Temperature Measurements of the "HotPot": A Solar Cooker

Paul Arveson* and Bruce Joseph**

*Solar Household Energy
** Tucson Citizens for Solar

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In order to evaluate the performance of any cookstove, the most basic measurement is of its internal temperature vs. time while being heated. From a record of these temperatures vs. time, a cooker's heating power and other parameters may be inferred.

It is convenient (although not absolutely necessary) to obtain a time series of uniformly-spaced temperature measurements using an automated data logger connected to a thermometer (or temperature sensor) inserted in the food or liquid to be cooked.

In the common case of food being cooked in a pot, this requires a sensor with a wire lead to connect the sensor to the data logger. If the pot is covered with a lid, the thickness of the wire can produce an air gap when it passes over the rim of the pot. This air gap can increase heat loss significantly and thus alter the cookstove performance measurements.

One way to reduce this problem is to create a flexible seal around the lid that prevents excessive hot air from escaping. However, the seal cannot be made airtight, because that would cause pressure to build in the pot; this is undesirable except for pressure cookers. A limited amount of air exchange will generally be necessary in order to keep the pressure balanced; this will also cause some heat loss. The required small air gap may be used by the sensor wire.

This method was used in some heating experiments with the "HotPot" solar cooker. This cooker has a black enameled steel pot surrounded by a glass liner and a glass lid. It comes in 5-liter and 3-liter sizes. The pot has an outer glass liner, which serves to contain hot air around the pot (the "greenhouse"). The pot is surrounded by a series of polished anodized aluminum panels, called the "Morningstar" reflector. The pot components fit together as shown:

The experiments we will describe led to some lessons learned that may be extended to other designs of cookstoves that are intended to heat foods that are cooked in a pot.

Heating Experiments – Series 1

The first series of tests ("Series 1") were conducted in the summer of 2012. They were done in two locations: Tucson, AZ and Rockville, MD. The Tucson data were acquired by a local solar cooking expert, Bruce Joseph. This location not only has the advantage of frequent clear skies, but also it is located near one of the nation's official solar energy measurement centers (at the University of Arizona, Tucson), which provides daily records of solar irradiance and other data from precision instruments (please see annex below).

Instrumentation for Series 1

Temperature measurements were recorded using a Lascar Model EL-USB-TC data logger and thermocouple probe. These devices have a thin (2 mm) wire with high-temperature insulation connected to a small battery-powered data logger. The K-type thermocouple has a temperature range of -200 to +1350 deg. C. The instrument is accurate to 1 degree C. and allows up to 32,510 readings to be stored. The time interval is programmable; we set it to 30 seconds between readings. When measurements are complete, the data logger is plugged into the USB port of a computer and the data are downloaded to a text file for plotting. The current price is $85 ea. We purchased two probes, one to measure the temperature in the center of the pot and one to measure the outside ambient air temperature in the shade. This data logger, and the included software, proved to be easy to learn and use.

Wind speed, atmospheric pressure and humidity were measured with a rooftop remote-reading Acu-rite weather station.

Solar radiation was measured with a "Mastech" or "Dr. Meter" digital illuminance/light meter, Model LX1330B. This low-cost instrument (about $30) uses a silicon photodiode sensor, and has an accuracy of +/- 5% at high brightness levels. (In some tests a neutral gray filter with a known transmittance was placed over the sensor to allow higher levels of illuminance to be measured). The instrument reports illuminance in lux, which can be converted to irradiance values in watts/sq. m. using luminous efficacy data compiled by Perez (1989). The power P in watts (W) is equal to the illuminance E_v in lux (lx) times the surface area A in square meters (m^2), divided by the luminous efficacy η in lumens per watt (lm/W): $P_{(W)} = E_{v(lx)} \times A_{(m^2)} / \eta_{(lm/W)}$. (The clear-sky efficacy value is about 110).

In addition to the local solar irradiance measurements, the Tucson location also used official NREL-certified data from the nearby Observed Atmospheric and Solar Information System (OASIS) at the University of Arizona in Tucson. Their daily records

are posted on the Internet (see references). Solar irradiance data pertaining to our measurements are included in the Appendix.

Series 1 Experimental Setup

Figure 1 shows the typical experimental setup for the HotPot measurements in Tucson. The weather station is located to the right. A Lascar thermocouple probe was immersed in 1 liter of room temperature water, with the 1/8-inch wire lead passing to the data logger, which was kept in the shade behind the reflector. To reduce heat loss due to the wire across the lid, the edges of the lid were sealed with plastic tape.

Figure 2 below shows an example of three measurements of HotPot heating in Tucson. On three summer days with clear skies, the HotPot temperature was measured over the same time of day; nearby pyranometer data from the University of Arizona lab confirmed that the sky was clear (data are shown in the Appendix). One liter of room-temperature water was heated in the pot.
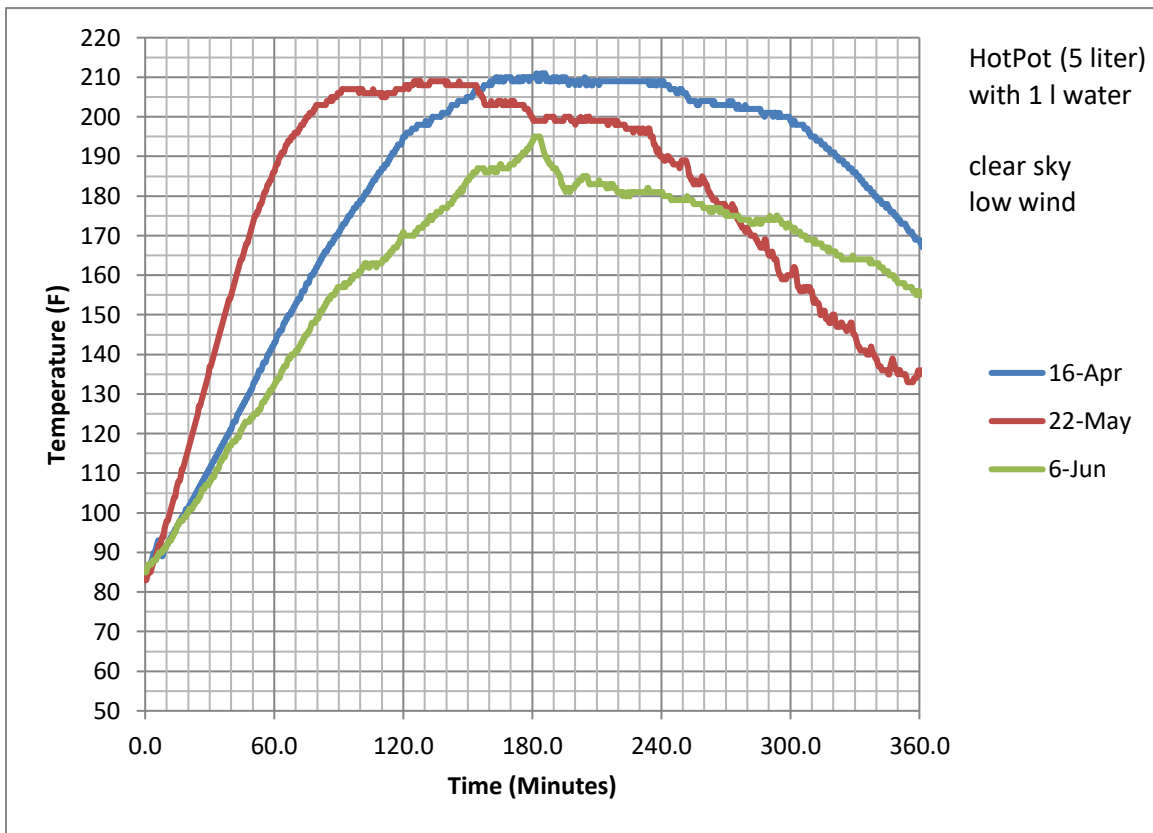
Figure 3. Measurements of HotPot on three days in Tucson.

Clearly these measurements are not repeatable. The measurements show a heating rate that varies by more than a factor of two. Something is causing these data to be non-repeatable. What could it be? We noted that the solar irradiance was nearly the same, as recorded by precision instruments (although there was a slight drop on June 6 due to thin clouds). Wind speed was monitored and was low in all three measurements. There was a slight difference in sun angle for the three dates, but these are not significant for a panel-type cookstove like the HotPot. Positioning of the reflector was kept the same for all tests.

Establishing Repeatability

When making measurements that may be affected by many variables, it is important first to make repeated measurements under what are believed to be the same conditions, and to determine by the results whether in fact repeatability was achieved. If not, this indicates that there are one or more important variables that have not been controlled. Continued careful testing may be necessary before these variables are discovered and controlled (either by eliminating them, keeping them the same in all experiments or finding a way to compensate for their influence).

After exhausting other explanations, we concluded that the cause must have to do with how heat is being lost from the pot.   We noticed that there are slight bends in the pot that prevent a perfectly flat, uniform seal, so that there is a small air gap around the rim. The presence of the temperature sensor wire also contributes to this air gap. Since heat loss by convection is believed to be more significant that that lost by conduction or radiation, we concluded that variations in the air gap in repeated experiments was not controlled. We placed marks on the pot and lid, and made sure to align the lid in the same position on successive tests. After doing this, the measurements became repeatable. This confirms our suspicion that air gaps around the lid represent an important variable that should be controlled.

**Cooling Experiment – Water Load**

Figure 4 below shows another repeatability experiment. In this case, the measurement was done indoors and the same two HotPots were compared side by side. (This experiment measures cooling rather than heating, so it eliminates the cooker reflectors as a possible variable.) One liter of hot water (about 90 deg. C) was poured into each of the two pots; the lid was placed on each and temperatures were recorded with the Lascar thermocouple sensors, while the water was cooling down to nearly room temperature over 2.5 hours. (Note the marks on the HotPot components, which are used to maintain consistent alignment in repeated experiments.)

Temperatures were recorded every 30 seconds with the Lascar data loggers. The raw data from the instruments are plotted below in Figure 5:
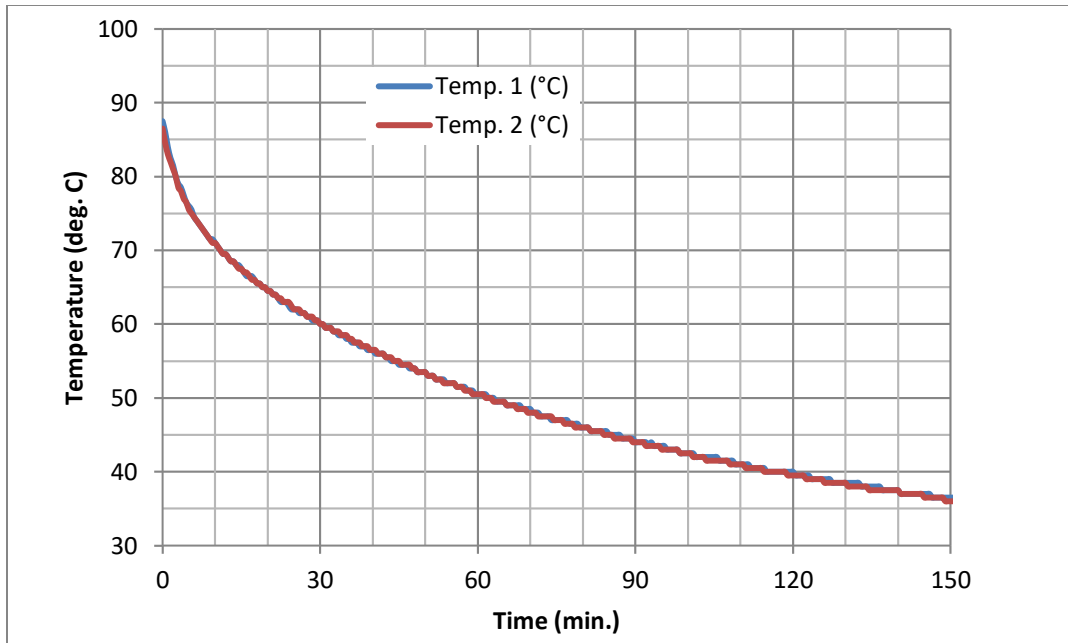
At this scale, the data from the two sensors overlap each other. To examine the degree of repeatability, the following chart shows the **differences** between the two sensors:
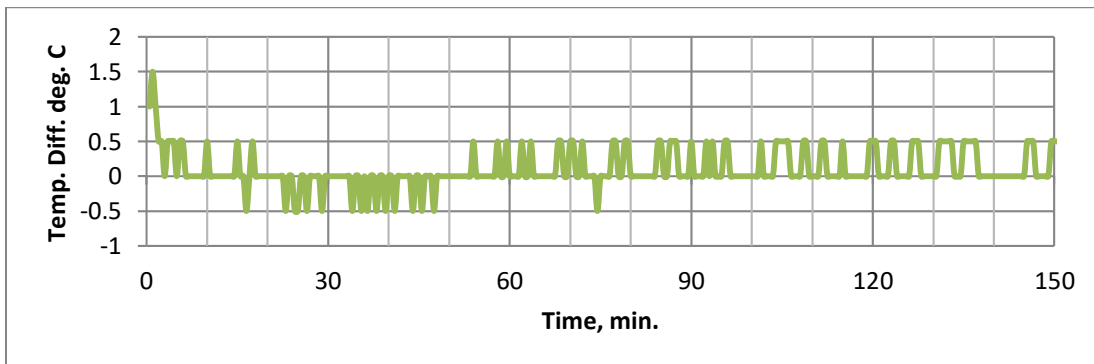
It is evident that after the first few seconds, the two thermometers gave readings that matched within 0.5 deg. C (the resolution of the instruments).

Discussion

Why was repeatability during cooling tighter than that during heating? And why was repeatability better with an oil load than with a water load? The data indicate that some variables were not tightly controlled between the two HotPots. We suspect that the main causes were: (1) slight differences in gaps between the lid and the pot, which affects the amount of heat loss; (2) slight differences in the shape of the reflectors, which affects the amount of heat input; (3) differences in the amount of condensed water on the glass lids, which affects the amount of scattered light. All actual solar

cookers can be expected to have some variations such as these, but further experiments will be conducted to confirm the main cause(s) of this variation.

Future experiments will be necessary to identify the remaining uncontrolled sources of variation, and minimize them. We will try out different types of reflectors, different tilt angles, and different ways to seal the lid and the greenhouse.   Many other questions must be answered in an attempt to optimize performance of this solar cooker.

Finally, it should be cautioned that establishing repeatability does not necessarily establish reproducibility. The latter implies the ability for another experimenter to independently conduct the experiment and obtain nearly the same results. This will require the use of calibrated instrumentation traceable to reference standards, adjustments for different latitudes, altitudes and other factors to be determined by "round robin" experiments.

Conclusions

Instrumentation for measuring and logging illuminance, temperature and wind speed data are now available at low cost from a variety of sources. A full package of basic instruments can be assembled for a few hundred dollars. This means that it is possible for researchers, nonprofit organizations and even hobbyists to conduct heating and cooling experiments that are far more sophisticated than before. All solar cooking researchers are encouraged to gather instrumentation such as is described here and use them to raise the quality and quantity of cookstove performance measurements. No longer do people need to rely on crude bimetallic strip oven thermometers. That is not to say that the low-cost instruments are "professionally" or "scientifically"-calibrated instruments, but they will be a great improvement at a surprisingly low cost.

Heating experiments should be conducted in a careful and meticulous way. Repeatability must be established first, before further tests are conducted. Full documentation of the measurement conditions (including photographs, date and time, ambient temperature data, wind speed data and other variables) should be reported.

The experiments we conducted on the HotPot may be generalized to any cookstove that is intended to heat a pot of water-based foods, such as rice, cassava, stews, *ugali*, polenta, soups etc. For such foods traditionally cooked in pots, it is highly desirable for cooking efficiency that the pot be covered with a lid. Food in solar cookstoves cooks slowly with uniform heat; hence there is no need to stir the pot. However, the lid must not fit too tightly; a small air gap is needed for pressure release.

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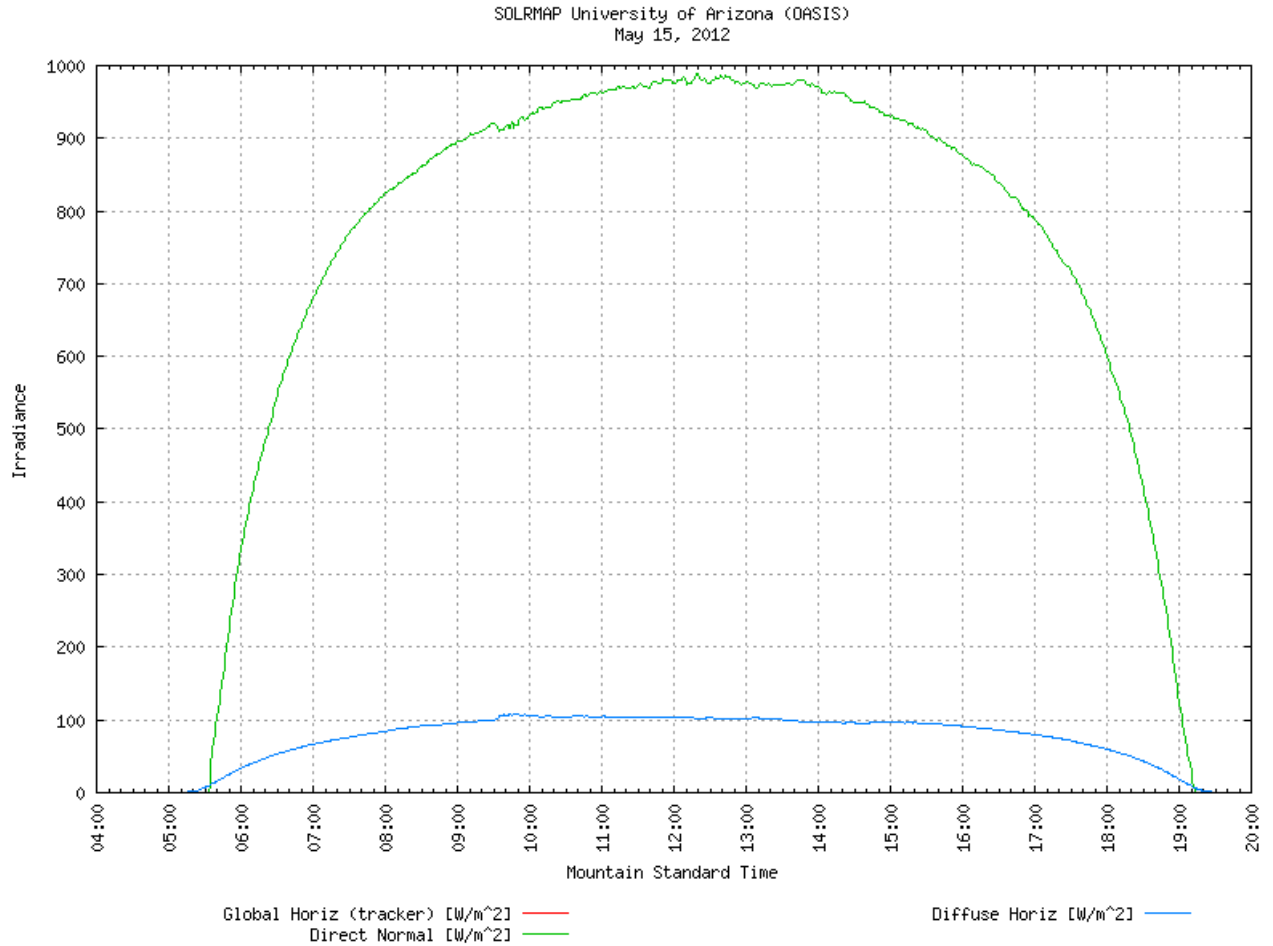http://dx.doi.org/10.5439/1052226
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Appendix A. Solar Irradiance Data for Tucson

The following plots show the solar irradiance curves for Tucson, AZ on the dates of the HotPot experiments reported herein. The direct normal data (green curves) are the most pertinent to define the irradiance for solar cookstoves that use reflectors such as the HotPot.

SOLRMAP University of Arizona (OASIS)
May 15, 2012

SOLRMAP University of Arizona (OASIS)
May 15, 2012

Irradiance

Mountain Standard Time

Global Horiz (tracker) [W/m^2]
Direct Normal [W/m^2]
Diffuse Horiz [W/m^2]

SOLRMAP University of Arizona (OASIS)
June 6, 2012

Global Horiz (tracker) [W/m^2]
Direct Normal [W/m^2]
Diffuse Horiz [W/m^2]