Solar Household Energy, Inc.
Solar Cooking for Human Development and Environmental Relief

SHE Technical Report no. TR-36

Standard Power Test Report - Haines Model 2 Solar Cooker

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Introduction

Solar Household Energy, Inc. (SHE) leverages the power of solar cooking to improve social, economic and environmental conditions in sun-rich areas around the world. Since 1998, Solar Household Energy has conducted research to develop and improve solar cookers, including the "HotPot" developed by SHE. SHE has also partnered with other non-governmental organizations, entrepreneurs and public sector entities to distribute solar cookers in many developing countries within a context of marketing, training, monitoring and evaluation activities [1].

In order to provide a fair and reproducible basis for evaluating the performance of solar cookers, an international standard has been developed, ISO-19867-1, "Clean cookstoves and clean cooking solutions -- harmonized laboratory test protocols" [2]. This standard provides protocols for emissions, power, safety and durability of all types of small cookstoves, including solar cookers. Development of this standard began in 2013, and included participants from SHE, Solar Cookers International (SCI), and Dr. Paul Funk. Dr. Funk had previously developed a standard power protocol for solar cookers which was published by the American Society for Agricultural and Biological Engineers, as ASAE S.580.1 [3]. That protocol is now included within the ISO standard.

Test item description

The test item is a Haines Solar Cooker, Model 2. This cooker was developed recently by Roger Haines of Del Mar, CA USA [4]. It consists of a reflector made of MPET (metallized polyethylene terephthalate), two clear polycarbonate sheets, and a black steel pot with a glass lid and silicone seal. This product represents the latest in a series of improved solar cookers created by Roger Haines, and it is intended to provide ample power within a very low-cost and durable package that is light in weight and affordable. Figure 1 shows a view of the cooker as seen from the top. The reflector is assembled from two sheets that link together using snaps. The reflector's shape can be adjusted to optimize performance based on the average altitude of the sun at the location where it is used. The width of the reflector as shown in the figure is 31 inches (0.787 m).

For this test, photographs were analyzed by the program ImageJ to measure the reflector intercept area, with a result of 0.50 square meter. The procedure for making this measurement is described in SHE TR-10 [5].

Figure 1. Haines Solar Cooker Model 2, top view.

Weight of the components is as follows:

Item	Weight in grams
MPET reflector	413
Polycarbonate cone	168
Polycarbonate cylinder	114
Steel pot (capacity 4 liters)	367
Glass lid with steam vent	586
Carrying bag	25
Total	1673 (3.7 lbs)

Test instrumentation

A set of commercial off-the-shelf products was assembled to provide a system for solar cooker power measurements. This system is described in SHE TR-09.1 [6].

Test setup

Solar cooker power tests must be conducted on days that have a very clear sky, in a location free from shadows during the test period. The wind speed must be low. The test protocol includes constraints on these environmental variables and data that does not comply with the protocol will be excluded.

The tests were conducted at the SHE test location, 39.0476 deg. N, -77.1413 deg. W, elevation 122 meters. The boiling point of water at this altitude is 99.59 deg. C.

Figure 2 shows the experimental setup for a test with the test item in place. The test item is placed on a leveled card table. The instruments are enclosed in a “Stevenson box” with sensors on top; a small solar panel is used to power the instruments.

Figure 2. Test setup.

Figure 3 shows a closeup of the top of the Stevenson box showing the sensors. In these tests, an anemometer was used to measure wind speed at the level of the solar cooker. Three pyranometers are visible: an Apogee SP-212 amplified pyranometer on its leveled base, a Brooks pyranometer next to it, and another Brooks pyranometer mounted on a tilted arm to measure direct normal irradiance. These instruments are described further in the technical report SHE TR-09.1 [6].

Figure 3. Closeup of test setup showing sensors.

Test procedures

The protocol calls for a load in the cooking pot of 7 times the intercept area in liters, or 3.50 liters of water in this case. The cooker reflector was turned toward the Sun once per hour. The following table shows additional information about the environmental conditions during each day of testing. All times are Eastern Daylight Time (EDT). The protocol permits measurements between 1100 and 1500 EDT (1000-1400 solar time).

	Test 1	**Test 2**	**Test 3**
Date of test	July 9, 2018	July 10, 2018	July 14, 2018
Local solar noon (EDT)	13:14	13:14	13:14
Start time (EDT)	11:54	11:14	10:58
End time (EDT)	15:00	15:00	15:00
Average relative humidity %	30	42	37

Other details regarding the data acquisition procedures using the SHE test system are provided in SHE technical report TR-16.2 [7].

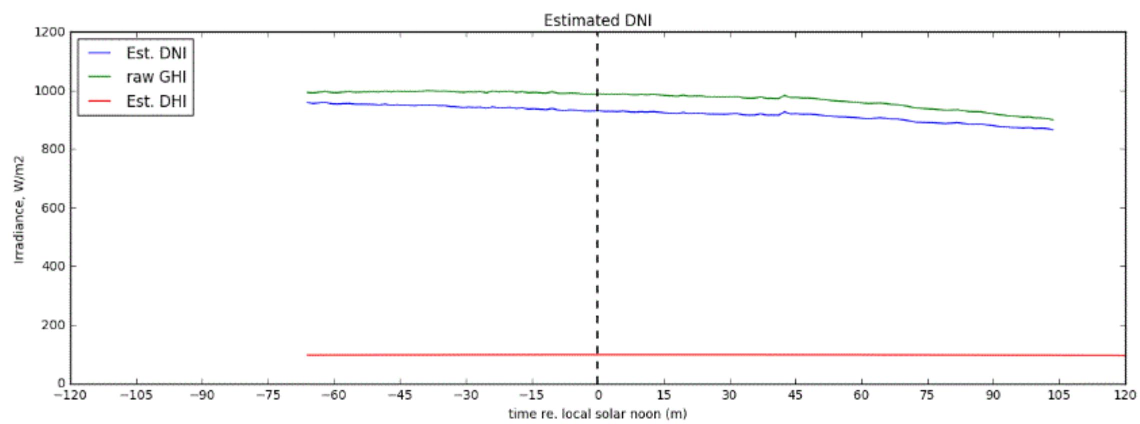
Intermediate test results

In the ISO/ASAE protocol, solar cooker power is calculated based on a time record of solar irradiance and thermocouple temperatures. The measurements require values of wind speed to be less than 2.5 m/s in a 10-minute interval. The following intermediate results for the tests on each day are provided for validation purposes, although they are not directly pertinent to the final test result, which is a single value of the test item's cooking power in Watts.

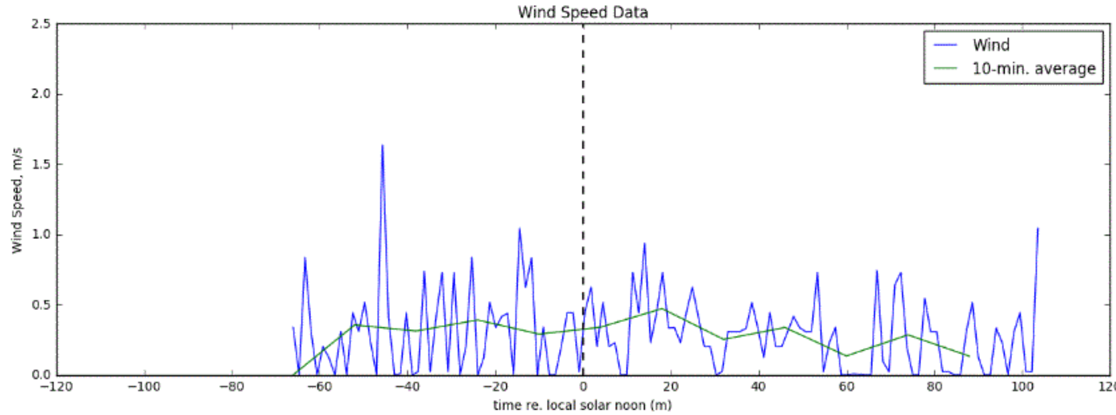
The protocol calls for measurements of solar radiation using a pyranometer directed toward the Sun. For these measurements, a pyranometer was pointed at zenith to measure Global Horizontal Irradiance (GHI), and a cosine adjustment for the pyranometer directivity was applied to the data based on the altitude of the Sun at the time of the measurement. In addition, the (estimated) diffuse component of the irradiance (DHI) was subtracted to give an estimate of the Direct Normal Irradiance (DNI), which is the radiation that is most relevant to concentrating solar reflectors such as the test item. Reference [8] provides more details about these types of solar measurements.

Test 1: July 9, 2018

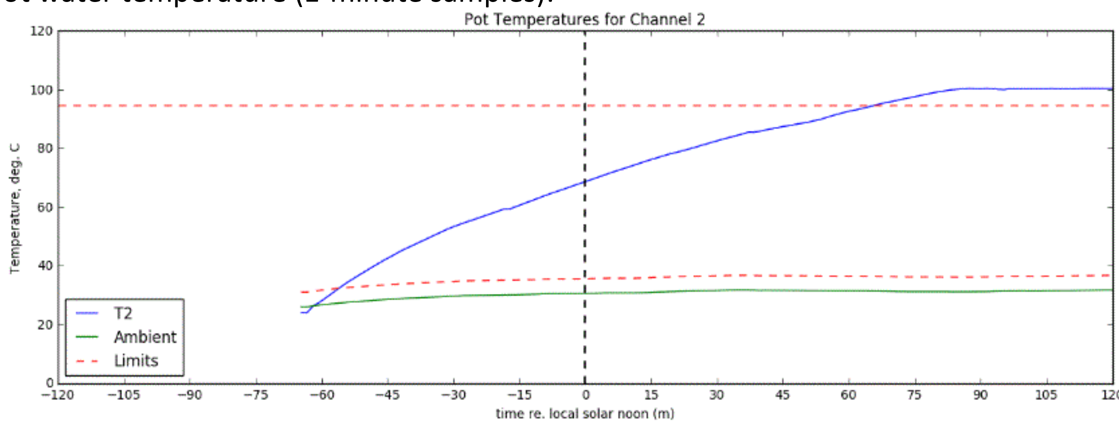
Solar Irradiance data:



Wind speed:
(includes 1-minute samples plus 10-minute averages).



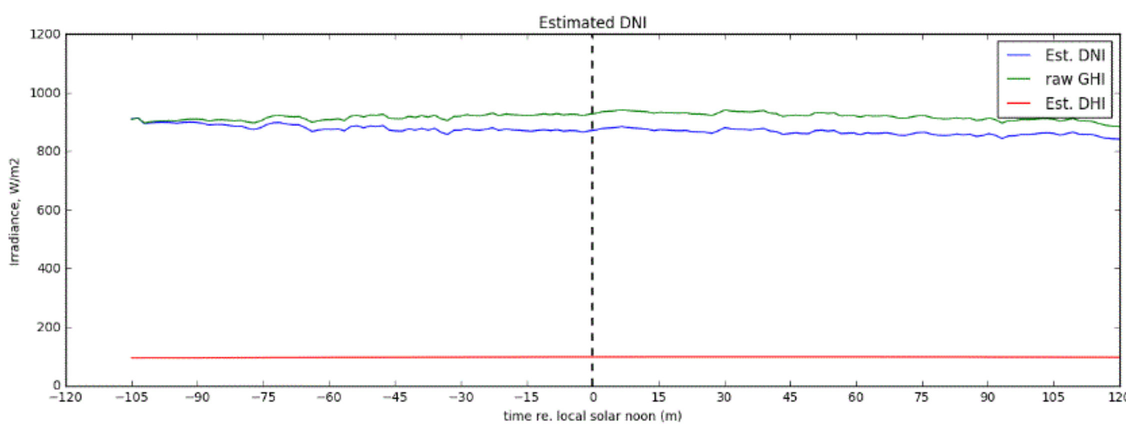
Pot water temperature (1-minute samples):



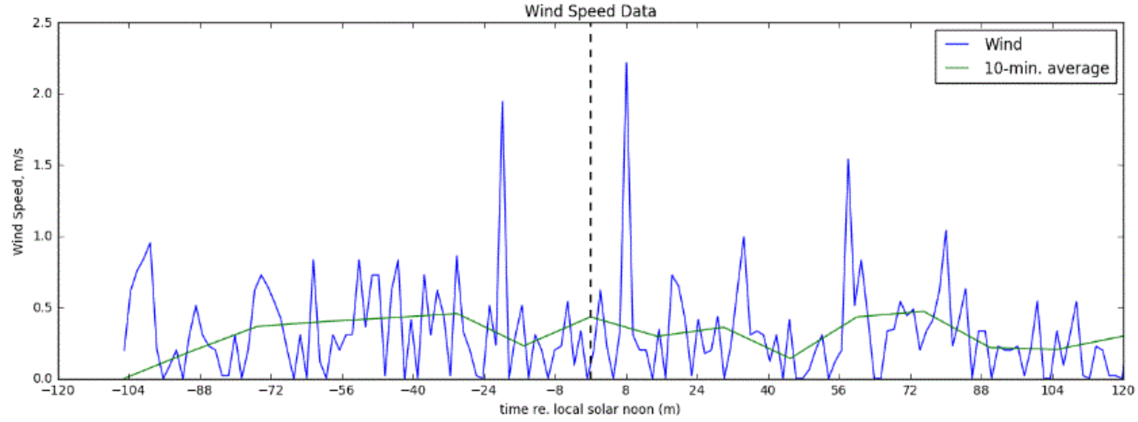
Red dashed lines on the plot indicate the limits within which standard measurements are accepted. Note: only one channel of temperature data was available for this test.

Test 2: July 10, 2018

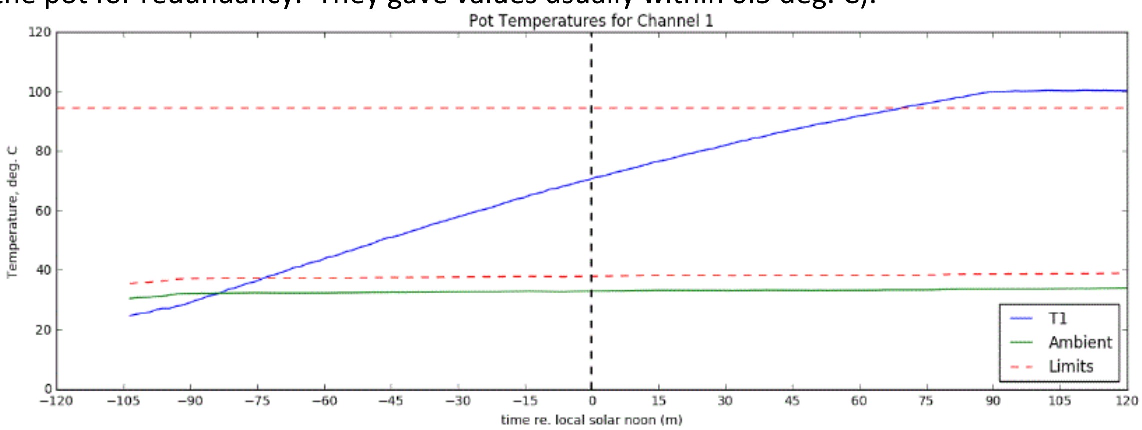
Solar Irradiance:



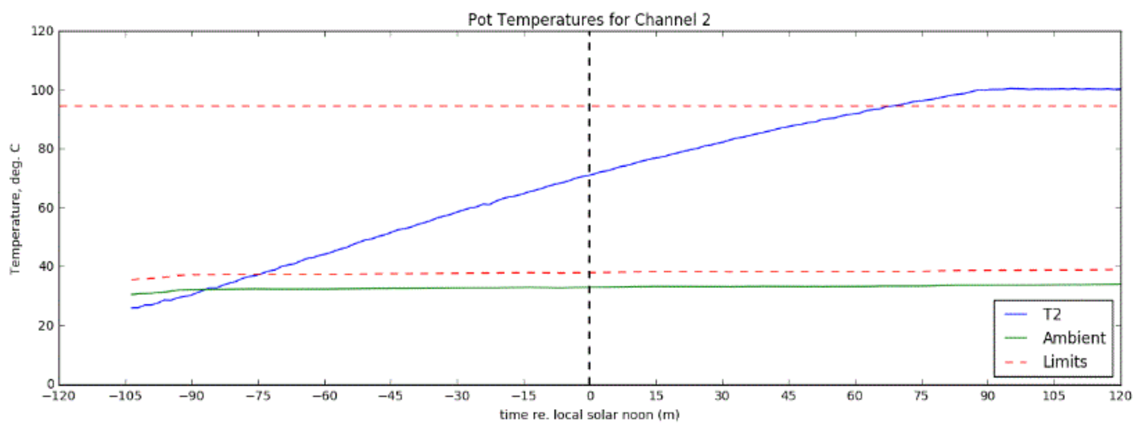
Wind speed:
(includes 1-minute samples plus 10-minute averages).



Pot water temperature, channel 1:
(For this test and the subsequent test, two thermocouples were placed in the water in the pot for redundancy. They gave values usually within 0.5 deg. C).

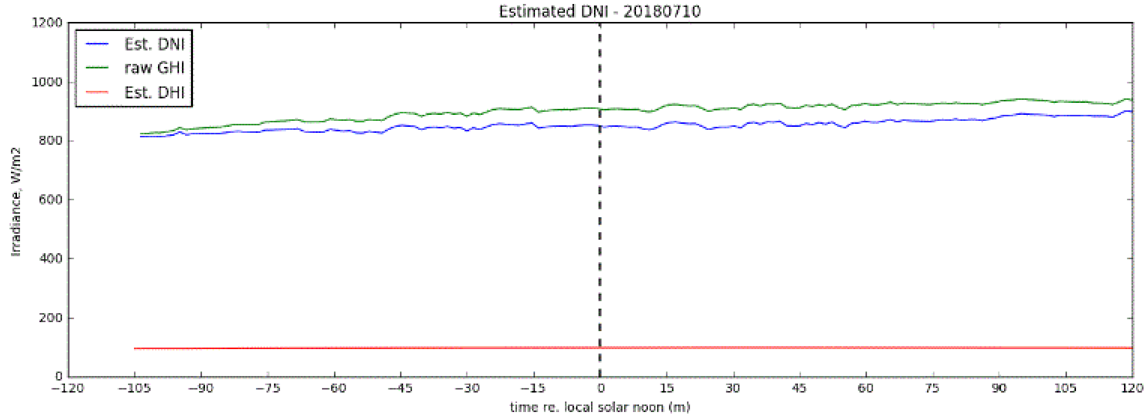


Pot water temperature, channel 2:

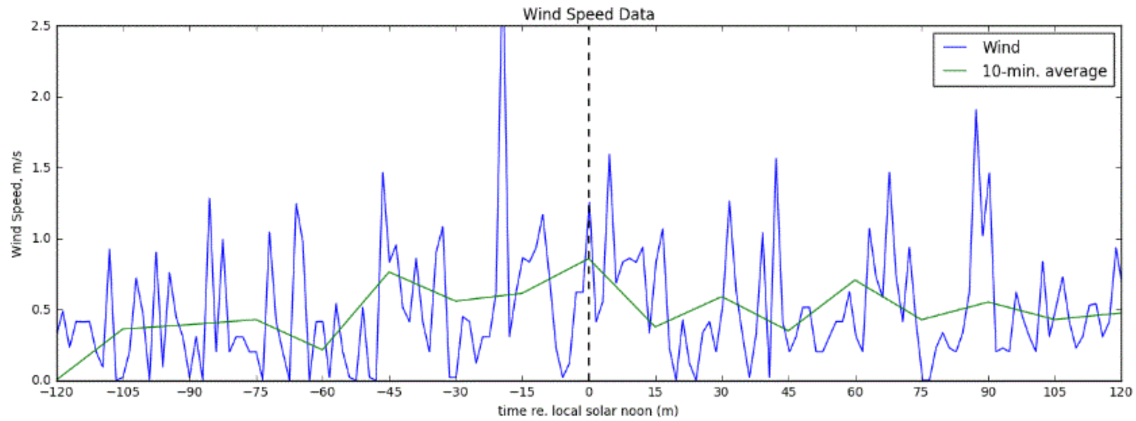


Test 3: July 14, 2018

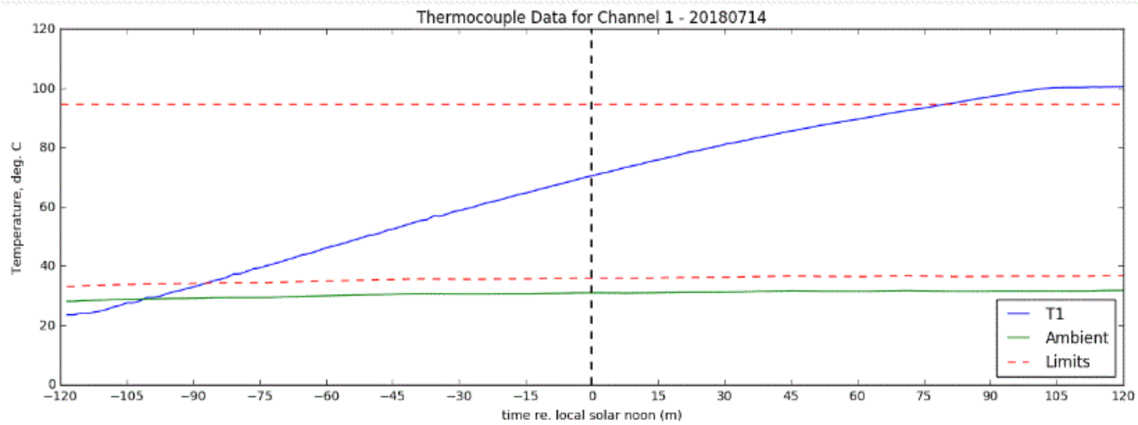
Solar Irradiance:



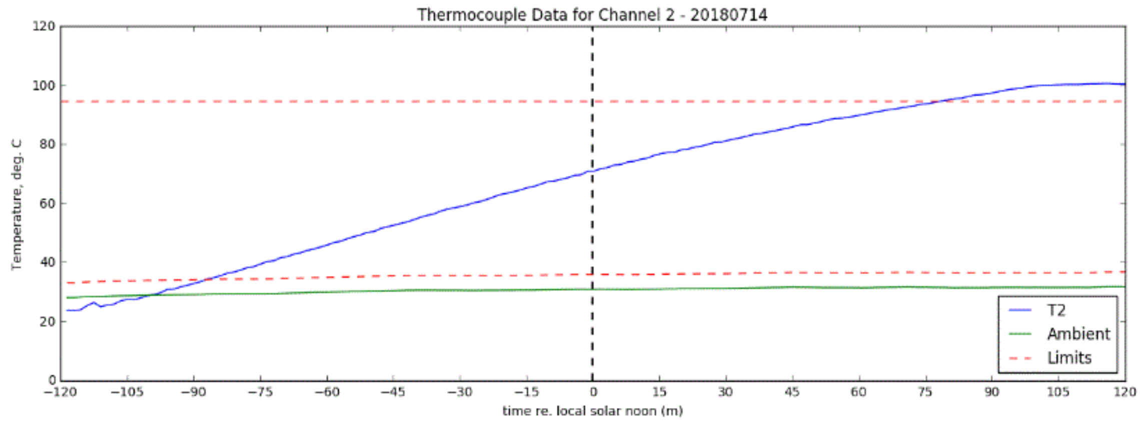
Wind speed:
(includes 1-minute samples plus 10-minute averages).



Pot water temperature, channel 1:



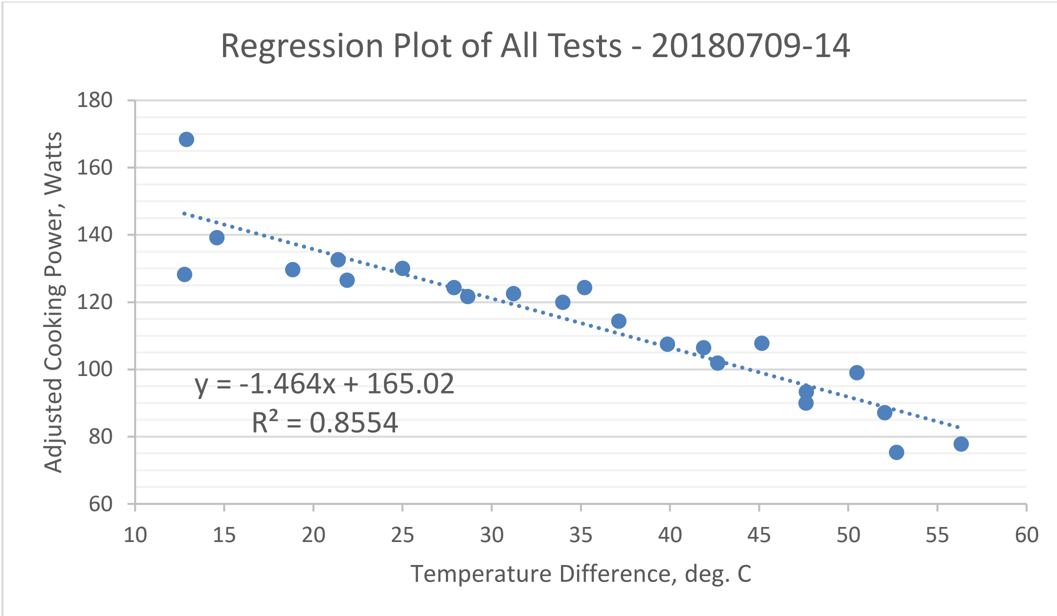
Pot water temperature, channel 2:



Regression analysis

All measurements that met the ISO/ASAE protocol's validity criteria were combined and a plot was drawn of the calculated cooker power vs. temperature gain for each 10-minute sample, as prescribed in the protocol. A total of 23 samples was obtained from the three tests. (This is less than the prescribed 30 samples, since the test item reached the limiting temperature of 95 degrees before sufficient samples could be acquired.) Two thermocouples were placed in the pot in two of the tests; both thermocouples yielded very similar results.

A lease-squares linear regression line was fitted to these data; the resulting plot is shown below. The data show the typical sloping line, which indicates that heating power decreases at higher temperatures, due to increased heat losses.



The protocol requires cooking power to be defined at a 50-degree C temperature difference (pot temperature minus ambient). By inserting the slope and intercept values shown on the plot, the power at 50 deg. C temperature difference was found to be **92 Watts**. This is the standard cooking power rating for the test item. The R^2 variance was 0.8554, which is higher than the minimum required value of 0.75.

The protocol requires power measurements to be adjusted for a solar irradiance of 700 W/m^2. During these particular tests, the Direct Normal Irradiance values were generally higher than this (about 850 W/m^2), so the actual cooking power was about 20% higher than the standard power value, i.e. about 110 Watts.

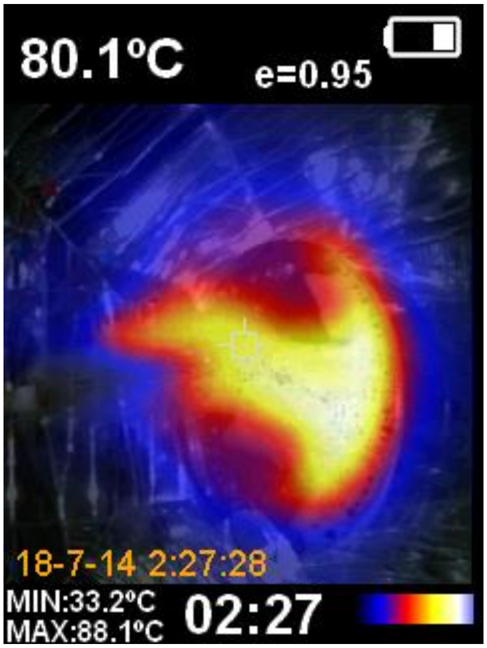
Additional observations

Although efficiency is not a required output of the ISO/ASBE protocol, it is easy to calculate as the ratio of standard power divided by the input power, which in this case is 350 Watts (intercept area in m^2 times 700 W/m^2). The energy efficiency comes out to about 26%. This is quite high for a panel type solar cooker in the author's experience. The explanation may have to do with the fact that the pot is enclosed within two polycarbonate sheets. Although they are clear in visible light, they are quite opaque at the longwave infrared radiation that is emitted by the heated pot. Therefore, the design provides an effective "greenhouse".

The pot used in this solar cooker also has a silicone seal on the lid, which is effective at reducing heat loss due to convection. This is usually the main weakness of low-powered solar cookers, so it is important to provide a tight seal on the pot (along with a small steam vent to prevent pressure buildup).

Still, observations revealed a source of heat loss. The figure below shows that the polycarbonate cone cover touched the rim of the pot, which allowed thermal conduction to the outside. When the pot reached the boiling point, steam escaping from the lid edge condensed on the inside of the cone, which lowers efficiency by scattering some of the sunlight away from the pot. Also, it allows outside air to remove heat from the cone.

Further evidence of conduction outside the conical cover is shown in this image taken with an infrared camera [9] (the orientation is from the side, so the front of the reflector is to the right):



In this image, the escaping steam and hot air from the pot transfers heat to the outside of the conical cover (the bright yellow areas). The rest of the image is dark, because infrared radiation does not pass through the opaque polycarbonate.

These observations suggest that for increased efficiency, it would be helpful to ensure that the conical cover does not touch or come too close to the pot, and to set the pot lid so that its steam vent is in the rear part of the reflector.

References

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2. Clean cookstoves and clean cooking solutions – Harmonized laboratory test protocols – Part 1: Standard test sequence for emissions and performance, safety and durability. Draft International Standard ISO/DIS 19867-1 (2017). https://www.iso.org/standard/66519.html

3. "Testing and Reporting Solar Cooker Performance", American Society of Agricultural and Biological Engineers, ASAE S580.1, Nov. 2013. (Open source: available from http://solarcooking.org/asae_test_std.pdf).

4. Haines Solar Cookers, http://www.hainessolarcookers.com/

5. Arveson, P., "Procedure for Determination of the Intercept Area of a Solar Cooker", Solar Household Energy Technical Report TR-10, June 7, 2017. http://www.she-inc.org/wp-content/uploads/2018/04/TR-10-Procedure-for-Determination-of-the-Intercept-Area-of-a-Solar-Cooker.pdf

6. Arveson, P., "A system for standard power measurements of solar cookers based on commercial off-the-shelf instruments", Solar Household Energy Technical Report TR-09.1, Apr. 26, 2018. http://www.she-inc.org/wp-content/uploads/2018/05/TR-09-A-system-for-standard-power-measurements-of-solar-cookers.pdf [earlier version]

7. Arveson, P., "Instructions for conducting solar cooker power tests using commercial instruments", Solar Household Energy Technical Report TR-16.2, May 2018. http://www.she-inc.org/wp-content/uploads/2018/05/TR-16.2-Instructions-for-conducting-solar-cooker-power-tests-using-comme....pdf

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9. Arveson, P., "Infrared imagery of HotPot and Haines Dutch Oven", Solar Household Energy Technical Report TR-28, Sept. 6, 2017. http://www.she-inc.org/wp-content/uploads/2018/05/TR-28_Infrared_Imagery_of_HotPot_and_Haines_Dutch_Oven.pdf