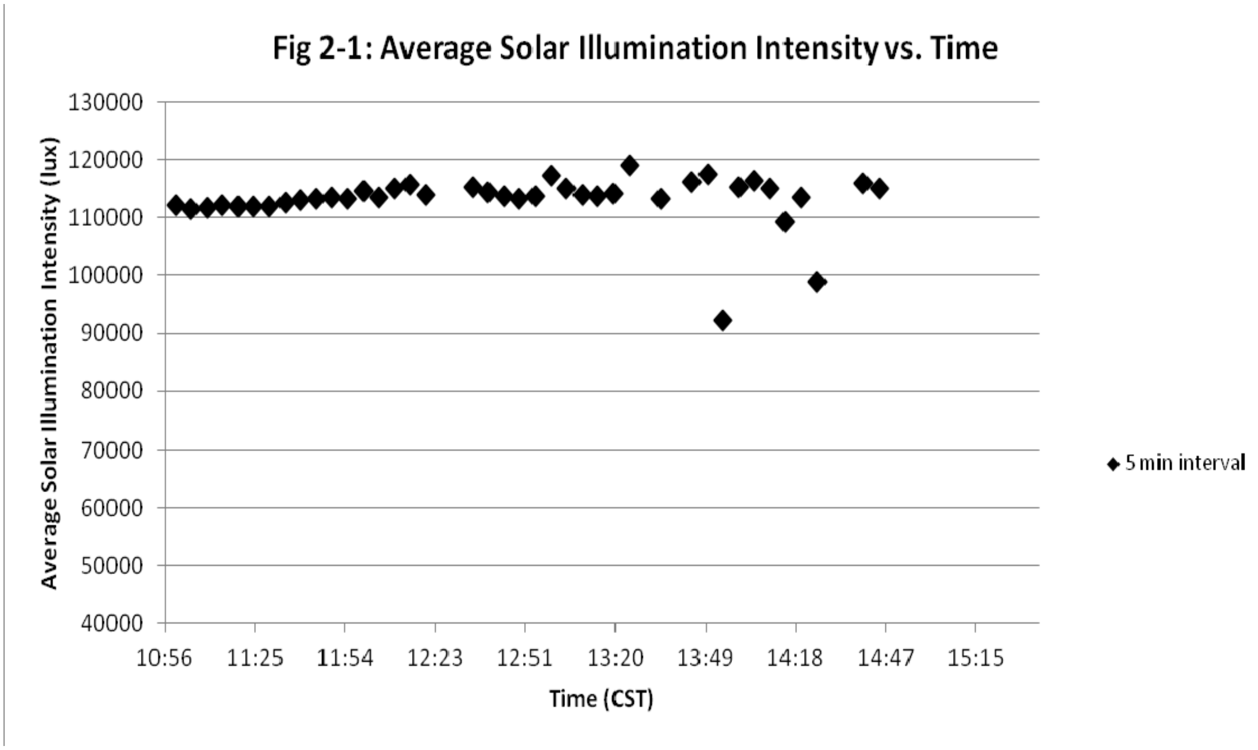


Figure 2-1 shows the average illumination intensity during the 6-minute interval misting (1minute misting on followed by 5 minutes of no misting). Any data that was collected during cloudy periods where illumination intensity was less than 90,000 lux was not included in the data analysis or in any of the graphs. The average illumination intensity was determined by summing the collected values and dividing that number by the quantity of data collection points. The average illumination intensity for the day was 113,103 lux.

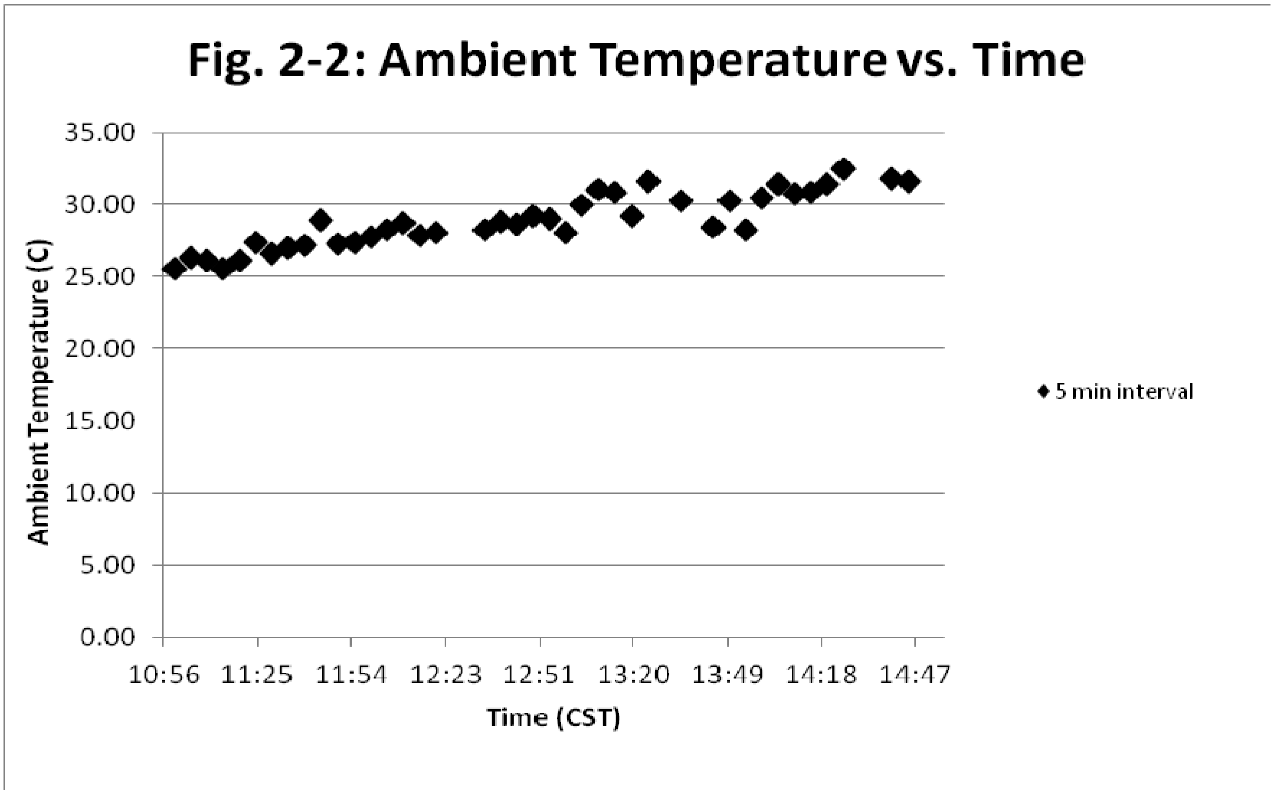


Figure 2-2 shows the average ambient temperature during the 6-minute interval misting. The average ambient temperature was calculated by summing the collected values and dividing that number by the quantity of data collection points. The average ambient temperature for the two days was 28.9°C (84° F).

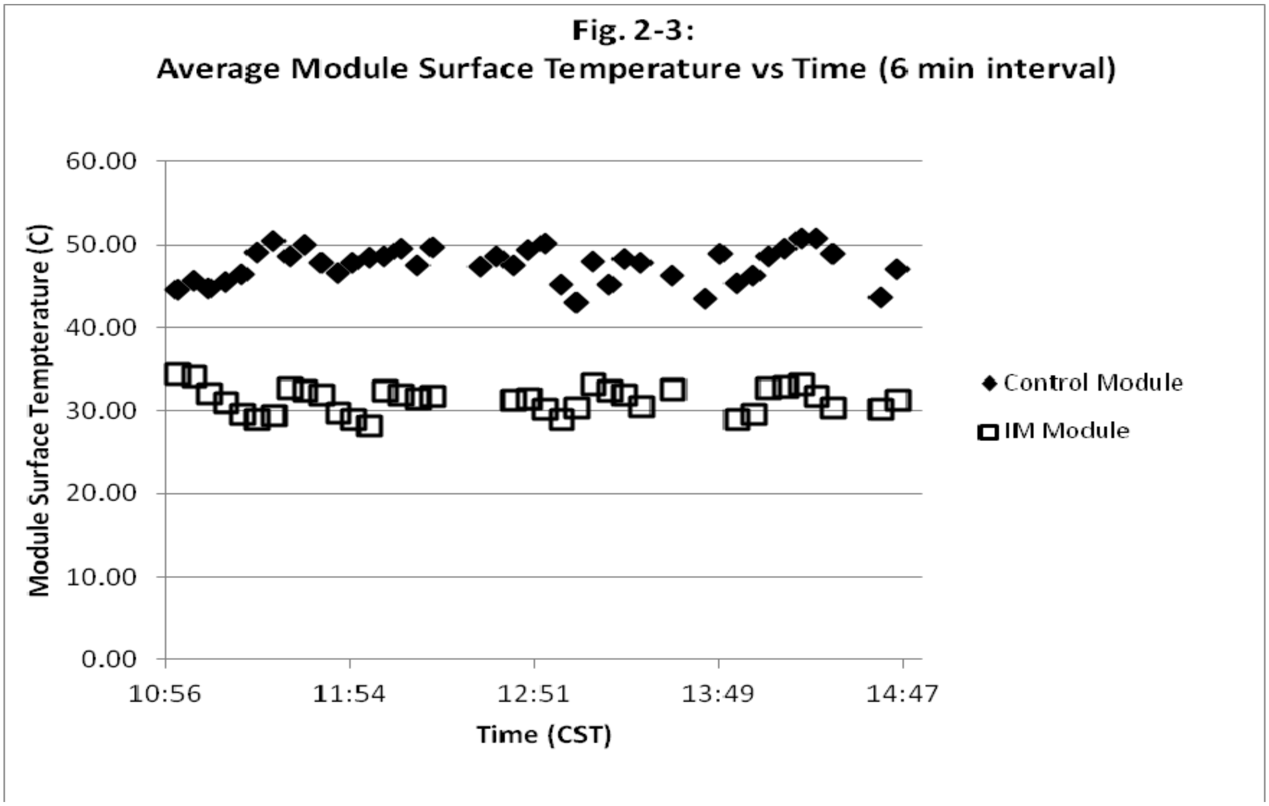


Figure 2-3 shows the average weighted surface temperature of both the control module (CM) and the intermittent misting (IM) module. The average weighted surface temperature was calculated using the formula

$$\left(\frac{2}{3} * \text{Center Temperature}\right) + \left(\frac{1}{3} * \text{Edge Temperature}\right) = \text{Weighted Surface Temperature}$$

This method was used in the previous summer 2011 experiments and has shown to be accurate in representing the overall average surface temperature of the module. The average surface temperature for the control module was 47.6° C (117.6° F). The average surface temperature for the intermittent misting module was 31.3° C (88.4° F).

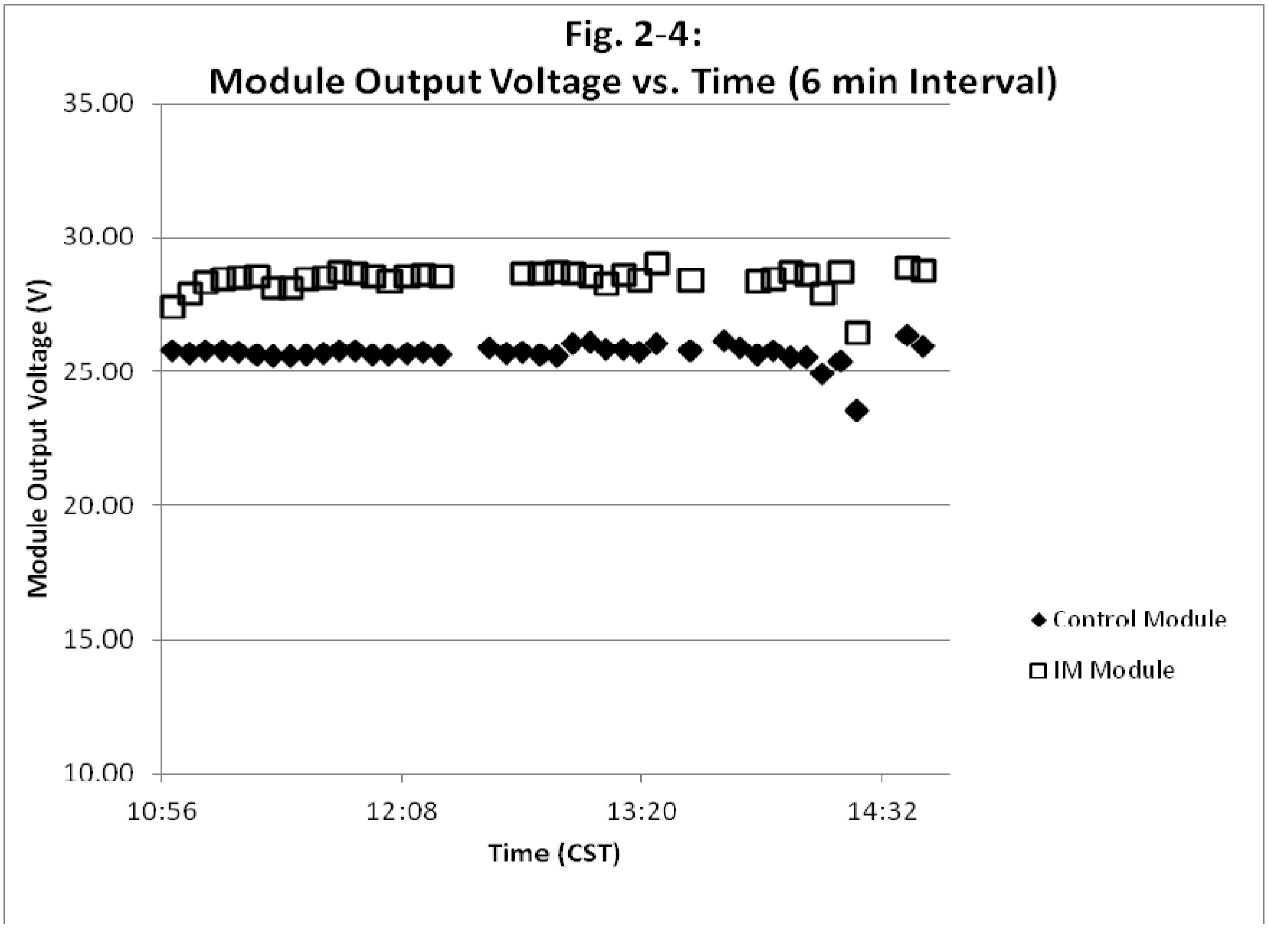


Figure 2-4 shows the average output voltage for both the control module and the intermittent misting module over the two days of testing. The average output voltage was found through separately adding the voltage values for each module and dividing that value by the number of data points collected. The average output voltage for the control module was 25.7 V. The average output voltage for the intermittent misting module was 28.45 V. Intermittent clouds resulted in reduction of solar illumination levels and consequently the output voltage levels at certain times (e.g., data points at 14:30 pm).

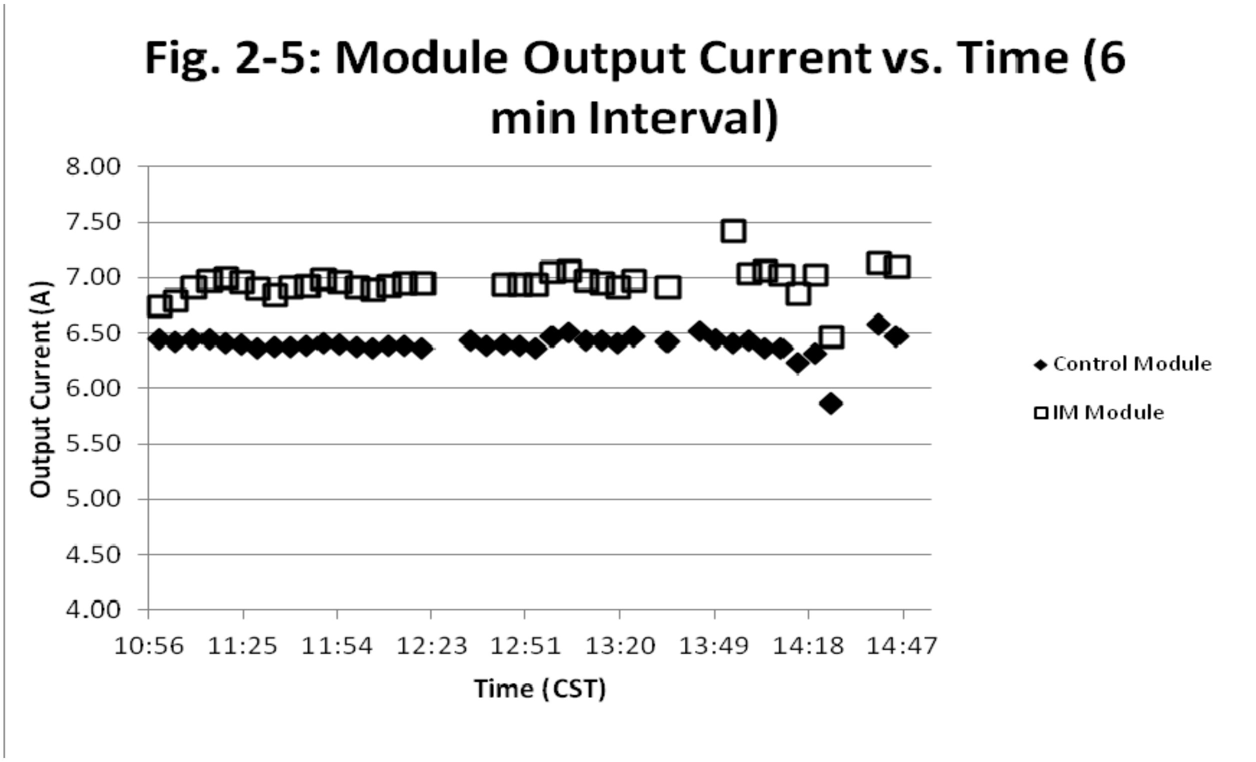


Figure 2-5 shows the average output current for both the control module and the intermittent misting module over the two days of testing. The average output current was found through separately adding the current values for each module and dividing that value by the number of data points collected. The average output current for the control module was 6.4 A. The average current for the intermittent misting module was 7.0. Intermittent clouds resulted in reduction of solar illumination levels and consequently the output current levels at certain times (e.g., data points at 14:30 pm).

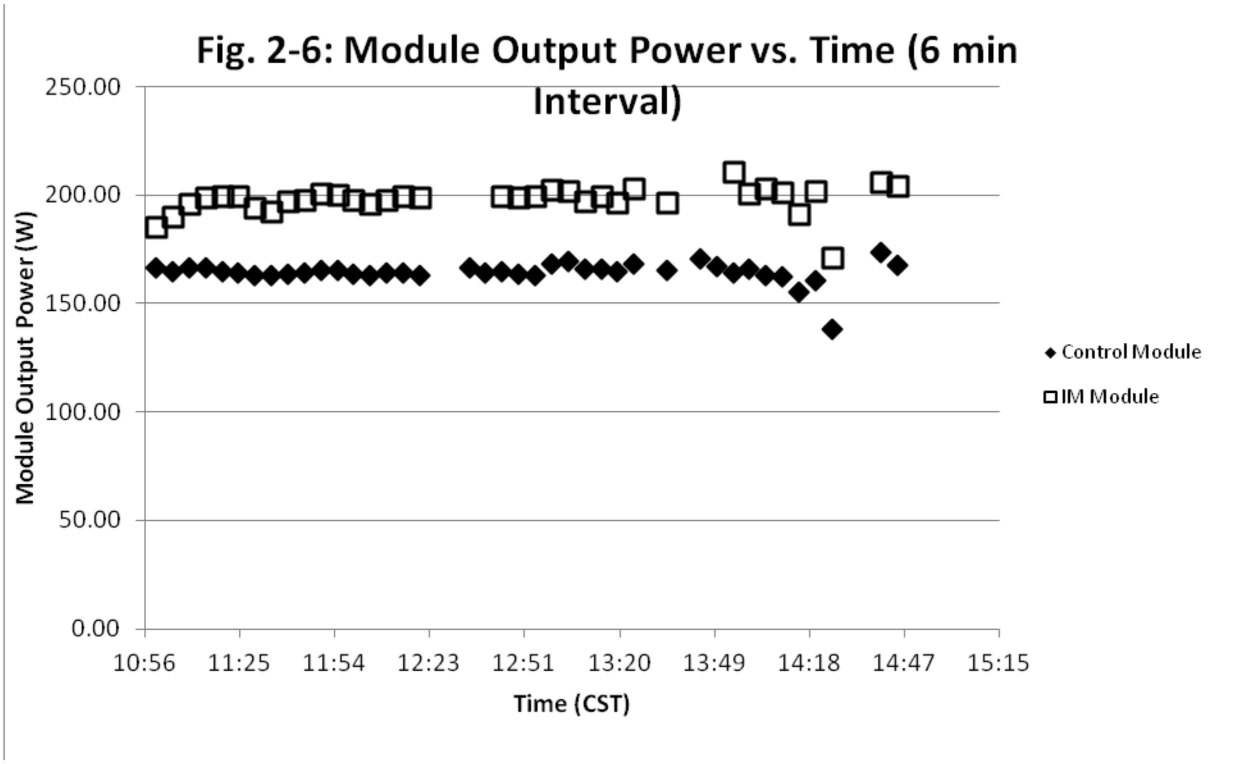


Figure 2-6 shows the average power output for both the control module and the intermittent misting module over the two days of testing. The average power output was found through separately taking the average output voltage and the average output current values and multiplying them together for each module. The average power output for the control module was 164.3 Watts (W). The average power output for the intermittent misting module was 198.0 W. Intermittent clouds resulted in reduction of solar illumination levels and consequently the output power levels at certain times (e.g., data points at 14:30 pm).

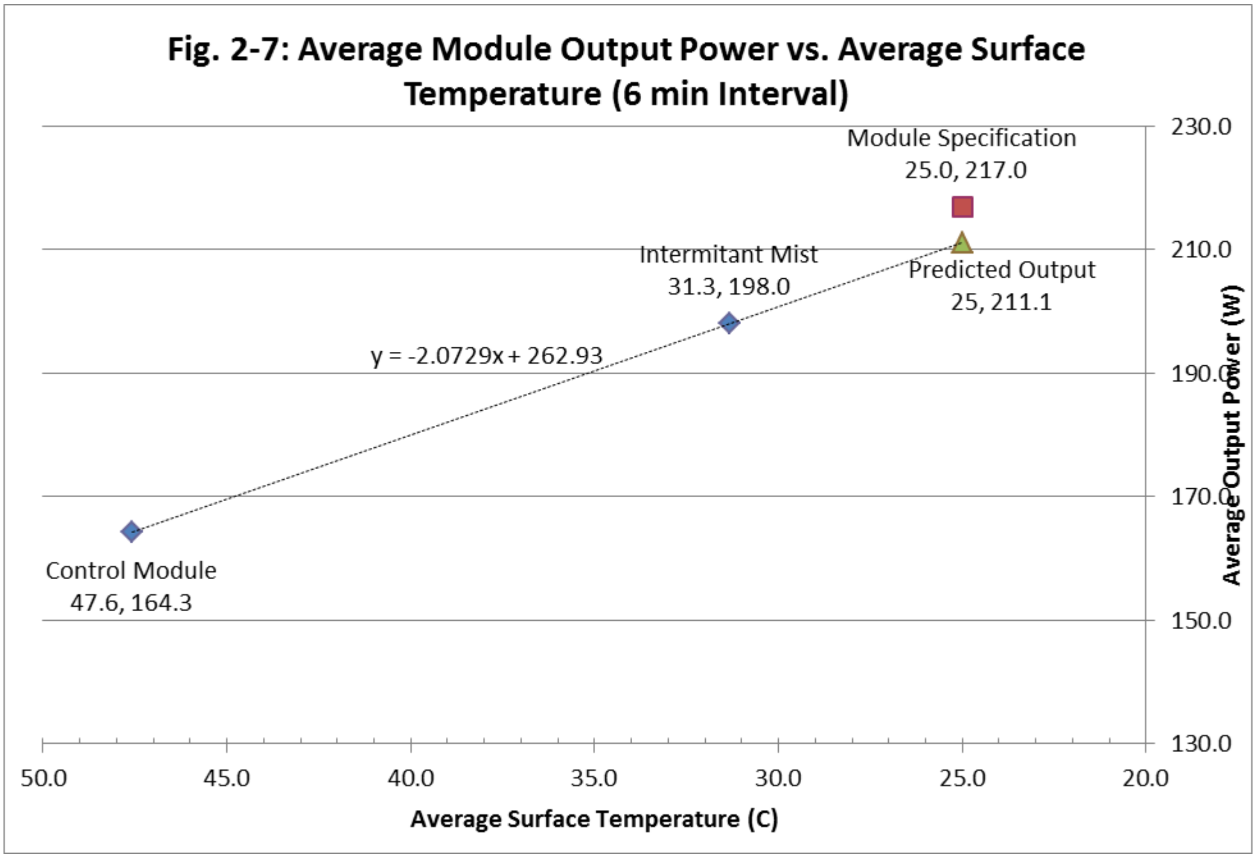


Figure 2-7 shows each module's average power output for the hours of 11:00am to 3:00pm over the two days of testing in comparison with its average weighted surface temperature. As seen from the trend line on the graph, the module power output vs. module surface temperature displays a nearly linear relationship when solar illumination levels are constant. A similar result was obtained in summer, 2011[1] and by the Project 1 Team in spring, 2012[2]. For the time period covered, the calculated linear trend line shows the predicted output at the solar module specification temperature of 25 °C is 211.1 watts. This is only 3.0 % below the calculated module specification output power for our system (217.6 watts). The module specification output power value is determined by the following formula:

$$\frac{(Max\ Potential\ Voltage)^2}{(Total\ Load\ Resistance\ in\ Ohms)} = Module\ Specification\ Power$$

When calculated with a specified maximum module output voltage of 29.5 volts (see Appendix I) and a 4 Ohm resistive load, our Module Specification Power output is equal to 217.6 watts.

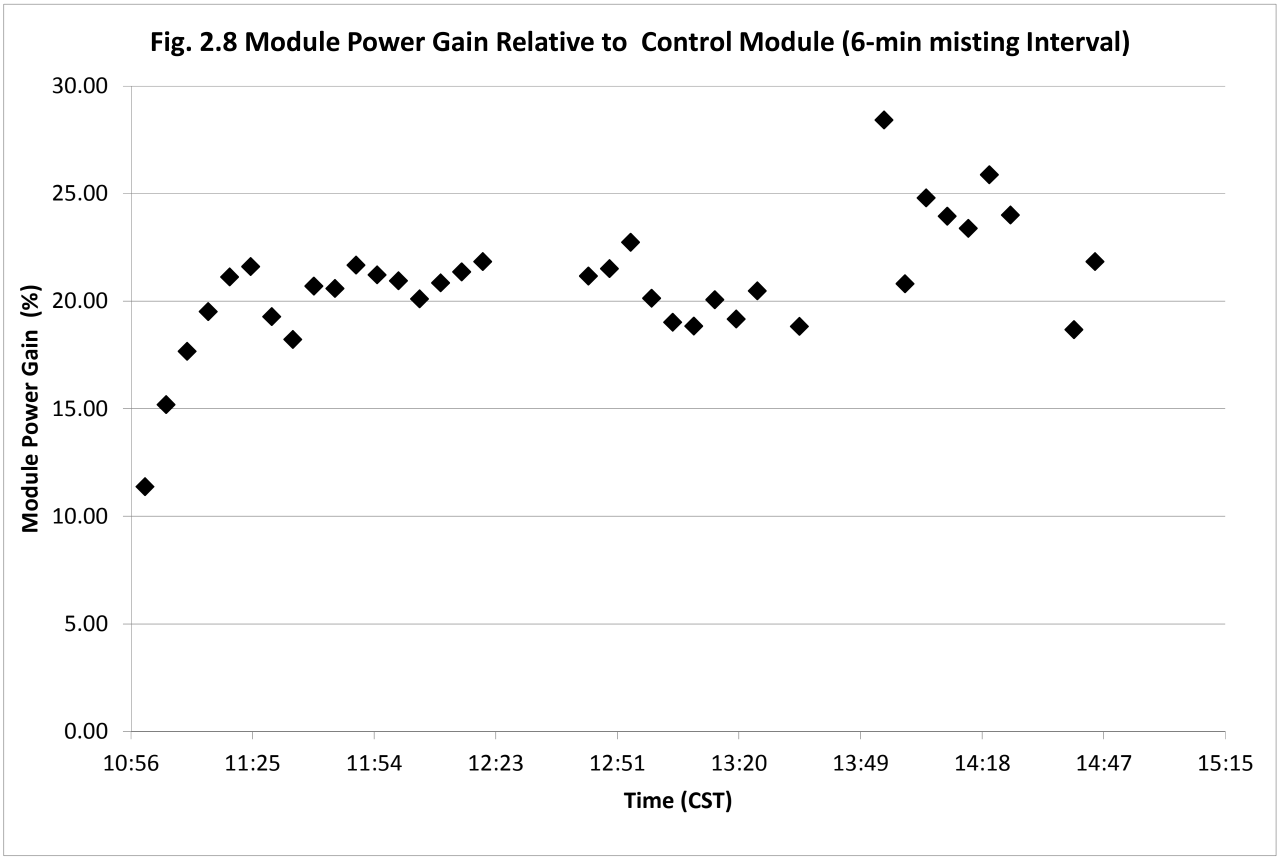


Figure 2-8 shows the average power gain in percent of the intermittent misting module relative to the control (noncooled) module. The average power gain was calculated by taking the control module's average power output and subtracting it from the intermittent misting module's average power output, dividing that value by the control module's average power output, and multiplying that resulting number by

100. The average power gain was 20.8%.

Measurements were taken of the time it took for the intermittent misting solar module's surface to dry after the misting was stopped. The "time to dry" was dependent on the illumination intensity and varied between 3 and 5 minutes. As a result, it was observed that for the 6 minute misting interval (1 minute on, 5 minutes off), the intermittent misting module was in most cases almost entirely dry when the misting system was turned on again.

RESULTS – 11-MINUTE MISTING INTERVAL (1 MIN ON, 10 MIN OFF)

The raw testing data for the one day that represented the 11-minute misting interval results are featured in Appendix III.

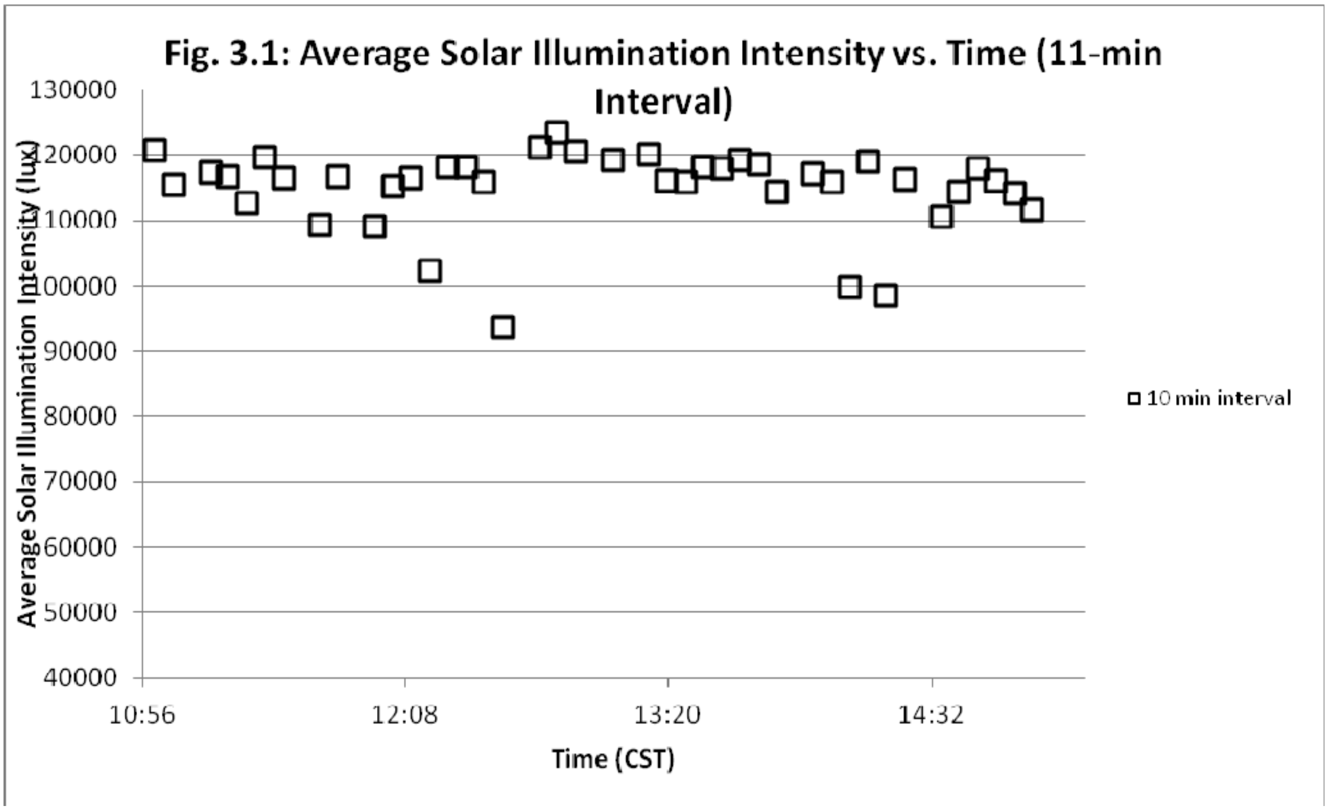


Figure 3-1 shows the average illumination intensity during the 11-minute interval misting. Any data that was collected during any illumination intensity that was less than 90,000 lux was not included in the calculations for this or any following results or graphs due to its insignificance in this research. The average illumination intensity was determined by summing the collected values and dividing that number by the quantity of data collection points. The average illumination intensity for the day was 114,977 lux.

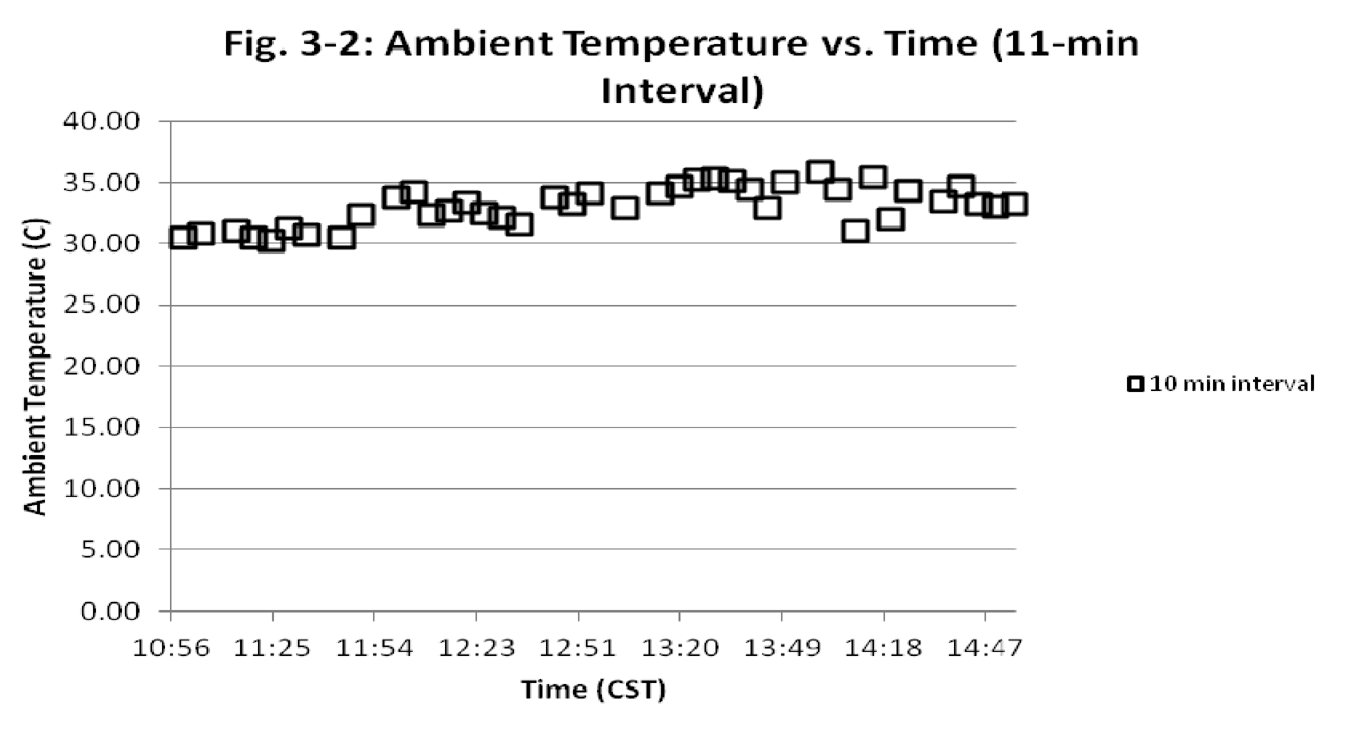


Figure 3-2 shows the average ambient temperature during the 11-minute interval misting. The average ambient temperature was calculated by summing the collected values and dividing that number by the quantity of data collection points. The average ambient temperature for the day was 33.1°C (91.6° F).

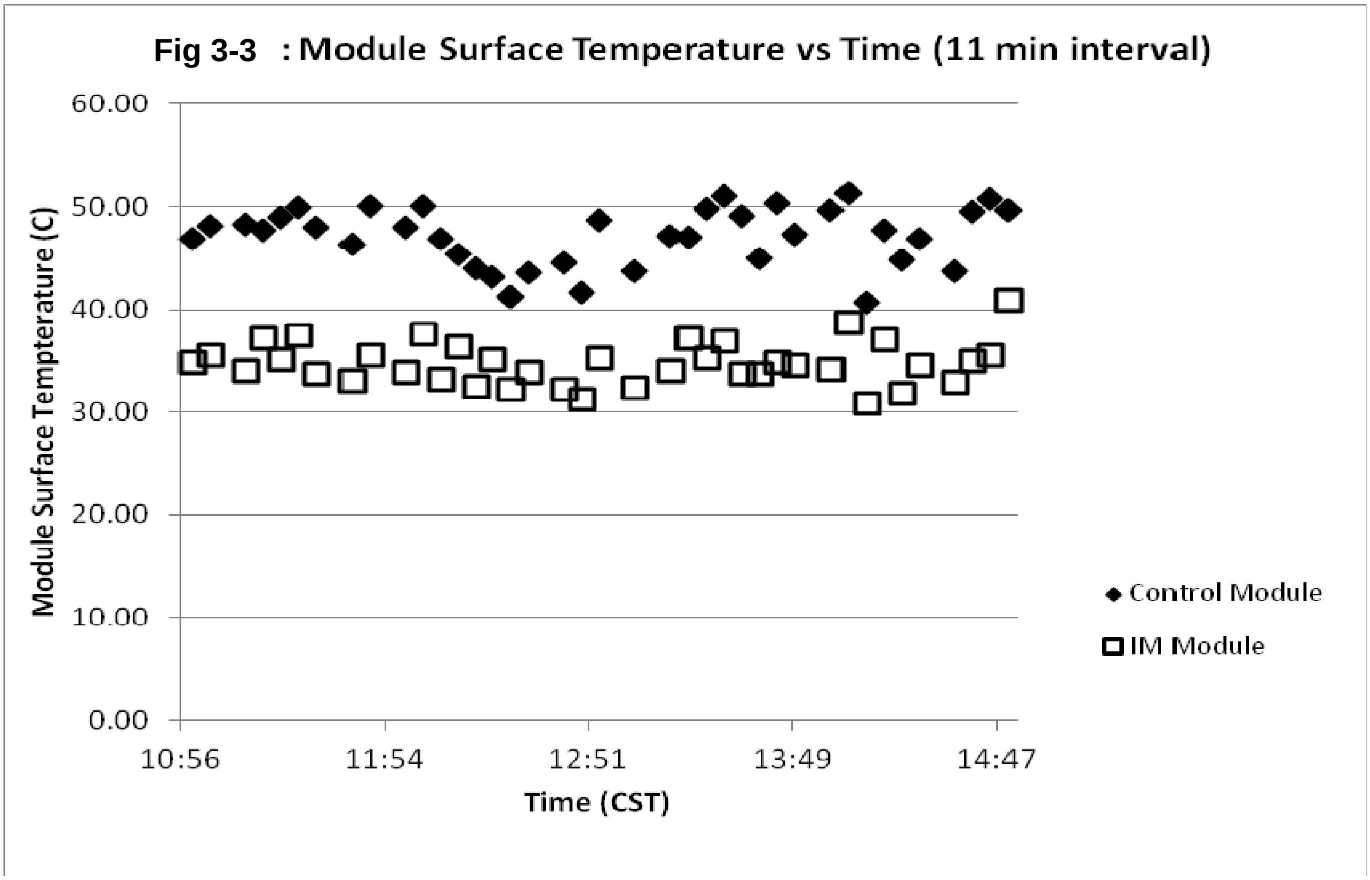


Figure 3-3 shows the average weighted surface temperature of both the control module (CM) and the intermittent misting (IM) module. The average weighted surface temperature was calculated using the formula:

$$\left(\frac{2}{3} * Center\ Temperature\right) + \left(\frac{1}{3} * Edge\ Temperature\right) = Weighted\ Surface\ Temperature$$

This method was used in the previous summer 2011 experiments and has shown to be accurate in representing the overall average surface temperature of the module.

The average surface temperature for the control module was 47.2° C (116.9° F). The average surface temperature for the intermittent misting module was 34.9° C

(94.8° F).

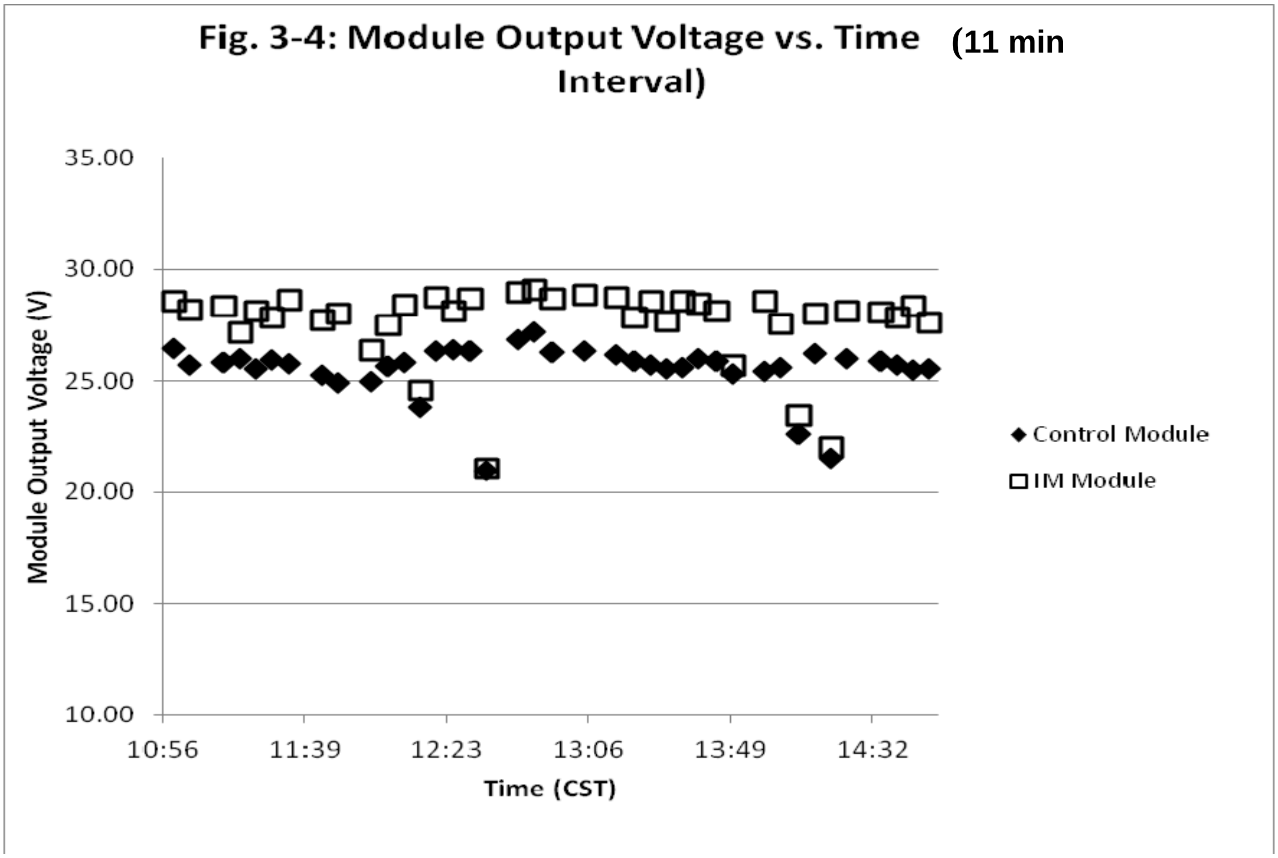


Figure 3-4 shows the average output voltage for both the control module and the intermittent misting module. The average output voltage was found through separately adding the voltage values for each module and dividing that value by the number of data points collected. The data was collected for one minute every 5 minutes. Since the misting was done on an 11 minute interval, the time when data was collected relative to the misting times varied throughout the test period; i.e., from right after misting ceased to just before misting started again. Since the water on the misted module usually dried completely within 5 minutes after being misted, the misted module surface temperature would then rise causing the voltage, current, and power output to decrease dependent on how long the misted module had been dry before data was collected. The average output voltage for the control module was 25.5 V. The average output voltage for the intermittent misting module was 27.6 V.

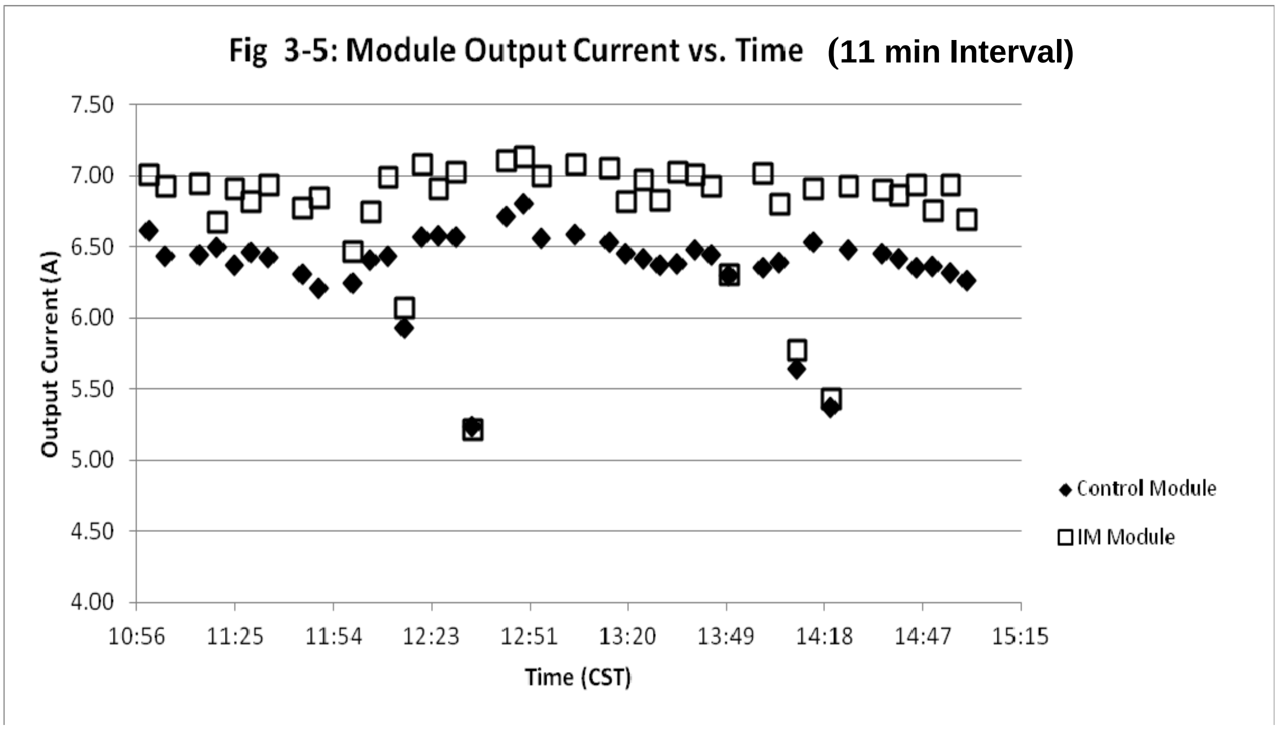


Figure 3-5 shows the average output current for both the control module and the intermittent misting module. The average output current was found through separately adding the current values for each module and dividing that value by the number of data points collected. The data was collected for one minute every 5 minutes. Since the misting was done on an 11 minute interval, the time when data was collected relative to the misting times varied throughout the test period; i.e., from right after misting ceased to just before misting started again. Since the water on the misted module usually dried completely within 5 minutes after being misted, the misted module surface temperature would then rise causing the voltage, current, and power output to decrease dependent on how long the misted module had been dry before data was collected. The average output current for the control module was 6.4 A. The average current for the intermittent misting module was 6.8 A.

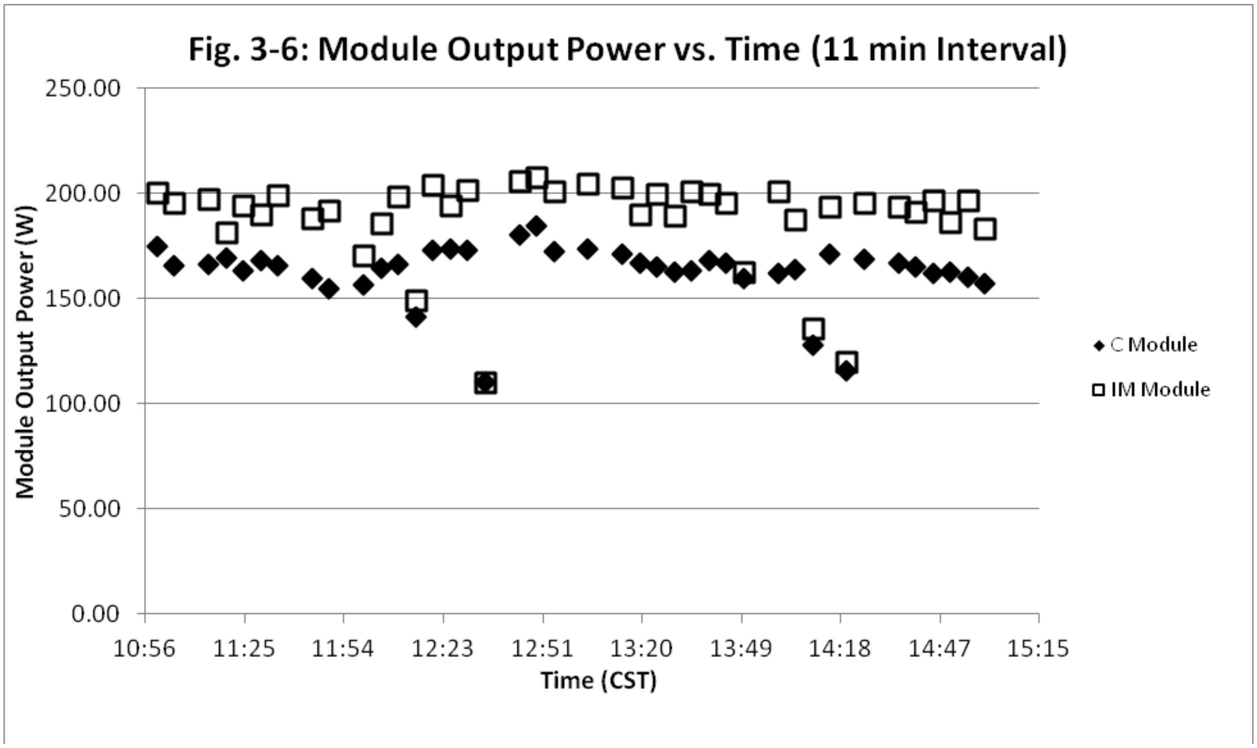


Figure 3-6 shows the average power output for both the control module and the intermittent misting module. The average power output was found through separately taking the average output voltage and the average output current values and multiplying them together for each module. The data was collected for one minute every 5 minutes. Since the misting was done on an 11 minute interval, the time when data was collected relative to the misting times varied throughout the test period; i.e., from right after misting ceased to just before misting started again. Since the water on the misted module usually dried completely within 5 minutes after being misted, the misted module surface temperature would then rise causing the voltage, current, and power output to decrease dependent on how long the misted module had been dry before data was collected. The average power output for the control module was 162.4 Watts (W). The average power output for the intermittent misting module was 187.6 W.

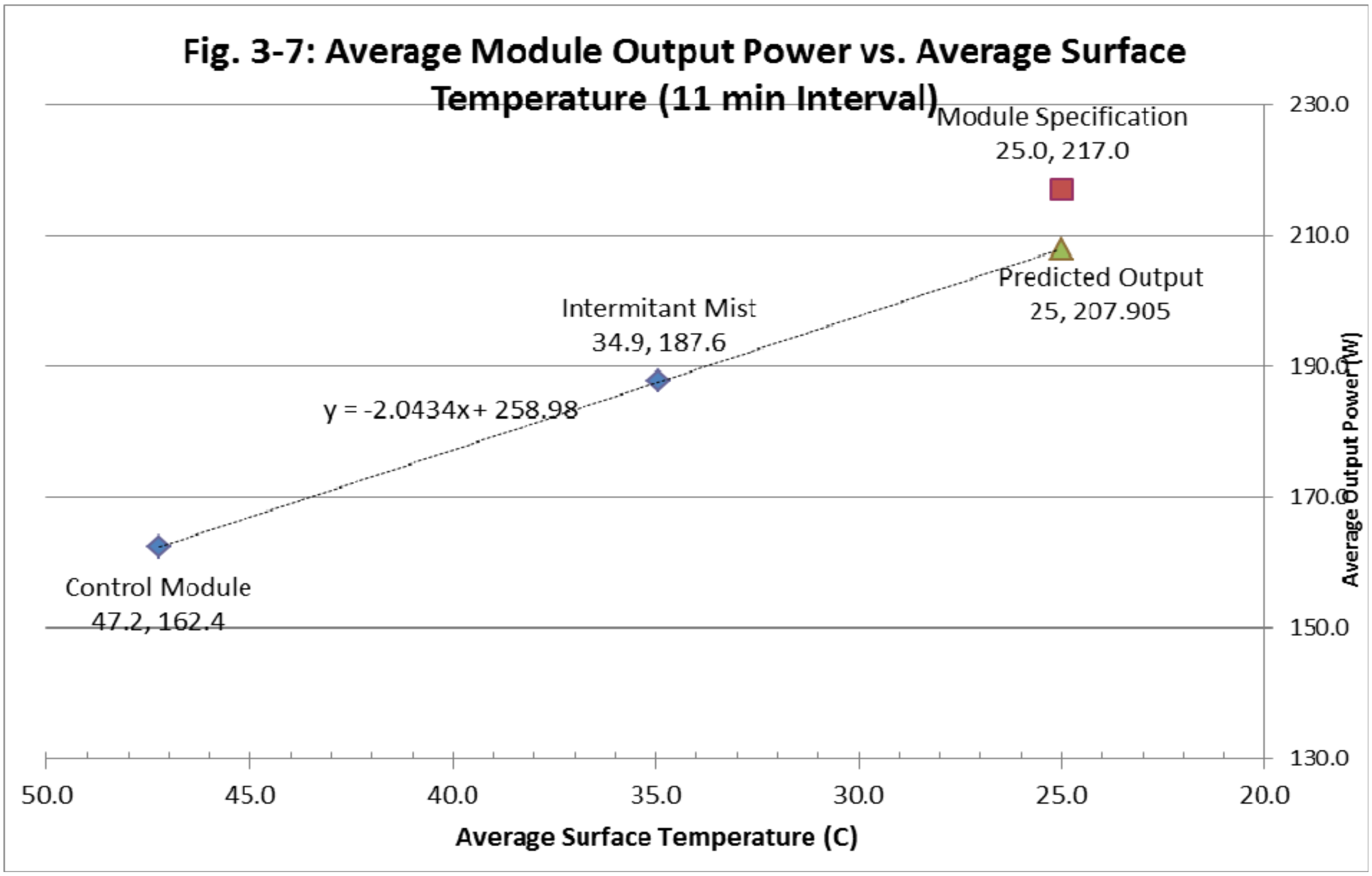


Figure 3-7 shows each module's average power output for the hours of 11:00am to 3:00pm over the two days of testing in comparison with its average weighted surface temperature. As seen from the trend line on the graph, the module power output vs. module surface temperature displays a nearly linear relationship when solar illumination levels are constant. A similar result was obtained in summer, 2011[1] and by the Project 1 Team in spring, 2012[2]. For the time period covered, the calculated linear trend line shows the predicted output at the solar module specification temperature of 25 °C is 207.9 watts. This is only 4.2 % below the calculated module specification output power for our system (217.6 watts). The module specification output power value is determined by the following formula:

$$\frac{(Max\ Potential\ Voltage)^2}{(Total\ Load\ Resistance\ in\ Ohms)} = Module\ Specification\ Power$$

When calculated with a specified maximum module output voltage of 29.5 volts (see Appendix I) and a 4 Ohm resistive load, our Module Specification Power output is equal to 217.6 watts.

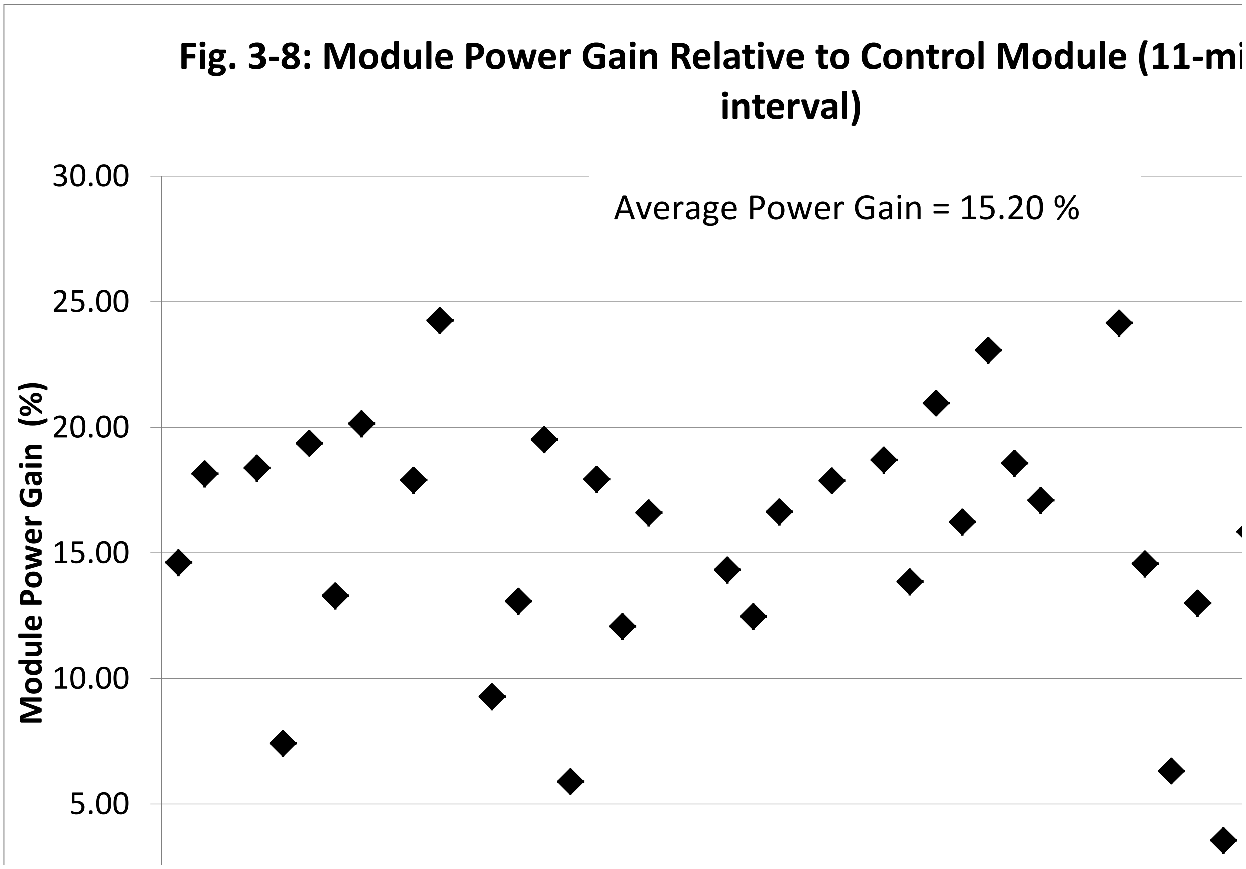


Figure 3-8 shows the average power gain in percent of the intermittent misting module relative to the control (noncooled) module. The average power gain was calculated by taking the control module's average power output and subtracting it from the intermittent misting module's average power output, dividing that value by the control module's average power output, and multiplying that resulting number by 100. The average power gain varied from 0% to nearly 25%. The average power gain over the entire test period was 15.2%.

It was noted how quickly the intermittent misting solar module surface dried after the misting was stopped. The "time to dry" was dependent on the illumination intensity and varied between 3 and 5 minutes. As a result, it was observed that for the 11 minute misting interval (1 minute on, 10 minutes off) the intermittent misting module was entirely dry before the misting system was turned on again. Since the data was collected for one minute every 5 minutes, the time when data was collected relative to the misting times varied throughout the test period; i.e., from right after misting ceased to just before misting started again. Since the water on the misted module usually dried completely within 5 minutes after being misted, the misted module's surface temperature would then start rising, in turn causing the voltage, current, and power output to decrease dependent on how long the misted module had been dry before data was collected. As seen, this caused the power gain of the misted module relative to the control module to vary substantially, at times decreasing the power gain to less than 5%.

DISCUSSION AND CONCLUSIONS

Cooling Methods	Average Ill. Intensity (lux)	Av. Module Temp.(°C)	Av Output Power (W)	Gain (%)
Continuous mist cooling (Project 1, Spring 2012)	112682.4	30.1	196.8	23.8
Continuous mist cooled (Summer 2011)	116732.2	38.4	191.1	22.7
Intermittent mist cooling (Project 3, Spring 2012) (6-min interval)	113103	31.3	198.0	20.8
Intermittent mist cooling (Project 3, Spring 2012) (11-min interval)	114977	34.9	187.6	15.2
Air Cooled (Project 1, Spring 2012)	112682.4	39.2	184.7	16.1
Air Cooled (Summer 2011)	116732.2	52.3	168.2	8.0
Continuous recirculated water cooling (Project 2, Spring 2012)	110683	46.2	175.5	11.6

Table 3: Comparison of Results for Spring, 2012 and Summer, 2011

The above table shows the key results for the three solar undergraduate research program projects in Spring, 2012 as well as the research project in Summer, 2012.

The following conclusions can be made from the results:

1. The continuous mist cooling systems provided the highest solar module average power gain (i.e., increased efficiency) ranging between 22.7 and 23.8%.

2. The intermittent mist cooling system-(the subject of this research project) provided good solar module average power gain (i.e., increased efficiency). The one minute misting followed by five minutes of no misting (6 min. misting interval) produced a 20.8% power gain while the one minute misting followed by ten minutes of no misting (11 min. misting interval) produced a 15.2% power gain. The intermittent misting systems used 85.7% (6 min misting interval) to 90.9% (11 min. misting interval) less water than the continuous mist cooling systems.

3. The continuous recirculated water cooling system provided an 11.6% average power gain.

4. The forced air cooling systems provided power gains (i.e., increased efficiency) between 8.0% and 16.1%. However, the actual power gain would be much less if the power required to operate the cooling fans was included in the efficiency calculations.

The final results support the conclusion that the optimum intermittent misting configuration that was tested is the 6-minute misting interval. The 20.8% power gain of the 6 minute misting interval system is slightly less than achieved with continuous water misting by Mr. Boehm in summer, 2011[1] (22.7%) and by the Project 1 Team in spring, 2012[2] (23.8%). However, the significant power output gain coupled with the approximately 86% reduction in water usage makes the intermittent misting cooling system more practical and economical than a continuous mist cooling system.

Knowing that intermittent misting is a viable option in cooling solar modules and conserving water, other future research projects may introduce similar approaches based on this research such as:

- *Intermittent-specification solar module misting:* Testing and determining the exact misting interval with optimal results (most likely between 5- and 10-minute intervals)
- *Solar module dryness intermittent misting:* Intermittent misting based on when the water has evaporated off the surface of the solar module
- *Temperature-based intermittent misting:* Using thermostatic and electronic equipment to control a solar module misting system
- *Temperature controlled water misting system:* Utilization of water cooling techniques to drop the water temperature below normal value
- *Chemical-mixture intermittent misting:* Utilization of chemicals mixed with public water to continue temperature control
- *Any combination of the above systems*

SPRING SOLAR RESEARCH PROGRAM PARTICIPANTS

San Antonio College

- Dr. Dan Dimitriu, Engineering Coordinator
- Klaus Bartels, Primary Faculty Advisor
- Tak Gurung, Faculty Advisor
- Adam Boehm, Student Advisor
- Katherine Bentley, Team 3 Project Leader
- Ram Bhattarai, Team 3 Project Participant
- Gabriel Velazquez, Team 3 Project Participant

OCI Solar Power

- Fazli Qadir, OCI Solar Power Senior Vice President of Engineering and Operations, Advisor

ACKNOWLEDGEMENTS

We would like to mention and thank everybody that was involved during the research session, without them the program would not have been successful. First we would like to thank our sponsors: OCI Solar Power, Inc. who donated the solar modules, procured test equipment and provided funding for individual parts needed for this project; NASA through the University of Texas in San Antonio for providing San Antonio College with grant funding; and USA Wire and Cable for providing connection wires for the solar modules.

In addition we would like to thank the individuals who helped make this research possible: OCI Solar Power Senior Vice President, EPC and Operations, Fazli Qadir, who answered our solar module questions and handled our requests; OCI Solar Power Executive Assistant, Julie Ohnstad, who arranged for the procurement, funding, and shipping of the modules and test equipment needed; Dr. Dan Dimitriu, Engineering Coordinator at San Antonio College, for the confirmation and support needed to proceed with the program; Klaus Bartels and Dr. Tak Gurung, San Antonio College faculty advisors, who provided advice, direction and help in all areas throughout the research. Finally, we would like to thank Adam Boehm, San Antonio College student advisor, who first started this research in the summer of 2011. His research created a precedent to look back on and a strong base to build off of.

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APPENDIX I - SOLAR MODULE SPECIFICATIONS

YL235P-29b/1650x990SERIES

ELECTRICAL PARAMETERS

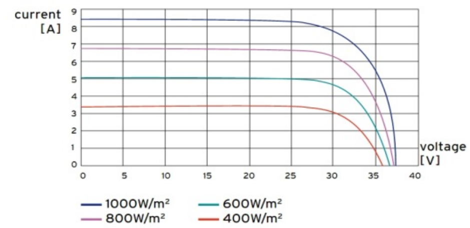
Electrical parameters at STC (1000 W/m², 25 °C, AM 1.5 according to EN 60904-3)

Module type		YL235-29b	YL230P-29b	YL225P-29b	YL220P-29b	YL215P-29b	YL210P-29b
Power output	[W]	235.0	230.0	225.0	220.0	215.0	210.0
Power output tolerances	[%]	+/- 3	+/- 3	+/- 3	+/- 3	+/- 3	+/-3
Module Efficiency	[%]	14.4	14.1	13.8	13.5	13.2	12.9
Voltage at Pmax, V_{mpp}	[V]	29.5	29.5	29.5	29.0	29.0	28.5
Current at Pmax, I_{mpp}	[A]	7.97	7.80	7,63	7.59	7.41	7.37
Open circuit voltage V_{oc}	[V]	37.0	37.0	36.5	36.5	36.0	36.0
Short circuit current I_{sc}	[A]	8.54	8.40	8.28	8.15	8.10	7.95
Max. system Voltage	[V]	IEC: 1,000 V DC ; UL: 600 V DC					

Parameters of the thermal characteristics

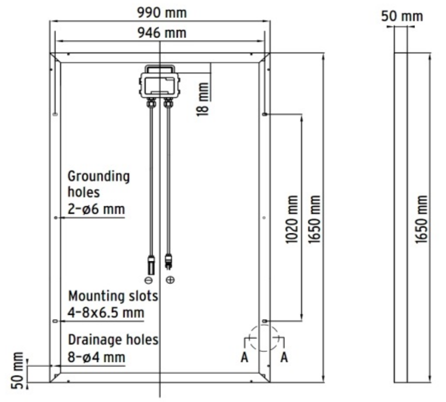
NOCT (Nominal Operating Cell Temperature)	[°C]	46 +/- 2
Temperature coefficient of the short circuit current I_{sc}	[%/K]	+ 0.06
Temperature coefficient of the open circuit voltage V_{oc}	[%/K]	- 0.37
Temperature coefficient of the MPP power P_{mpp}	[%/K]	- 0.45

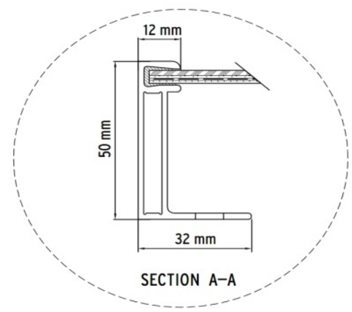
IV CURVES



MECHANICAL PARAMETERS

Dimensions (length [mm]/width [mm]/thickness [mm])	1650 / 990 / 50
Thickness with junction box [mm]	50
Weight [kg]	19.8
Junction box (manufacturer/protection degree/number of diodes)	CiXi / IP65 / 6
Junction box dimensions (length/width/thickness [mm])	151 / 122 / 25
Positive cable (manufacturer/length [mm]/cable cross-section [mm²])	TAIYO / 1200 / 4
Negative cable (manufacturer/length [mm]/cable cross-section [mm²])	TAIYO / 1200 / 4
Plug connector (manufacturer/type/protection degree)	MC4 / UV resistance and self-locking / IP65
Front cover (material/thickness [mm])	Tempered Glass, 3.2mm
Cell type (quantity/technology)	60 / polycrystalline / 156 x 156
Encapsulation materials	Ethylene Vinyl Acetate (EVA)
Rear cover (material/thickness [mm])	Le/PET/PVDF,0.287
Frame (material)	robust anodized aluminum alloy





Electrical equipment, check with your installer

OPERATING CONDITIONS

Operating temperature [° C]	- 40 to + 85
Max. wind load [Pa]	2.4K

PACKAGING

Number of modules per box	20
Box size (length [mm]/width [mm]/depth [mm])	1700 / 1140 / 1165
Box Gross weight in Kg	450
Boxes per pallet	1

* The data does not refer to a single module and they are not part of the offer, they serve for comparison only to different module types.

Subject to modifications and errors

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