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Repeatability of HotPot Solar Cooker Heating Experiments

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When making any physical measurements that may be affected by many variables, it is important first to identify variables that may affect the results, and control them. This requires us to make **two** or more 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 one or more important variables have not been controlled. Continued careful research 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).

One of the most important measurements needed to evaluate the performance of a cookstove is its internal temperature vs. time while being heated. From a record of these temperatures vs. time, a cookstove's heating power and other parameters may be inferred.
It is most useful and convenient (although not absolutely necessary) to obtain a time series of uniformly-spaced temperature measurements using an automated data logger connected to a temperature sensor inserted in the food or liquid to be cooked.

This was the method used to study repeatability between two copies of a widely-used panel type solar cooker, the HotPot. This cooker has a black enameled steel pot surrounded by a glass liner and a glass lid. The outer glass liner (the "greenhouse") serves to contain hot air around the pot. The 3.5-liter pot is surrounded by a series of polished anodized aluminum panels, called the "Morningstar" reflector. The three components fit together as shown:

Instrumentation for Heating Experiments

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; it was set 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 in Microsoft Excel. This data logger, and the included software, proved to be easy to learn and convenient to use.

Wind speed, atmospheric pressure and humidity were measured with an Acu-rite weather station. Solar radiation was measured with a “Mastech” or “Dr. Meter” digital illuminance/light meter, Model LX1330B. This low-cost instrument uses a silicon photodiode sensor, and has an accuracy of +/- 5% at high brightness levels. 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 for the sun is about 100 lm/W). (A pyranometer would be preferable for direct measurements of solar irradiance, but one was not available.)

Experiment 1 – Oil Load – July 31, 2015

Figure 1 shows the typical experimental setup for the HotPot measurements. The location was in Rockville, MD (39.047° N, -77.141° W, elev. 108 m). Both copies of the HotPot were new, with only light usage. In order to measure their heating power over a wide temperature range, the pots were loaded with 1 liter of room-temperature canola cooking oil, not water. They were placed side by side in a sunlit area.

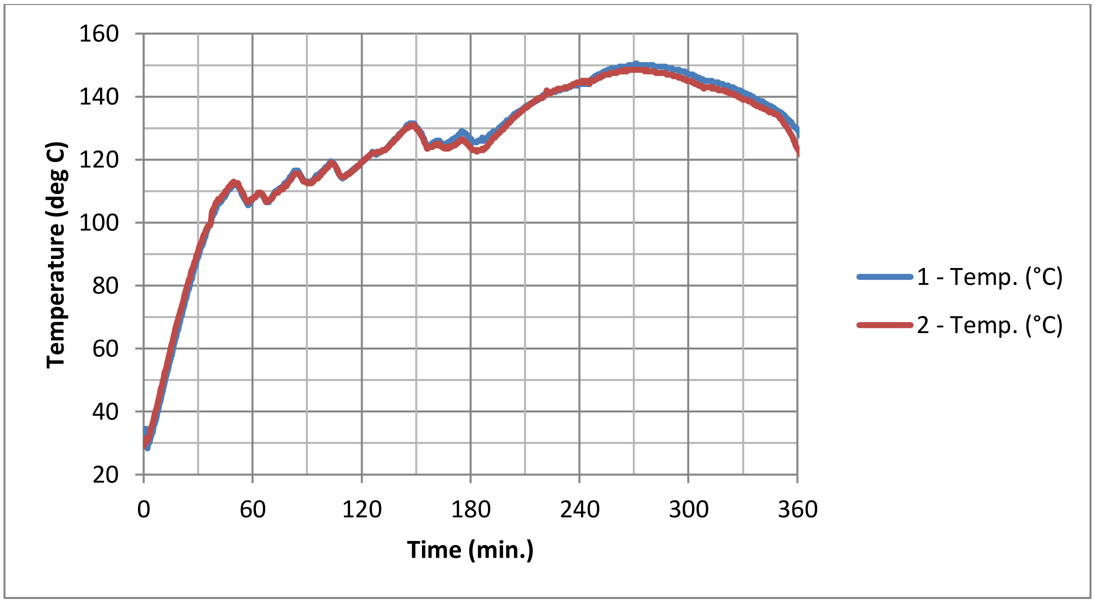
Each HotPot's internal temperature was measured with a Lascar thermocouple probe, which was set in the center of the pot, supported off the bottom and sides. The probe wires have a thickness of 2mm. This requires a small air gap that allows some heat to escape from the pots. The HotPot's three components were marked with small strips of tape, so that they could be placed in exactly the same positions for repeated experiments. Both pots were placed on level ground and the reflectors aimed to point in the sun direction. They were turned once per hour to track the sun's azimuthal position.

For July 31, 2015, the following supporting data were recorded in addition to the temperature vs. time data.

Local time	Amb. Temp. deg. C	Relative Humidity %	Wind speed m/s	Cloud Fraction %	Luminance, lux
12:30pm	29	45	Calm	0	158000
1:30	32	40	Calm	20	142000
2:30	32	37	Calm	15	137500
3:30	34	33	0-3	0	130200
4:30	n/a*	n/a*	Calm	5	122200
5:30	28	46	Calm	0	104400

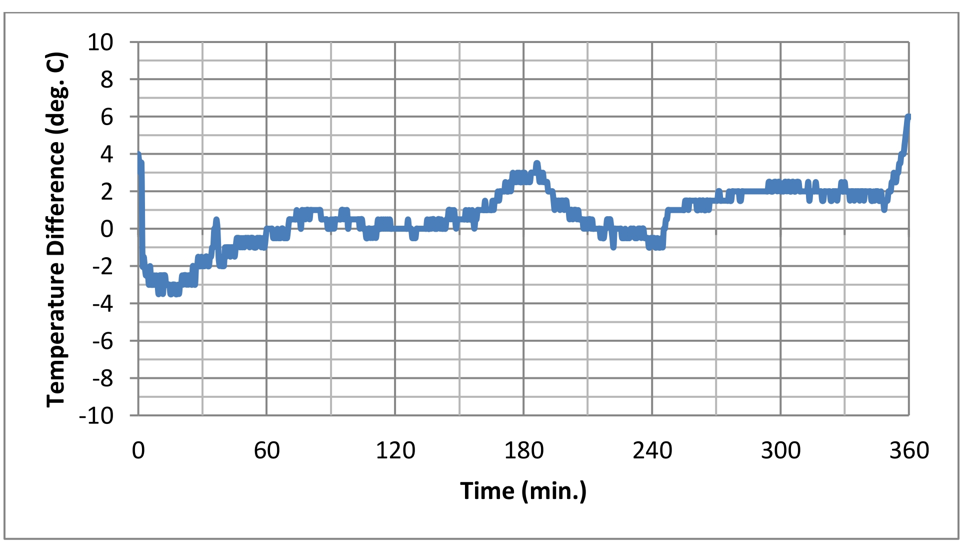
*Not reported because instrument was exposed to the sun

The chart below shows the temperature vs. time plots from the thermocouples in the pots.



The plots show that temperature rose rapidly, reaching 100 deg. C within 37 minutes, during the initial period when the sky was clear. Then some light cumulus clouds passed by for the next few hours. After 3:30pm, the clouds diminished and the day ended with a clear sky. The effect of clouds on performance is clearly seen in the period from 45 minutes to about 180 minutes. However, the purpose of this experiment was to check repeatability of two pots measured under the same (variable) conditions. The results clearly showed good agreement.

Figure 3 below shows a plot of the ***difference*** between the temperature measurements in the two pots. This is a highly sensitive way to compare the data. We note that after an initial stabilizing period of a few minutes, the two pot temperatures agreed with each other within +/- 2 deg. C about 80 % of the time.



This measurement indicates the degree of repeatability that is achievable between two typical HotPots with an oil load and equal conditions on a reasonably clear day.

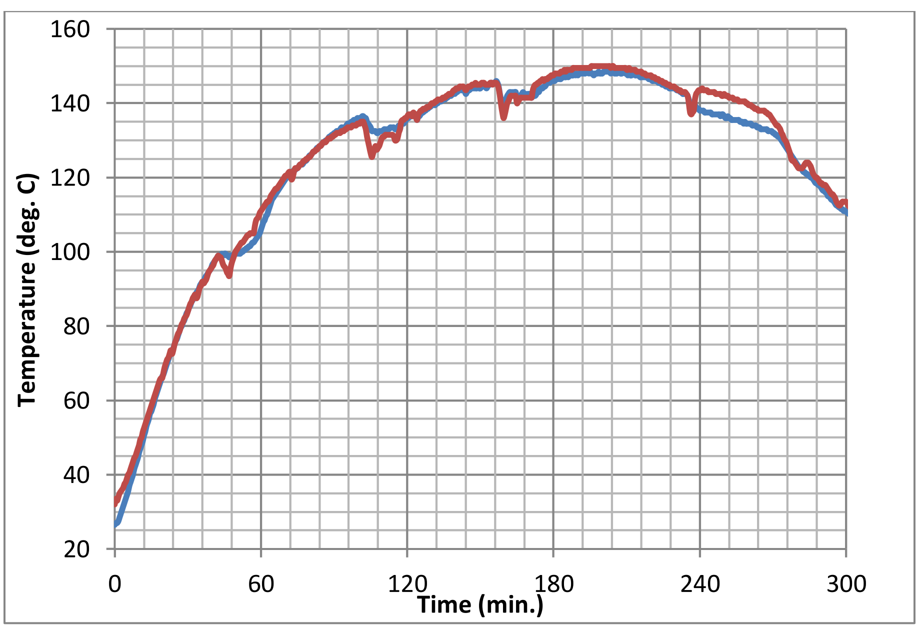
Experiment 2 - Oil Load – Aug. 5, 2015

A second experiment was done with the two HotPots on Aug. 5, 2015. In this experiment the setup was the same as in the previous test on July 31, except that one of the temperature probes was resting on the bottom of the pot and the other was suspended above the bottom. This test checks for variations due to the placement of the sensors.

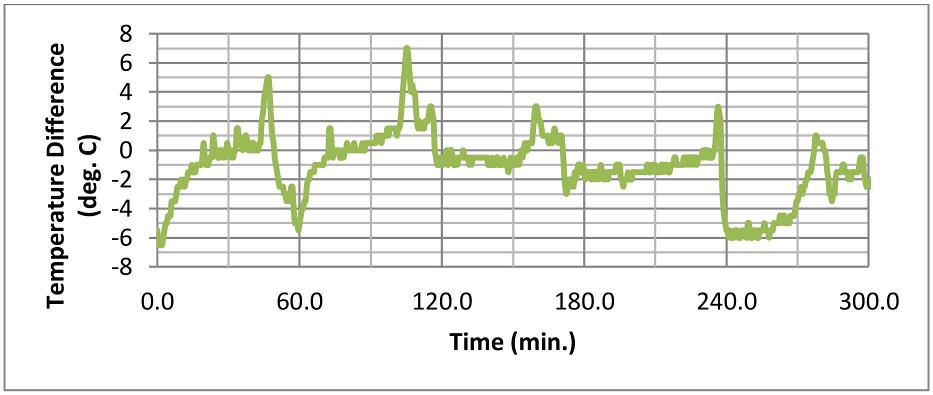
Here is the environmental data for this test:

Local time	Amb. Temp. deg. C	Humidity %	Wind speed m/s	Cloud Fraction %	Luminance, lux
12:10pm	-	-	Calm	5	-
1:10	28	55	Calm	10	133000
2:10	29	50	~2	10	135500
3:05	30	48	Calm	5	130100
4:10	31	42	Calm	5	115500
5:10	-	37	Calm	2	99000

Here are the temperature records for this test:



It can be seen that the probe touching the side of the metal pot (the red curve) heats up more rapidly when clouds pass over. These temperature differences indicate the importance of keeping the temperature probes from making contact with the sides of the pot. Here is the difference curve (blue minus red):



Most of the data match within about +/- 3 degrees despite the placement of the thermometer probe, so this is a small but controllable source of error. For subsequent experiments, the thermistor probe was prevented from touching the wall of the pot by the use of an aluminum wire guard, as pictured here:

Experiment 3 – Water Load – Aug. 24, 2015

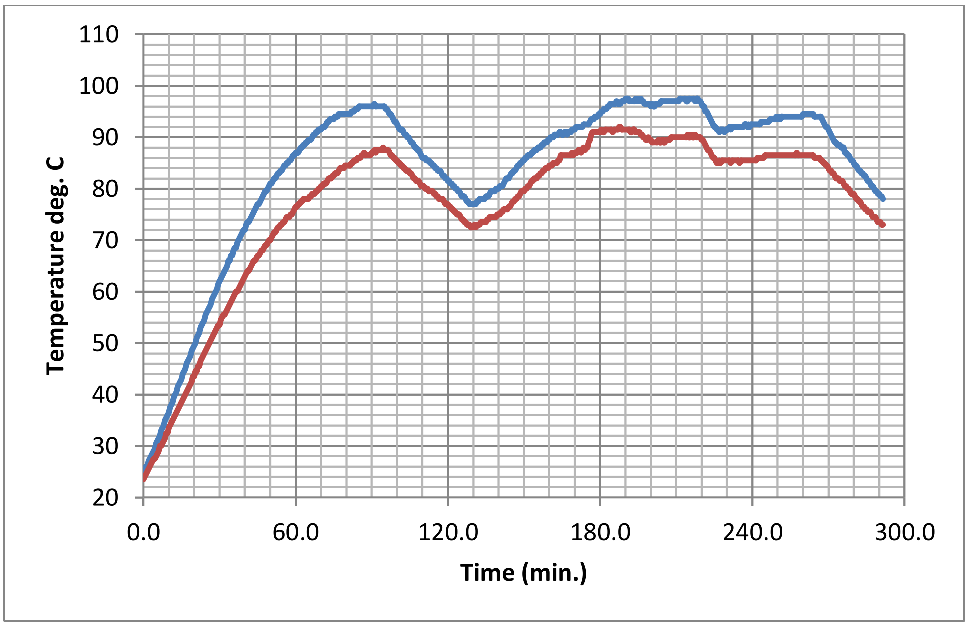
On Aug. 24, the weather was clear in the morning, so another comparison test was conducted. This time a water load was used: two HotPots filled with 1 liter of tap water. In this experiment, the same two HotPots were used as in the oil experiments, and instrumentation was the same.

Here are the environmental data for the first water heating test, on August 24, 2015:

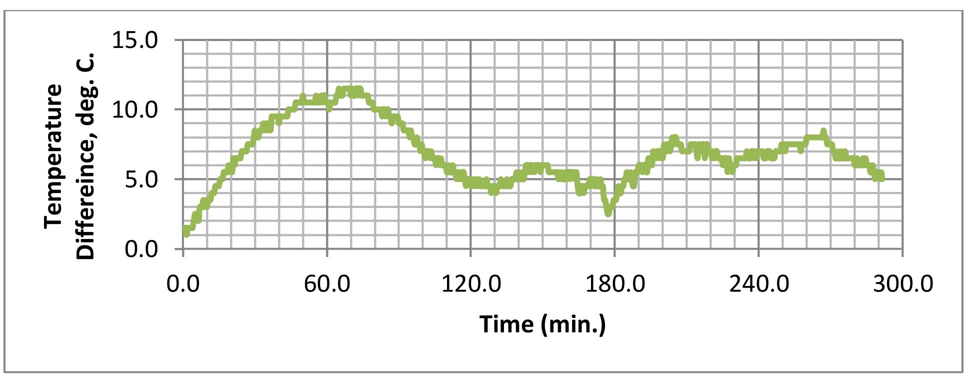
Local time	Amb. Temp. deg. C	Humidity %	Wind speed m/s	Cloud Fraction %	Luminance, lux
11:35am	27	70	Calm	Clear	119000
12:35pm	29.5	62	Calm	10	124000
1:35	30.5	58	Calm	50	32500
2:30	33	50	3	30	133000
3:30	-	-	-	90	-
4:30	-	-	-	100	-

The weather got cloudy in the afternoon, so the heating was not ideal for performance tests, but it should not affect this comparison because solar irradiance was identical for both HotPots.

In this first water heating test, the temperature measurements in the two HotPots did not show the kind of agreement that was obtained using an oil load:



The temperature differences between the two HotPots are shown below:



This relatively large difference between the two apparently identical units needs an explanation. One possibility is suggested in the photograph of this experiment:

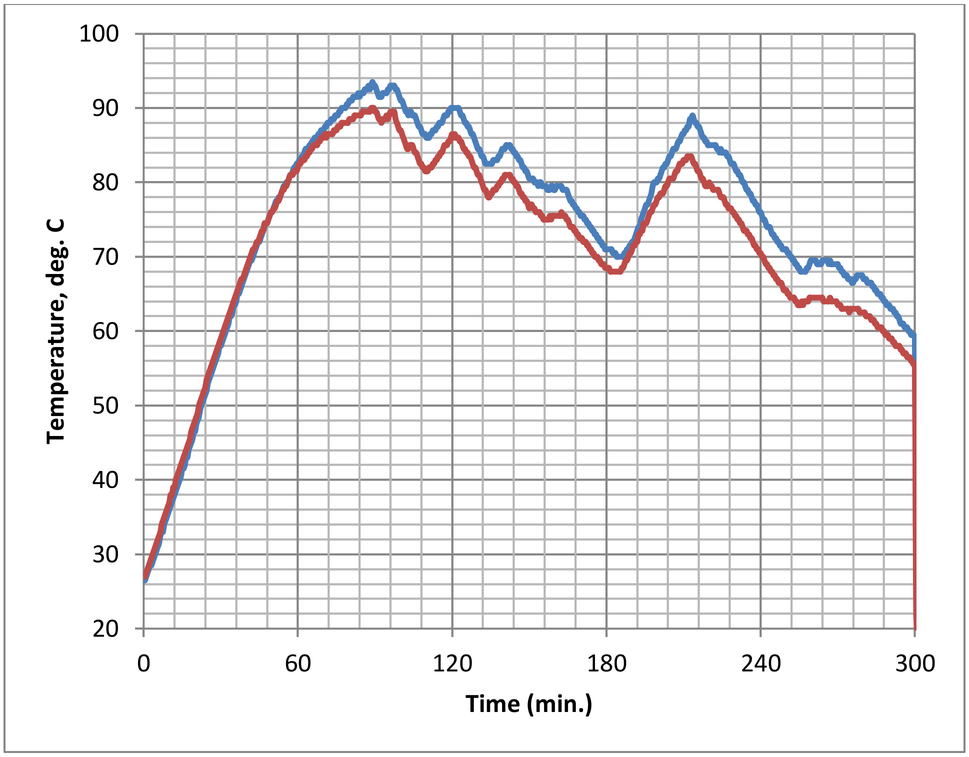
It can be seen that the lid of the left HotPot is brighter, due to scattered light from water droplets on the inside of the lid. This could cause a reduction in sunlight passing through the lid. To eliminate this, in subsequent experiments the lids were thoroughly cleaned with steel wool and detergent. Another possible cause of variation is that the dimensions of the Morningstar reflectors were somewhat different; unit no. 2 was about an inch wider than unit 1.

Experiment 4 – Water Load – Aug. 27, 2015

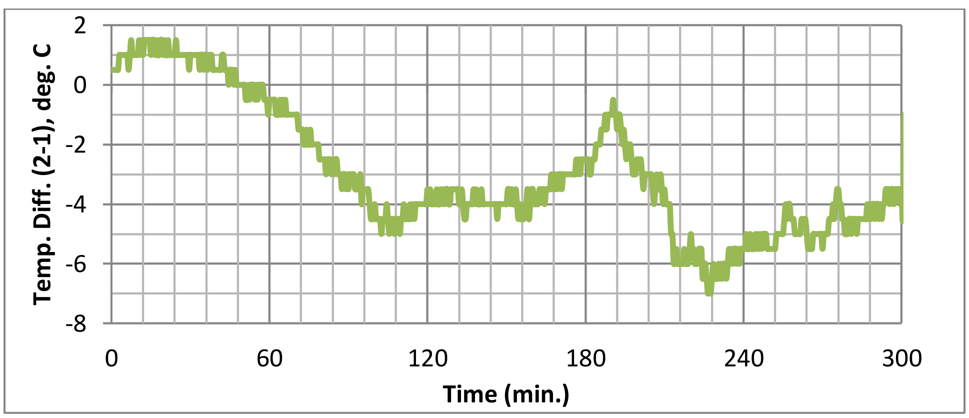
A second water heating test was conducted on a partly cloudy day, Aug. 27, 2015. One liter of tap water was placed in each HotPot. Environmental conditions were similar to those on Aug. 24. The following environmental data were recorded:

Local time	Amb. Temp. deg. C	Relative Humidity %	Wind speed m/s	Clouds	Luminance, lux
11:10am	22	56	Calm	cirrus	125000
12:35pm	26	50	Calm	cirrus	138000
1:35	-	-	Calm	cumulus	-

When the measurements started, the sky was clear except for some thin cirrus. The measurements were stopped at 1:35pm due to increasing clouds. However, these variations are not significant for the repeatability evaluation since both HotPots encountered the same solar input. The temperature comparison is shown below:



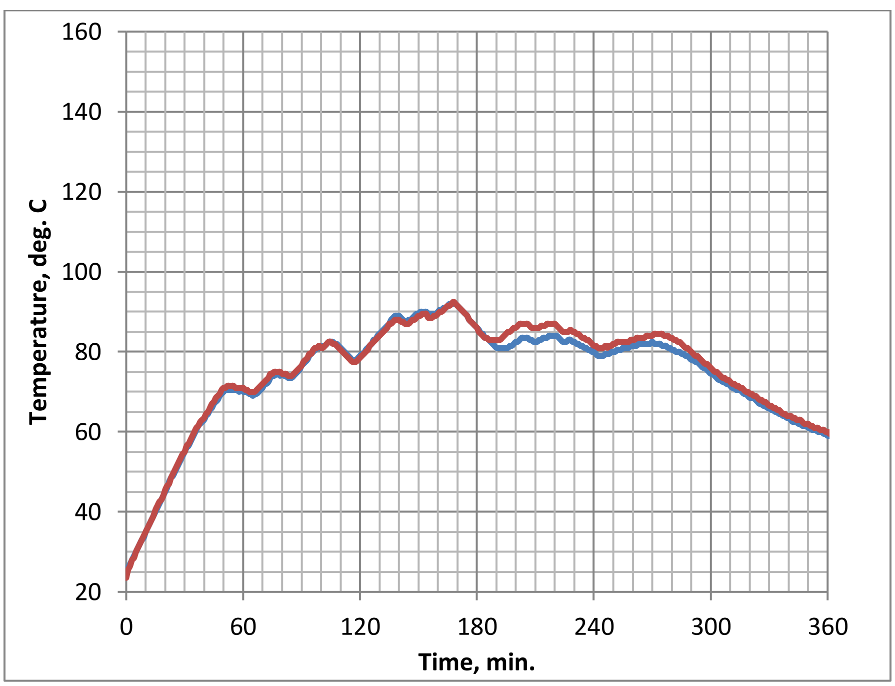
The temperature in both HotPots rose rapidly while the sky was nearly clear, at the beginning of the measurement period. However, the temperatures tended to level off and did not stay above 90 degrees C. Below is a plot of the differences (blue minus red curves):



Here, differences up to 7 deg. C occurred, but the average difference was ~3.5 deg. Still, this is a much bigger discrepancy than the oil experiment showed.

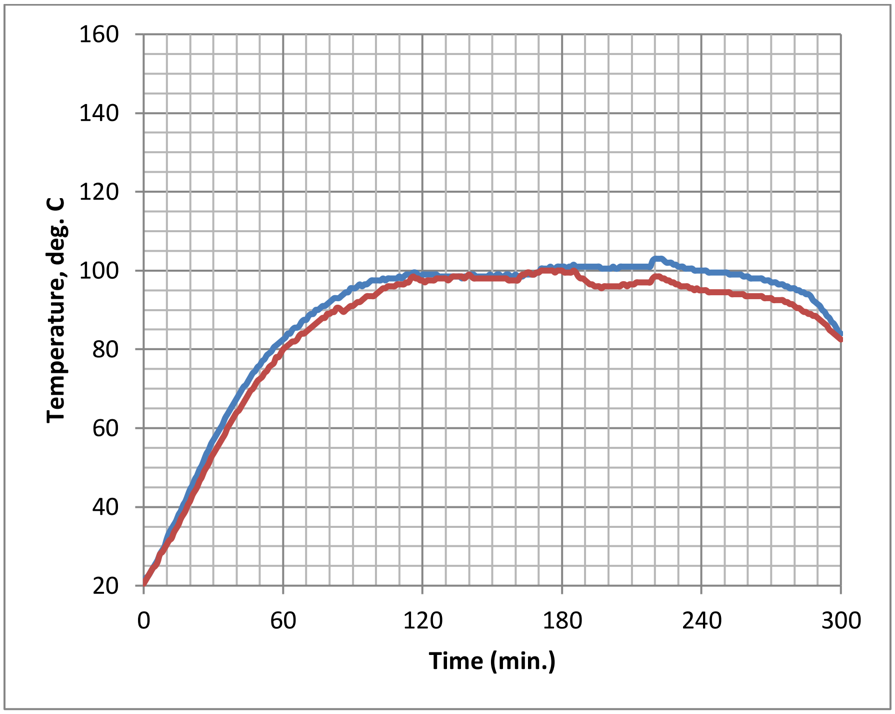
Experiment 5 – Water load – Haines Solar Cooker

The figure above shows two Haines solar cookers under test. The white box in the middle contains the data loggers. "Dutch Oven" pots are provided with the Haines Solar Cooker reflectors. These pots have a precision silicone rubber seal, and there is no lid gap since the pots also have a vent hole in the glass lid which is suitable for inserting the thermometer probe. Measurements were made on a partly cloudy day, Sept. 1, 2015 with 1 liter of tap water in each pot.



The results showed that temperature data were highly repeatable. Unit #1 (blue) was partly shaded by trees after 180 minutes.

Experiment 6 – 2 Sealed HotPots



The purpose of this experiment was to see if HotPots can get to a full boil and show good repeatability if the lid gaps are mostly sealed with aluminum tape. Only small gaps were open for the probe wires. One liter of tap water was placed in each HotPot.

Result: the temperatures reached a full boil after 2 hours. This test demonstrates that a full boil is achievable if the lids have a good seal. The sky was clear all day, though there was a gusty wind. Temperature differences of up to 5 deg. C were noted.

Discussion

Why was repeatability better with an oil load than with a water load? Why was the repeatability of the Haines Solar Cookers better than the HotPots? The data indicate that some variables were not tightly controlled between the two HotPots. We hypothesize 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.

The lid gaps caused variability especially with a water load near the boiling point. Vapor pressure of water increases greatly near boiling; 1 liter of water becomes 1800 liters of gas at the boiling point. The pressure of expanding water vapor also constitutes a significant source of heat loss, and it is likely that small variations in the size of lid gaps can make a significant difference in the amount of this heat loss. 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.

In any case these experiments established that under matched solar input conditions, the measurements of two HotPot solar cookers with a water load can be repeatable within about +/- 3.5 degrees C. With an oil load, the repeatability is generally +/- 2 degrees C. or better.

Having established these rather wide bounds on repeatability, it is now necessary to identify the 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.

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