Performance Testing of American Solar Low Cost Polymer Solar Air Heating Panel

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Background

American Solar is a solar air heating company that develops, markets, and installs solar air heating products of its proprietary systems. American Solar has developed a reputation as one of the most innovative developers of solar air heating products. American Solar's systems have been used in new applications and demonstrate fundamentally different uses of traditional building materials to harvest solar energy from building walls, roofs, and from ground mounted systems.

American Solar's primary market for its new polymer based solar heating systems is not the suburban home. Instead it is;

- the rural agricultural --
  - greenhouse,
  - poultry house,
  - farm building and housing and
- rural commercial or industrial facility which require heat for any purpose.

The common thread among these target markets is that,

- they have high cost traditional heating sources such as propane, fuel oil, or electricity,
- they have large land areas and/ or large flat roof or wall areas
- they have large needs for heated air that are not primarily for human comfort or domestic human needs and
- their heating needs can be partially met by pre-heating of air, as a first step in a final heating applications, whether they be air heating, or water heating, or process heating.

As a result, they do not require continuous delivery temperatures at above 90 F for air or 120 F for water. Instead they can make use of lower temperature energy sources which vary over daily and seasonal periods. The lower temperature air can provide the preheating to the end need at lower cost than the final, conventional heating system.

American Solar operates on the principle that the most important objective for the customers in this market is to:

> Select the best investments, among all alternative investments, that improve the return (increased profits/ increased costs) from their business operations by the greatest margin possible.

Therefore, the solar heating systems must save the customer more money in conventional heating energy cost than it costs to purchase and operate over a period of about 3 years or less. (~ 33+% return on investment).

American Solar is interested in developing technologies that meet the investment needs of these markets. American Solar believes that the rural agricultural and industrial and commercial markets are a good point of entry because

- their greatest annual energy need is for heat,
- their conventional heating energy sources are some of the most expensive, (propane , fuel oil and electricity) and

- their solar energy systems do not require the attachment on the roof of occupied buildings with extensive plumbing, and heating requirements and code approvals and
- these markets are already using the same lower cost materials and systems in their own processes that can be used to capture and deliver solar heat.

American Solar has developed two new solar air heating collectors and several new solar applications for use in these markets.

American Solar wished to collaborate with the North Carolina Solar Center to deploy and validate the performance of the new collectors in a way that can make them visible to the target markets and create visibility for American Solar and for NCSC within these markets. American Solar believes that testing of the new systems by NCSC will create a baseline measurement of the technical performance.

System Description

American Solar worked with the North Carolina Solar Center (NCSC) staff to construct three solar air heating collector panels totaling 90 square feet of collecting surface from material supplied by American Solar. Two twinwall fluted panels (TFP) were constructed of primarily two 4' by 8' sheets of ½" inch twinwall fluted (corrugated) polymer sheets and smaller twinwall pieces used to create the collecting air plenum in each collector. Some of the construction details of the two identically constructed panels may be seen in the photographs on this page. An outlet duct was attached to each plenum. One of these collectors was outfitted with an array of thermocouples and back-insulated with a ¼" sheet of white twinwall polymer. Due to budgetary constraints the second twinwall collector was not outfitted with thermocouples, and therefore provided no performance data. In total, approximately 60 square feet of TFP were constructed.

During some tests glazing was added to the top of the TFP in an effort to increase performance. Glazing material was off-the-shelf clear corrugated polymer panels laid on top of the TFP collector. This same glazing material was used to construct the second variety of low cost American Solar air heating panel, known as a glazed transpired panel (GTP).

American Solar and NCSC staff constructed two glazed transpired panels (GTP) that did not go through testing. Photos of the glazed transpired panels are shown below displaying the construction of the panels. The panels are basically two layers of corrugated clear polymers with a black shade cloth stretched between the two layers in a manner that would require air passing through the collector to repeatedly pass through the shade cloth, removing the solar energy absorbed by this material. To collect heat from the panels, an air plenum would need to be constructed to allow for controlled collection of solar heated air. Due to NCSC project budget constraints and a lack of air plenum design or materials these collectors were not performance tested. The two collectors are approximately 32 square feet of GTP.

American Solar supplied all of the materials for these two types of collectors as well as 100 feet of black polymer duct and a fan to operate the system. The ductwork was 4" corrugated HDPE pipe. The fan was a 110 Volt AC blower with a free air capacity of over 100 CFM. American Solar assisted in the assembly and preliminary testing of the ground mounted panels and the connection of the ductwork, panels and fan.

Data Collection

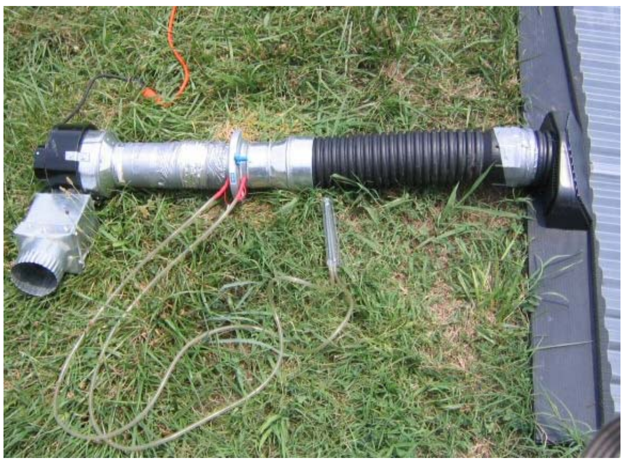
The testing was completed in Raleigh, NC in the Research Annex at The North Carolina Solar Center in the summer of 2005 by NCSC staff. The panel was placed flat on the ground as shown in the figure below. Re-bar stakes were used as anchor points for the heavy black rope that held the collector flush to the ground. All of the tests were conducted with the American Solar-supplied fan (Dayton 2C647) sucking air through the collector and exhausting the solar heated air from the fan. This allowed for accurate temperature measurements of the solar heated air from before entry (ambient) to collector exit (maximum temperature).

Thermocouples

The twinwall fluted panel that was performance tested was outfitted with an array of 11 thermocouples. Nine of these were installed to measure the air temperature in the channels, or flutes, containing the collection air as it passed through the collector. A small hole was drilled in the bottom of the collector and the small thermocouples were inserted to approximately the middle of the channel, careful attention was paid to ensure the thermocouples were not inserted to far into the channel where they could make contact with the backside of the collecting surface. After insertion of the thermocouples, the insertion holes were sealed with silicon sealant to ensure no air leakage and to lock the thermocouple in place. Each thermocouple was inserted into separate channels to remove the affect of each thermocouple on other thermocouples downstream. This also limited the pressure drop in the measured channels, which served to maintain the accuracy of the measurements. Nine thermocouples were installed in three rows: i) one row of three thermocouples one foot from the collector inlet (1 foot from left edge, center, 1 foot from right edge), ii) one row at the center (4 feet from inlet) of the collector (left, center, right), iii) one row at 7 feet from the collector inlet (nearly 1 foot from the outlet plenum) (left, center, right). The thermocouples used were type T thermocouples. Each thermocouple was tested in both an ice bath and ambient air and showed to be within 0.5 °F of the 32.0 °F in the ice bath and within 0.6 °C of the average air temperature reading, 82.8 °F

Airflow Measurements

The collector airflow measurements were made using a 4 inch Fantech Iris Damper (IR4) installed between the collector and the fan as shown in the figure below. Two feet of straight duct was provided before the damper and over one foot of straight duct was installed between the damper and the fan inlet. Although the exterior pipe diameter experiences a change less than a foot before the damper, the interior diameter remained constant.



The Iris Damper not only allowed for airflow measurements to be made by measuring the static pressure difference before and after the iris, but it also functioned as a simple and repeatable way to adjust the airflow through the collector. Unfortunately with the large flow resistance of the collector, even large adjustments to the size of the damper opening had only moderate affects on the flow rate through the collector. With the fan connected to the collector and the damper set to the largest marked opening setting, a K-factor of 5.1 as seen in the photo below, the flow rate through the collector was 21.5 cubic feet or air per minute (CFM). With the damper set to the smallest marked opening setting, a K-factor of 1.6, the flow rate through the collector was only reduced to 17.8 CFM. When the fan and damper were disconnected from the collector just after the collector exhaust, so that the long straight section of duct before the damper was maintained, the flow rate at a K-factor 5.1 resulted in a flow rate of 97.4 CFM, and a damper setting of 2.0 resulted in a flow rate of 37.5 CFM. Clearly the collector added a significant amount of pressure drop which will have an effect on the amount of fan energy needed to create the desired air flow rate through the collector.

The damper was physically adjustable to greater extremes than the K-factor scale provided, from fully open to nearly closed, but these positions were off of the non-linear K-factor scale so no K-factor was able to be determined for these extreme positions and thus no flow rate could be calculated. In the testing the lowest K-factor used was 2.0 because the only lower factor, 1.6, created a differential pressure of over 0.1 inches of water column, which required the use of the less accurate scale on the available manometer (up to 1.0 inches of water versus up to 0.1 inch of water). The equation to calculate flow rate provided by the damper manufacturer was Q (CFM) = (K-factor * 33.4) * delta P (in H_2O). The manometer used to measure the pressure difference at the two pressure taps contained in the damper is shown in Figure XX. In order to achieve maximum accuracy with this analog device multiple measurements were taken throughout each testing period and averaged. Fan curve data was only available for flow rates down to 79 CFM, thus ruling out using this data as a redundant method of calculating flow rate.

Datalogging station

The detailed testing station was based around a CR10X Campbell Scientific Inc. (CSI) datalogger in a ground mounted weather tight box. The collector testing setup, including a view of the weather tight box containing the datalogger may be seen in the photo below. The datalogging system was constructed by NCSC staff from equipment they previously owned. The station allowed for real-time data collection of global horizontal radiation via a LiCor pyranometer, wind speed at approximately 4 feet above the ground via a NRG Hall Effect anemometer, ambient temperature and relative humidity via a CSI shielded probe, and the many air temperature readings in the collector via small hand-mounted type-T thermocouples. The reference temperature for the thermocouples was obtained by a CSI thermistor mounted near the surface of the datalogger. All of these measurement devices are of research caliber and are expected to provide accurate readings.

Preliminary Testing

After the panel construction, some initial testing was completed with the guidance of American Solar. On December 21, 2004, Tommy Cleveland of NCSC and John Archibald of American conducted some initial testing including temperature rise in a long section of duct (100 feet) and collector performance with air being blown through the collector rather than sucked through the collector as in the later tests. The results of these tests are not presented here, but were recorded in an American Solar notebook.

Before the equipment for the datalogging station and for airflow measurements were available to NCSC, some more detailed preliminary testing was completed on the TFP outfitted with thermocouples. The temperature readings were made one at a time with a Fluke handheld thermocouple reader. These tests took place on April 15th in the early afternoon under full sun. The collector was on flat ground and had been wiped clean to remove collected dirt and pollen. The wind was gusting up to an estimated 10 or 15 miles per hour (this was not measured on estimated). There was 10 feet of flexible corrugated duct between the collector and the fan. The data from this testing is presented in the table below.

		1:20pm	1:35pm	2:00pm	2:10pm
		Temperatures with no flow (F)	Temperatures after 10 mins of flow (F)	Temperatures with clear glazing, ridge parallel to flow (no flow) (F)	Temperatures with clear glazing, ridge parallel to flow (after 10 mins full flow) (F)
1 foot from inlet	left	101.6	77.8	115.1	94.4
1 foot from inlet	center	105.2	75.3	118.1	89.6
1 foot from inlet	right	104.7	80.0	115.8	94.1
4 feet from inlet	left	114.3	99.0	122.4	114.7
4 feet from inlet	center	112.4	93.0	125.3	108.1
4 feet from inlet	right	113.9	102.8	126.5	115.7
before plenum	left	98.3	96.7	102.5	114.7
before plenum	center	105.0	99.6	105.3	117.5
before plenum	right	104.1	102.8	112.8	124.0
ambient		65.0	64.0	63.8	63.9
center of exit duct (start of flex duct)		99.6	115.5	107.9	139.0
			peaked at 120F		peaked at 142F

These tests show a maximum temperature increase of 78 degrees Fahrenheit with the maximum flow available from the supplied fan and clear corrugated polymer glazing sitting on the collector parallel to the airflow. A temperature rise of 56 degrees Fahrenheit was measured without the glazing. Although these tests should only be considered preliminary because no air flow measurements were made, this collector clearly produced a very significant temperature rise.

Detailed Testing

Detailed testing was not able to occur until the datalogging station was constructed, which required retrieving the equipment from an unrelated completed monitoring project.

The testing occurred in early and mid July (see accompanying spreadsheet for the data). The testing took place on hot days in the full sun, thus testing the temperature limits of the polymer materials.

TFP – Full Flow: 21.5 CFM – no glazing

Stagnation: up to 45 °F above ambient: highest interior air temperature seen was 135 °F at an ambient temperature of 90 °F and sustained incident radiation of 800 W/m^2 occurring at a low angle of incidence

Temperature Rise: maximum steady state temperature rise experienced was **56.5 °F** occurring with steady incident radiation of 800 W/m^2 and wind average speed below 3 mph.

Energy Output: maximum steady state energy output experienced was 0.33 kW for the entire collector. This is an output rate of **0.12 kW/m^2**. This occurred at the same time (~1pm July 10th) as the maximum temperature rise.

System Efficiency: average of **17.9%** at a solar incidence angle of about **35 degrees,** experienced at about 4pm July 19th**.** This is a fairly high incidence angle so a slightly higher efficiency may occur at lower incidence angles. This piece of data was chosen for system efficiency representation because of the steadiness of the both the inputs and the output over a few minutes.

The following graphs display some of the data in an easy to comprehend format. The first graph shows the temperatures of the air in the collector as measured by the 9 thermocouples in the collector and the 2 thermocouples at the collector exit. The first data point is at the moment in time that the air flow was first initiated. The drop in temperature of the three measurement points near the inlet shows that it took several minutes to reach a quasi-steady state. The temperature drop in the center of the collector was much less dramatic, but still took over 6 minutes. The reason for the initial low temperature in the middle of the three thermocouples across the middle of the collector is not known. It may be possible that this thermocouple had shifted to very low in the channel or perhaps the insertion was leaking some air. The measurements from this single thermocouple appears lower than the surrounding thermocouples on other days of testing as well, however at night when the collector cools to the temperature of the surroundings this thermocouple has good agreement with the other thermocouples in the collector. A time delay similar to those experienced at the first two lines of collectors also occurred in the sensors near the exit plenum. The incident solar radiation is also graphed so that its influence may be noted.

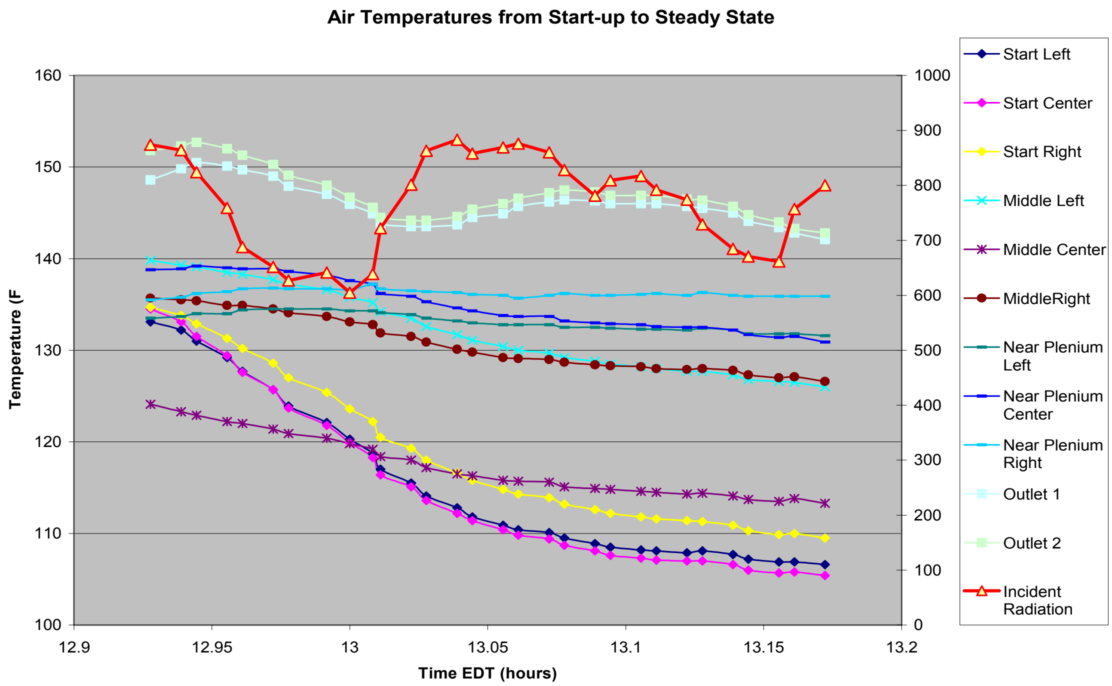


Figure 1: Air Temperatures from Start-Up to Steady State on July 10th

The following figure, Figure 2, displays the enthalpy and temperature increases in the air as a function of incident solar radiation. The temperature and enthalpy increases are very closely related. The enthalpy of the moisture in the air was accounted for along with the dry air.

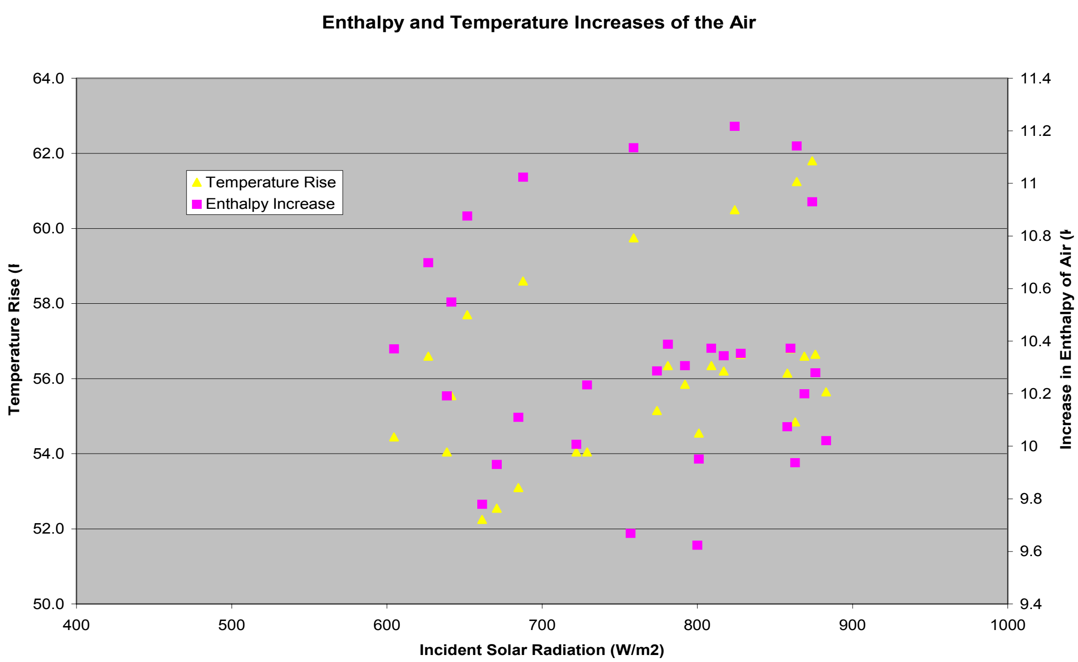


Figure 2: Enthalpy and Temperature Increases of Air Through Collector on July 10th

The graph below (Figure 3) displays the collector efficiency as a function of (T_{outlet}-$T_{ambient}$/G). A similar graph typically serves as the basis for the common $F_R U_L$ and $F_R(ta)_n$ model of a flat plate collector, both water and air heating. This type of graph serves to determine important performance properties of a collector from simple test data. The model is based on the input of T_{inlet}-$T_{amb,}$ however because the inlet to the tested collector is always equal to ambient this important input variable is always equal to zero. This situation severely limits the usefulness of this common model. With additional measurements and analysis a model may be able to be developed that is based on either the average collector air temperature or the average collector surface temperature. Development and application of these models is out of the scope of this testing project.

Typically the x-axis is T_{inlet}-T_{amb}/$G_,$ which in the case of this collector is always zero! It is possible to plot collector data along a T_{outlet}-$T_{ambient}$/G that may be find modified collector parameters that may be converted to $F_R U_L$ and $F_R(ta)_n$. This air collector, in the $F_R U_L$ and $F_R(ta)_n$ model, is always operating at its most efficient point (where T_{inlet} - T_{amb} equals zero). Following this model, the collector is always operating with an efficiency equal to $F_R(ta)_n$, therefore the efficiency of the collector at any measured T_o-T_a/G_1 should have the same efficiency, $F_R(ta)_n$. This means that all of the variation seen for a single radiation level is due to transient changes (i.e. not in steady state, which is a primary assumption of the model) in T_o-T_a caused by the small timescale and changing inputs coupled with the thermal capacitance of the collector. This transient nature can be easily understood by a close inspection of the data. Because the inlet temperature always equals ambient there is no way to produce a typical efficiency curve from the data. The best that can be done is to average the efficiencies to find the y-intercept of a typical efficiency curve, $F_R(ta)_{n.}$ In order to plot any other points on this graph the input temperature would need to be adjustable to temperatures above ambient.

This collector efficiency curve is not printed for the other collector tests because little may be learned beyond the average efficiency, which is presented elsewhere.

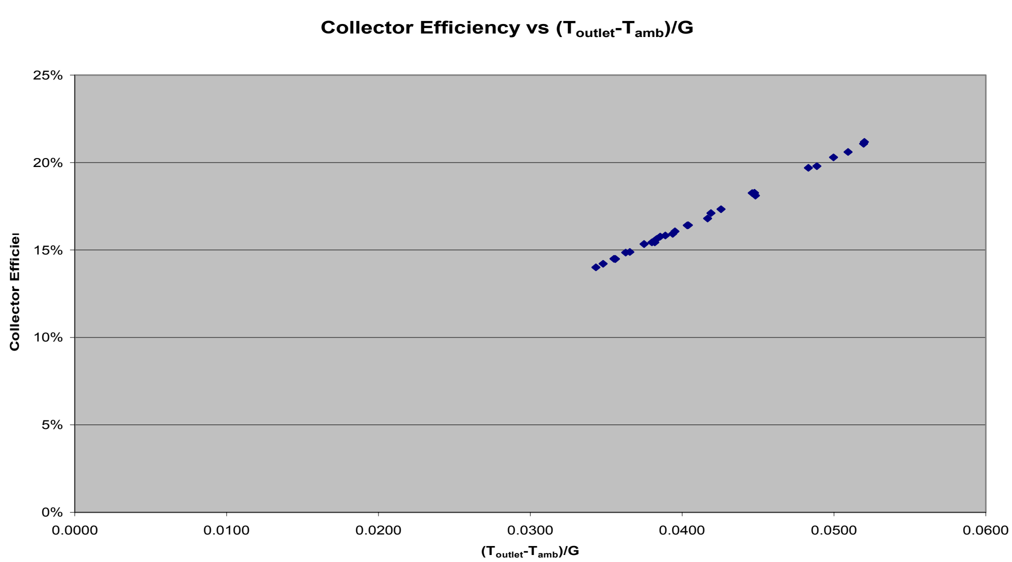


Figure 3: Collector Efficiency vs. T_{outlet}-T_{amb}/G

TFP – Low Flow: 18.4 CFM – no glazing

Stagnation: Same as full flow with no glazing
Temperature Rise: Maximum air temperature rise seen was 54.0 °F, however this was under partly cloudy skies
System Efficiency: **11.6%** at an average incident angle of 16° over 35 minutes under partly cloudy skies. This data had somewhat unstable incident radiation, which caused the efficiency of 30-second periods to range from 8.3% to 15.9%. This slower flow rate appeared to have a dramatic affect on the system efficiency.

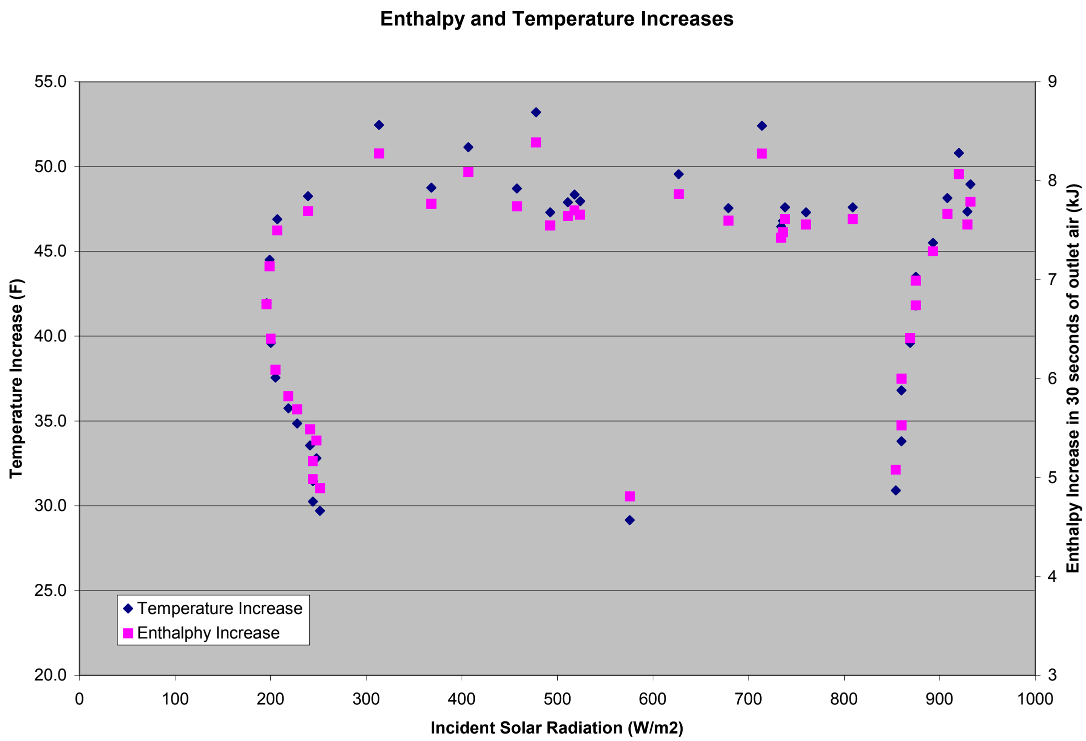


Figure 4: Enthalpy and Temperature Increases in Air at Low Flow with No Glazing

TFP – Full Flow: 21.5 CFM – with Glazing

The collector was tested with the addition of simple corrugated glazing. The glazing was not adhered to the collector surface, just simply laid flat on the collector and secured under ropes tied between the collector stakes. As can be seen in the photograph below there was limited effort made to seal along the edges of the glazings. In places this resulted in up to 1 inch gaps between the glazing and the edge of the collector. The potential gain from a tighter union of the collector and the glazing is not known.

Stagnation (glazing): No damage or deformation after two consecutive 101°F days, ground-mounted with twinwall and polyiso back insulation

Temperature Rise: 74.3 °F was the maximum temperature rise seen. This occurred when the collector experienced sustained incident solar radiation of 850 W/m^2 for over 10 minutes. A higher temperature rise (78°) was seen during preliminary testing at a higher, but unmeasured, air flow rate.

System Efficiency (low angle): 19.6% at an incident angle of 18.7° which was the average efficiency over 20 minutes under clear skies from 2:25 to 2:45 pm on Sunday July 10th. This region was chosen for the relatively stable incident solar radiation, stable output energy, and therefore stable efficiency.

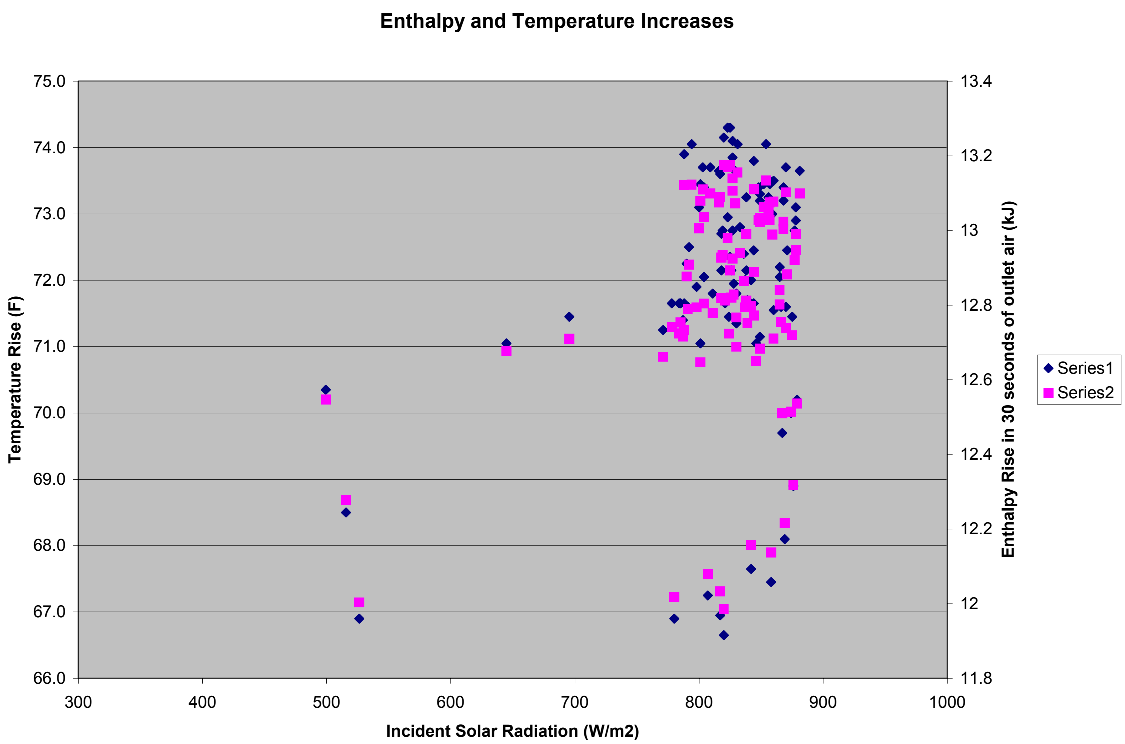


Figure 5: Enthalpy and Temperature Increases in Air at Full Flow with Glazing

TFP – Low Flow: 18.4 CFM – with Glazing

Stagnation (glazing): No damage, same as above

Temperature Rise: 54.5 °F after 6 minutes of 950 W/m^2 insolation with some clouds before this period, on July 7th

System Efficiency: Average of **14.5%** over 20 minutes of partly cloudy skies at an incident angle of 13.3° on July 7th. This period experienced moderate swings in both incident radiation and short-term (30 seconds) efficiency.

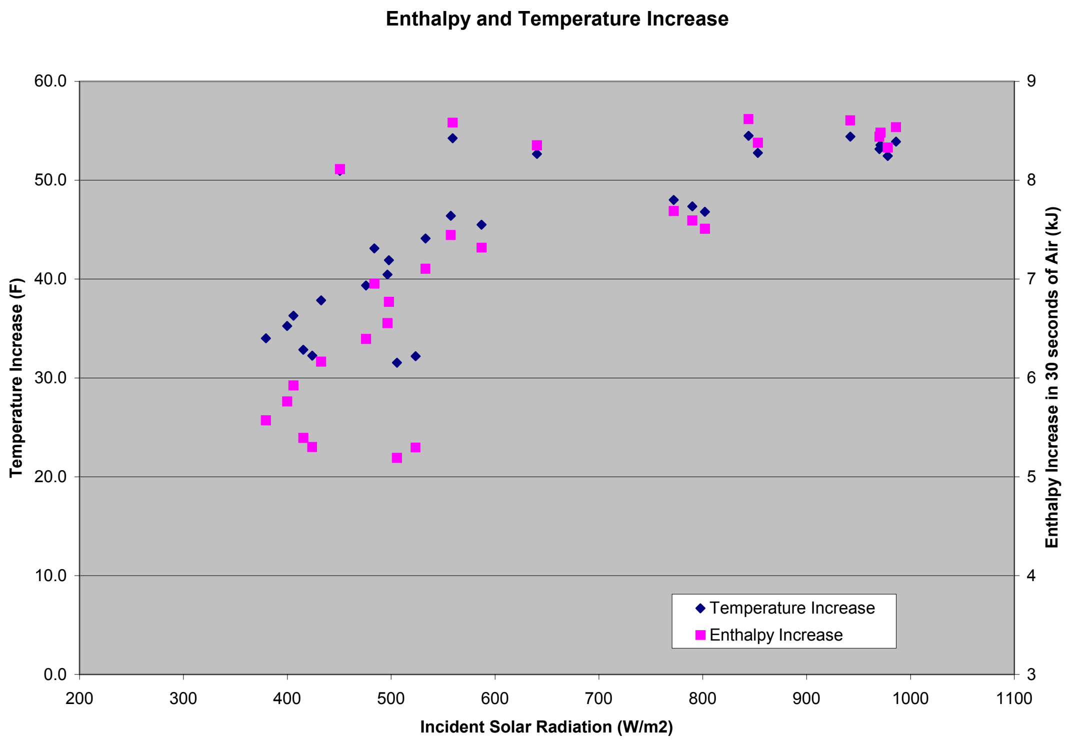


Figure 6: Enthalpy and Temperature Increases in Air at Low Flow with Glazing

Added insulation below collector

A piece of polyiso insulation was added under the initial thin twinwall insulation, between the collector and the ground. The insulation was added immediately after a 17 minute data collection period that had the iris damper in the fully open (out of range of the provided K-factor scale). Therefore the true flow rate is not known, but one was estimated for the sake of comparison between the collector performance before and after the insulation was added. This occurred at 11:45 am on July 19th. Data was taken for a second 17 minutes with no changes made to the system except for the addition of the bottom insulation. The calculated efficiency effectively remained unaffected, in fact the calculated efficiency (using an estimated constant flow rate) was reduced from 18.1% to 17.8%. It was noted that the underside of the thinner white twinwall insulation was warm to the touch near the center of the collector, indicating heat loss to the ground and the potential for performance improvements with increased bottom insulation. It is expected that over a longer test period and/or a test period with more stable solar radiation the benefit of the increased insulation would be measurable.

Collector Time Constant

The collector time constant was determined by observing data collected during one of the panel tests presented above. Although a specific test was not executed to determine the collector time constant, a reasonable determination of the collector time constant may be determined from some of the data. During the testing on July 19th at 12:18 in the afternoon the sun was covered by a cloud providing a period of over 7 minutes with significantly reduced solar radiation on the collector. The standard test to determine a collector time constant involves totally blocking off, or otherwise removing, all incoming radiation. The less-than-total removal of radiation experienced in the data may be accounted for by determining the temperature rise due to the known radiation using the efficiency of the collector.

The collector time constant is defined as the time required for the existing working fluid to drop to 1/e (36.8%) of its temperature rise at the moment the radiation was removed. In the noted data the initial temperature rise across the collector was 48.3 °F. After the drop in radiation the constant radiation was approximately 200 W/m^2, which at the average efficiency of the TFP collector with Low Flow and no glazing produces a predicted temperature rise of 14.0 °F. In an attempt to account for the presence of this reduced radiation, this temperature difference of 14.0 °F is used to modify the temperature decay baseline for the collector. In other words, if the incoming radiation were truly zero the exiting fluid temperature would slowly decay to the entering fluid temperature, but because of the incident 200 W/m^2 the exiting temperature will slowly decay to 14 °F above the entering fluid temperature.

The collector time constant is still defined as the time required for the existing working fluid to drop 1/e of the total potential drop, but the total potential drop is less than in the case of zero radiation. In the given data this is the time it takes the exiting air to drop to (91.5°F + 14°F) + 0.368 * (48.3°F – 14°F) = 118.1 °F, or the temperature of the entering air plus 14 degrees to account for the 200 W/m^2 incident on the collector times 1/e times the total potential temperature drop. Unfortunately the cloud moved from in front of the sun before this temperature was reached. The lowest temperature reached by the exiting air was 120.4°F, which is over a 20 degree drop from the beginning of the reduced radiation, but still over 2 degrees from the temperature needed to define the time constant. A simple extension of the decay curve during this 7 minute drop suggests that a temperature of 118 °F would be reached after a period of approximately 9 minutes from the initial drop in radiation. This period of 9 minutes is the approximate collector time constant. More detailed testing would produce a more accurate answer, but this value is expected to be adequate to provide an initial value for a model of the collector.

Duct Standalone Testing

Testing of the duct without the solar collector was not completed in more detail than the initial tested done under the guidance of American Solar. This preliminary testing did not suggest much energy gain was occurring in the unmodified duct. It was determined by American Solar that the interior and exterior polymer linings and sleeves that were considered as possible enhancements to the performance of the ducts would not be tested at this time.

Long Term Panel Testing

The collector has been secured to the ground in its current position since April 22nd. No degradation of the panel is noticeable at this time, but more exposure time could start to reveal some degradation. The panel did collect moderately heavy deposits of dust and pollen during the late spring. The grass upon which the panel rests started to grow over the edge of the panels, by as much as 3 inches. When the nearby grass was cut with large riding lawn mowers the collector was covered with scattered grass clippings. After only a day or two these moist clippings dry out and greatly reduce in size and weight. The dry grass then blocks limited radiation and is light enough to be blown off of the panel, or at least to the edge of the panel, in a strong wind. The remaining grass at the time of testing was quickly removed by hand and the panel wiped clean before each testing series. The silicone caulk used in the construction and air sealing of the panel did not appear to show signs of degradation.

There have not been any extreme storms during this long term period, but the typical summer storms, which can be quite strong, have not noticeably affected the collector.

Suggestions for Further Testing

The testing reported here has laid a foundation of understanding of the performance of American Solar Twinwall Fluted Panels. The collector efficiency has been shown for two air flow rates, both with and without a simple low cost glazing. However, higher air flows were not tested due to the power limitations of the provided fan. It is suggested that further testing be completed with several higher flow rates to determine the collector flow rate that provides the maximum efficiency. It is possible that a significantly higher efficiency may be achievable with higher flow rates. A second simple change that might provide an increase in efficiency is an improved method of attaching the low cost glazing. Experiments with horizontal standoffs to reduce contact and therefore conduction losses to the cover and improved air sealing along the sides and ends of the glazing may show improvements in collector efficiency. Similarly an improved method of attaching the polyiso bottom insulation may show to improve collector efficiency.

The testing conducted for this report did not explicitly look at the effect of the solar incident angle. It is suggested that further testing strive to define the effect of the incident angle. It is expected that at low incident angles (less than 30°) there will be limited effect, but the extent of the effect at higher angles is more of a question. This information will allow for more accurate models that would be capable of accurately predicting system performance throughout a wide range of locations, installations, and times.