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Experimental Solar Collector as a Possible Source of Thermal Energy

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Abstract

The growing concern of depleting fossil fuels and the current expense involved with alternative energy methods spurred the design of a low capital cost, concentrating solar collector as a possibly viable source of thermal energy. The data that was collected, as a result of testing, is shown and explained in later sections, which will provide a stepping stone to making alternative energy an option in communities across the world. The perceived problem was approached from both empirical and experimental analysis methods. Empirical analysis was done in order to obtain relatively close values involving the size and material of the actual collector, as well as some theoretical values of what the output should be. Then 30-minute experiments were performed on various days in order to obtain real time data, which was then used for the calculations of what was achieved as opposed to what was theorized. From this it was decided that the average output of the collector proved to be approximately (0.955 ± 0.951) watts. What was learned from this is that there would have to be more data points taken in order to obtain a higher confidence level in the data and reduce the amount of uncertainty in the output. With this information, the solar collector can be improved upon and provide instruction to the average person so that this may be repeated for home use. It is hoped that from this alternative energy will be prominent in every household.

Introduction

In today's society, energy is of great concern. The current petroleum resources of the world are rapidly depleting and, globally, there is a large push to "go green." Presently, scientists and engineers are seeking new ways to utilize current alternative energy sources as well as develop other forms of sustainable energy which will reduce or eliminate petro based energy dependence. Although there are several alternative energy options available, many of these are not economically viable for the average consumer. Thus, a low capital concentrating solar collector was proposed as a possible solution.

The main goals of this project were to design, construct, test, and analyze a low capital solar collector as a possible source of thermal energy for the average home owner. The design criteria behind the collector were to have a minimal initial investment, locally available materials, and easy assembly. To maintain low capital cost, the implementation was constrained to inexpensive and durable materials that also met the remaining design criteria. The test and analysis phase was necessary to determine important thermal parameters such as collector efficiency and heat transfer rates. These parameters provide the necessary data to determine whether a solar collector is an economical alternative to products such as solar panels and windmills.

Theory and Analysis

Solar collectors are devices that receive diffuse solar radiation (solar insulation) and convert it to useful thermal energy. Concentrating collectors, a category of solar collectors, operate by reflecting rays of solar insulation onto an absorber that lies at the focus of the device. The reflected radiation then generates useful thermal energy through a net increase in kinetic energy of the absorbers' constituent particles. This type of collector is built by using equations to ensure that solar energy is indeed being concentrated on a single point.

Collector Design Equations

The concentrating collector for this project was designed using the following equations. The height, H, of the paraboloid used in the design calculations was 30.48 cm and the diameter, D, was 60.96 cm. With these parameters, the coefficient of growth of the paraboloid was found to be 0.003279 cm-1 and the focus was calculated to be at 7.62 cm. The detailed design calculations can be found in Appendix I.

$$H = (x^2 + y^2) = \frac{aD^2}{4} \tag{1}$$

$$D = 2\sqrt{\frac{H}{a}} \tag{2}$$

$$f = \frac{1}{4a} \tag{3}$$

Collector Analysis Equations

The rates of heat transfer and collector efficiency were both calculated using equations (5) through (9). Equation (5) is the rate of radiation heat transfer, equation (6) is the rate of convective heat loss, and equation (4) is the time rate of change of the internal energy of the test specimen. The , , and in equation (5) are emissivity, Stefan-Boltzmann constant, and cross-sectional area respectively. The in equation (6) is the coefficient of convective heat transfer. Equations (5) and (6) were obtained from Cengel and Boles[1].

$$\dot{Q}_{in} - \dot{Q}_{rad} + \dot{Q}_{conv} = \frac{dE}{dt} \tag{4}$$

$$\dot{Q}_{rad} = \varepsilon\sigma A(T_s^4 - T_{sur}^4) \tag{5}$$

$$\dot{Q}_{conv} = h_c A(T_s - T_{sur}) \tag{6}$$

Equation (7) and (8) are used to calculate the rate of heat transfer into the test specimen. The 'm' in equations (7) and (8) is the mass of the test specimen and 'c' is the specific heat of pure aluminum, provided by Incropera and DeWitt[2].

$$\frac{dE}{dt} = mc\frac{dT(t)}{dt} \tag{7}$$

$$\dot{Q}_{net,in} = mc\frac{dT(t)}{dt} \tag{8}$$

Equation (9) is an expression for the efficiency of the collector. $\dot{Q}_{solar}$ is an average value for the rate of solar insulation incident on the collector aperture; it was obtained from The National Renewable Energy Laboratory website[3].

$$\eta_{collector} = \frac{Rate\ of\ heat\ transfer\ into\ block}{Rate\ of\ solar\ radiation\ incident\ on\ collector} = \frac{\dot{Q}_{in}}{\dot{Q}_{solar}} \tag{9}$$

Experimental Analysis

The objective of the experimental analysis was to test the output of the solar collector under standard operating conditions in order to understand its efficacy. Since a solar collector can be very efficient or not efficient at all, thermodynamic analysis must be done in order to determine the efficacy of this particular solar collector. This test protocol was used as a moderator during the testing to collect data used in the calculations.

There were some criteria that reduced the amount of uncertainty in the data obtained. For example, the same equipment and materials were used for every test, ensuring that there were no extra variables. Also, every test was conducted for 30 minutes during various times of the day, on different days. This was to simulate constant use. To ensure that this variable was accounted for, the weather and solar irradiances were recorded for the time and day of each testing session, along with a control for recording ambient temperature.

Figure 1: Test apparatus. The thermocouple is taped in place on an insulated hanger and inserted into the bottom of an aluminum block.

The materials and equipment used in the testing each had an important role in the data acquisition. First and foremost is the solar collector. Then two aluminum blocks were machined to have relatively similar volumes and densities. The blocks, in conjunction with two K-type thermocouples, were used to obtain temperature readings of a control ambient temperature as well as from the focus of the solar collector. The thermocouples were connected to a multimeter, a device that takes various electrical measurements and displays it, that was thermocouple compatible and gave readouts in degrees (either F or C). With the thermocouples connected to the multimeter, the sensor ends were placed into the center of the aluminum blocks for core temperature readings. The aluminum blocks with thermocouples still in place were then placed on insulated wire hangers, which held them aloft to reduce influence from the ground temperature. One block was placed in a general sunny area as a control, while the other was placed at the focus of the concentrating collector. Lastly, a stopwatch was used to ensure that a data point was taken every minute for consistency.

To prepare for the actual testing, the aluminum block/hanger assemblies were placed on a flat surface in a sunny spot. One block/hanger assembly was placed in the focus of the solar collector and the other was left outside as a control. The multimeter dial was then turned to either the T1 or T2 option. Then, the thermocouples were connected to the multimeter so that the T1 option was the control block temperature readout and the T2 option was the solar collector’s temperature readout. The solar collector was then positioned so that it was bathed in direct sunlight.

The first item that was recorded was the time that the testing started, immediately followed by an initial reading of the temperature of each block. The stop watch was started and a reading was taken every minute for thirty minutes, re-starting the stopwatch after every reading. Upon completion, the time that the testing was finished was recorded, along with the date and the solar irradiances obtained from the National Weather Service website. Comments should also be noted by the experimenters as to any abnormalities that may skew data, such as slight wind, scattered cloud cover, or sun position.

Data and Results

The ultimate objective of this project was to determine whether or not a low-capital cost solar collector is a viable source of thermal energy. With that in mind, the following points were analyzed.

- φ Temperature, as a function of time, of a test block positioned at the focus of the solar concentrator and of a control block exposed solely to atmospheric conditions
- φ The average collector efficiency, defined in equation (9)

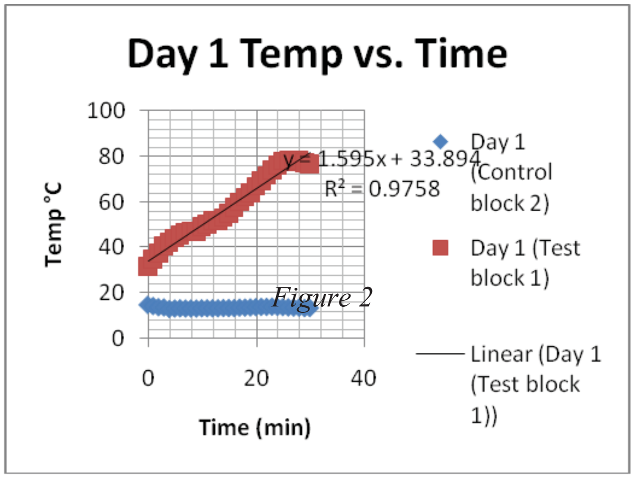


Figure 2 (above) and Figure 3 (below).

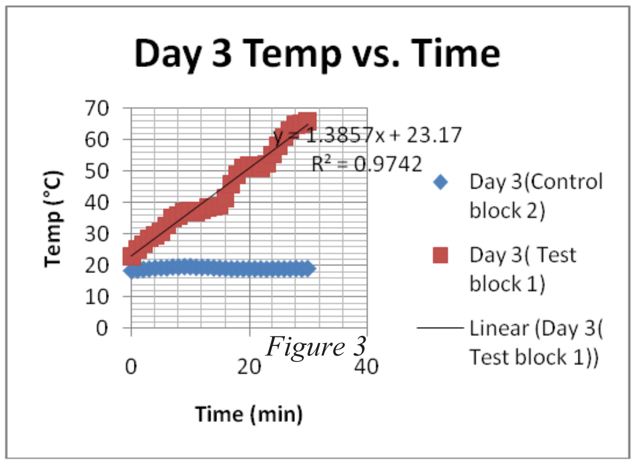


Figure 2 shows a temperature versus time plot for both blocks on the first day of testing. The data for the test block depicts a linear correlation between 0 and 25 minutes, thus a linear trend line is suitable for an approximation of the net rate of heat transfer. Figure 3 also shows a temperature versus time plot, but for both blocks on the third day of testing. Again, the data for the test block shows a linear trend thus allowing for a suitable approximation for the net rate of heat transfer. [The data and plots for all four testing days are given in Appendix II]

Table 1, below, shows the calculations of the net rate of heat transfer for the test block over the four days of testing. These values were obtained using equation (7) and the slope of the linear trend lines.

Table 1

	Day 1: Feb 21	Day 2: Feb 28	Day3: Mar 01	Day 4: Mar 04
Rate of heat transfer (watts)	1.150	0.715	0.999	0.285

An estimate of the collector efficiency was calculated using equation (7), the solar insulation data provided by NREL, and the calculated heat transfer rates in Table 1. The efficiencies calculated for each day of testing are found in Table 2, along with overall efficiency.

Table 2

	Day 1: Feb 21	Day 2: Feb 28	Day 3: Mar 01	Day 4: Mar 04
η	9.03E-03	5.76E-03	7.37E-03	2.12E-03
η(overall average)	6.07E-03			

Discussion

The objective of the project was to design a solar collector as a viable source of thermal energy, with an emphasis on low capital cost. It was to be designed such that the solar radiation incident on the collector was concentrated at a focal point where it heated an absorber and allowed for thermal energy to be measured.

There is a large spread of values for calculated heat transfer rates, as shown by the data in Table 1. The calculations showed, for day one, an estimate of 1.15 watts; day two, 0.715 watts; day three, 0.999 watts; and day four, 0.285. The data of day four, 0.285 watts, biases the data considerably and was neglected as an outlier in a secondary calculation. When the data for day four was neglected, the estimated heat transfer rate was found to be (0.955 ± 0.645) watts, which was a slight improvement. Although neglecting the data from day four produced slightly better results, the uncertainty was still considerably large; it was found to be 67.5%. These uncertainty calculations were computed assuming a 90% confidence interval on a t-distribution. With this in mind, an increase in the confidence interval to 95% yielded a heat transfer rate of (0.955 ± 0.951) watts. This interval, over which the true heat transfer rate lies, covered a large span of values, which did not include the value from day four, thus verifying the assumption that the data of day four can be considered an outlier and neglected.

Data in Table 2 depicts collector efficiencies that were estimated over the four days of testing. These efficiencies were computed using equation (9). The average efficiency over the four days of testing was estimated to be 0.607%. These calculations are only good estimates of the true collector efficiency since the solar insulation data, provided by NREL, is a 50-year average for a 1-axis flat plate collector through the months of February and March. The data for a flat plate collector was used in the calculations due to the fact that the data for concentrating collectors is for direct beam solar radiation. The designed collector has a large aperture, thus the radiation incident includes both direct beam and ambient radiation which created a dilemma as to which data to utilize in the calculations. Therefore, that data for a flat plate collector was used as a suitable estimate of the total insulation incident during testing.

Conclusion

Through all of the experimental and empirical analysis, important information was obtained despite being flawed with uncertainty. From this a better understanding of a low cost concentrating solar collector was attained, as well as some data points for qualification. The concept was demonstrated to be feasible. It is still to be tested for durability, life span, and the output that would be achieved from year-round use (i.e. testing in all four seasons). This also may have skewed the results as they would have been much higher in the summer and may have a greater output with the reflection from snowfall in the winter. Also, there is a high amount of uncertainty due to the small number of data points taken from the testing. Also, due to the relatively inexpensive cost of the kilowatt hour, the return on investment is not ideal.

The key findings from this study were the actual temperature that can be achieved from a concentrating solar collector. In addition, the concept was proven to not only be feasible from a theoretical and academic standpoint, but also highly feasible for the use by an average person. Some examples included, but are not limited to: use as a solar cooker outdoors rather than using a conventional stove, therefore saving gas or electricity; a heat source for a heat engine that converts solar energy into electricity. Lastly, this can be used to heat water as opposed to the traditional water heater.

In the future, in order to improve upon the design, it is recommended that multiple data points are taken, as well as year round data. Also, different shapes and positions should be attempted to truly obtain the maximum output. In addition, more analysis should be done on the material selection to determine if this is a major factor and then used in the construction of a more efficient concentrated collector available for home use.

References

[1] Cengel, Y., Boles, M., 2008, Thermodynamics An Engineering Approach Sixth Edition, McGraw Hill, New York, NY., pps. 2, 70-74, 93-95, Chap. 2

[2] Incropera, F., DeWitt, D., 1996, Fundamentals of Heat and Mass Transfer Fourth Edition, John Wiley & Sons Inc., New York, NY, pp. 827

[3] National Renewable Energy Laboratory, "Solar Radiation Data Manual for Flat-Place and Concentrating Collectors," http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/93037.txt

Appendix I

Design Concept

First, calculations were done in order to create an ideal size for a desirable amount of output. The parabola is to have a height of one foot and diameter of two feet after construction. There will be four radii used to calculate the proper length and width of "wedges" that will be used in making the parabola. The four radii to be used are inner, small, large, and outer. This will give accuracy to the shape. The inner radius of 4' will be removed to allow for the collector to be placed at the focus. The small radius comes to 8", the large radius is 12", and last but not least, the outer radius of 18". The template is traced directly onto the sheet metal. The template will be removed and the sheet metal will be cut with a pair of sheers.

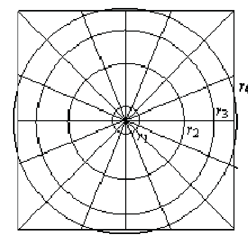


Figure 1 Blueprint of sheet metal still intact.

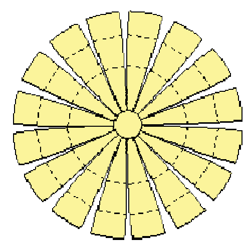


Figure 2 Sheet metal beginning to take shape

The same template used for the sheet metal can be used for the reflective Mylar, which is a highly reflective "mirror" paper often used in green houses. The pattern can be cut and then the adhesive side applied very carefully to the metal. The difference being, these pieces will overlap to ensure homogeneous reflectivity.

Collector Design Calculations

Variables:

H: height of paraboloid   D: diameter of paraboloid   R: radius of paraboloid

a: coefficient of growth   f: focus of paraboloid

Equations

$H = a(x^2 + y^2)$, $\quad R^2 = x^2 + y^2 \quad D = 2\sqrt{\frac{H}{a}}$, $\quad R = \frac{D}{2} \quad f = \frac{1}{4a}$

Constraints: (based upon general assumptions of maximum collector size for this application)

$$H_{max} = 30.48\ cm, \qquad approx.\ 12\ in.$$
$$D_{max} = 60.96\ cm, \qquad approx.\ 24\ in.$$

Calculations based upon constraints:

$$a = \frac{4H}{D^2} = \frac{4(30.48\ cm)}{(60.96\ cm)^2} = 0.032808\ cm^{-1}$$

$$f = \frac{1}{4a} = \frac{1}{4(0.032808\ cm^{-1})} = 7.62\ cm$$

Thus the general equation for the paraboloid is given by:

$$H = 0.032808\ cm^{-1}[(x^2 + y^2)\ cm^2]$$

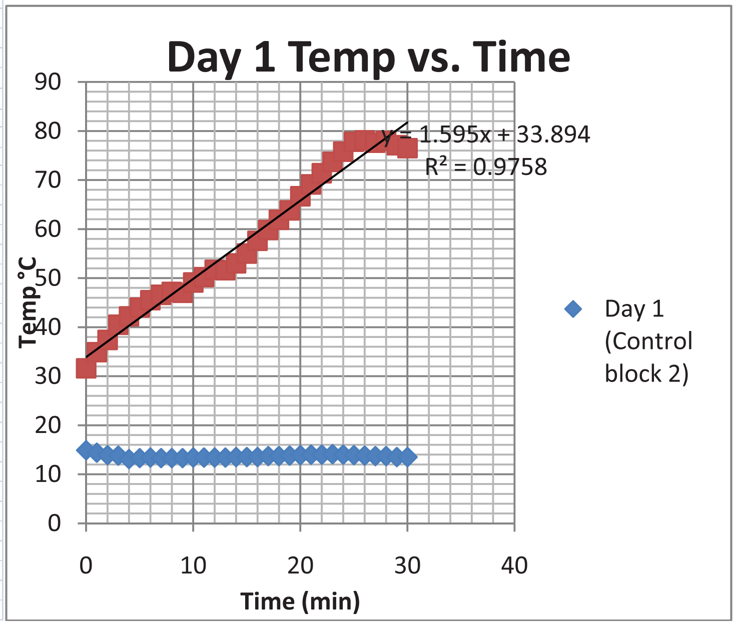
Appendix II

Testing Day 1: Data and Plot

time (min)	T1 (control) °C	T2 (test) °C
0	14.9	31.6
1	14.4	34.9
2	13.9	37.4
3	13.8	40.5
4	13.1	42.2
5	13.3	44
6	13.4	45.5
7	13.3	46.6
8	13.3	47.2
9	13.3	47
10	13.4	49.1
11	13.4	50.2
12	13.4	51.7
13	13.4	51.6
14	13.5	53
15	13.5	55
16	13.5	57.6
17	13.7	59.8
18	13.7	61.9
19	13.8	63.8
20	13.9	66.7
21	14	69.1
22	14	71.4
23	14.1	73.7
24	14	75.8
25	13.9	77.8
26	13.8	78.1
27	13.7	77.6
28	13.7	78
29	13.5	77.1
30	13.5	76.5

Colorado Springs
104.72 Elev: 6201
21, 12:54 pm MST

Fair		
	Humidity:	27%
	Speed:	S 8 MPH
40°F (4°C)	**Barometer**	30.23" (1027.9 mb)
	Dewpoint:	8°F (-13°C)
	Wind Chill:	35°F (2°C)
	Visibility:	10.00 mi.

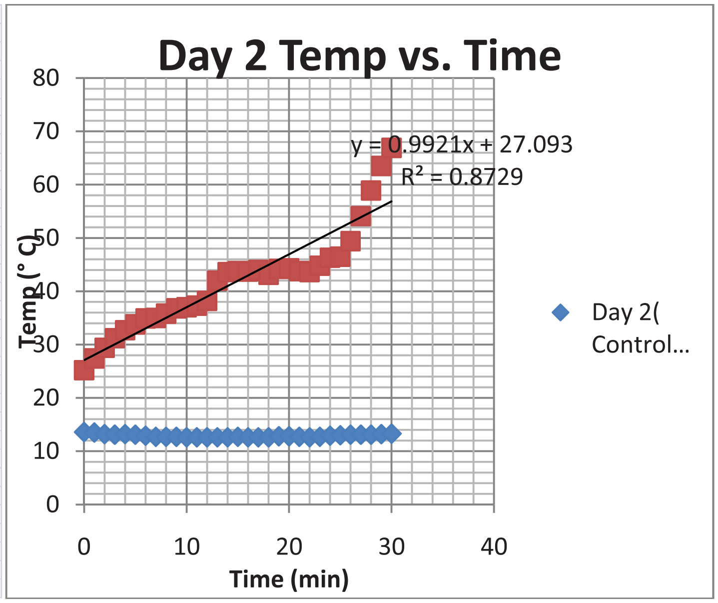


Testing Day 2: Data and Plot

time (min)	T1 (control) ° C	T2 (test) ° C
0	13.6	25.2
1	13.5	27.4
2	13.2	29.4
3	13.1	31.2
4	13.2	32.7
5	13.1	33.8
6	12.9	34.9
7	12.7	35
8	12.7	35.8
9	12.7	36.8
10	12.6	37
11	12.6	37.3
12	12.6	38.2
13	12.6	42
14	12.6	43.6
15	12.7	43.8
16	12.6	43.7
17	12.6	44
18	12.6	43.1
19	12.8	44.2
20	12.8	44.3
21	12.7	43.8
22	12.6	43.6
23	12.7	44.8
24	12.9	46.3
25	13	46.5
26	13.1	49.4
27	13.1	54.1
28	13.1	58.9
29	13.2	63.5
30	13.3	66.9

Colorado Springs
104.72 Elev: 6201
12:54 pm MST

Fair	Humidity:	19%
	Speed:	S 13 G 20 MPH
41°F	Barometer:	1033.5 mb)1033.5 mb)
(5°C)	Dewpoint:	2°F (-17°C)
	Wind Chill:	34°F (1°C)
	Visibility:	10.00 mi.

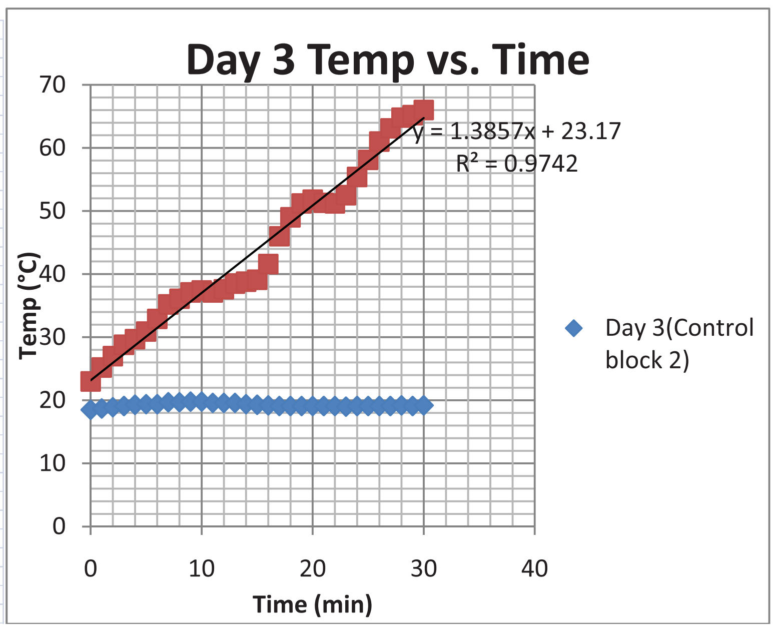


Testing Day 3: Data and Plot

time (min)	T1 (control) ° C	T2 (test) ° C
0	18.5	23
1	18.7	25.2
2	18.9	27
3	19.1	28.8
4	19.3	29.7
5	19.4	30.9
6	19.4	32.9
7	19.7	35.2
8	19.7	36.1
9	19.8	37.1
10	19.8	37.4
11	19.6	37.1
12	19.6	37.6
13	19.6	38.5
14	19.4	38.8
15	19.3	39.1
16	19.2	41.6
17	19.1	46
18	19.1	49
19	19.1	51.2
20	19.1	51.8
21	19.1	51.3
22	19.1	51.2
23	19	52.5
24	19.1	55.4
25	19.1	58.1
26	19.1	61
27	19.1	63.1
28	19.2	64.8
29	19.1	65.2
30	19.2	66

Colorado Springs
104.72 Elev: 6201
12:54 pm MST

Fair	Humidity:	15%
	Speed:	S 6 MPH
40°F	Barometer:	30.23" (1026.9 mb)
(4°C)	Dewpoint:	3°F (16°C)
	Wind Chill:	45°F (7°C)
	Visibility:	10.00 mi.



Testing Day 4: Data and Plot

Time (min)	T1 (control) °C	T2 (test) °C	Colorado Springs		
0	20.8	24.4	Lat: 38.83 Lon: -104.72 Elev: 6201		
1	20.9	27.3	Last Update on Mar 4, 3:54 pm MST		
2	21.1	29.8			
3	21.3	32.4	Fair and	**Humidity:**	10%
4	21.4	34.4	Breezy	**Wind Speed**	SW 25 G 32 MPH
5	21.6	35.8	67°F	**Barometer:**	29.81" (1004.0 mb)
6	21.7	36.9	(19°C)	**Dewpoint:**	8°F (-13°C)
7	21.8	38.6		**Visibility:**	10.00 mi
8	21.8	38.8			
9	21.8	38.5			
10	21.9	39.3			
11	21.9	39.2			
12	21.9	38.6			
13	22.1	39.5			
14	22.1	40			
15	22.1	41.5			
16	22.2	43.4			
17	22.3	45.1			
18	22.3	44.1			
19	22.2	43.3			
20	22.2	42.7			
21	22.3	43.2			
22	22.4	44.4			
23	22.2	44.8			
24	22.2	43.7			
25	22.2	42.7			
26	22.2	41.6			
27	22.2	40.8			
28	22.2	38.4			
29	22.1	38.5			
30	22.1	39.3