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Challenges in measuring cooking vessel internal temperatures

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Introduction

Since 2012, researchers at Solar Household Energy have been conducting heating experiments on various solar cookers. The general goal of these experiments is to establish repeatable, quantitative measurements of solar cooker performance. Once we have learned how to obtain quality measurements, it will be possible to make comparisons between different products in order to improve performance. Having reliable measurements will also increase the credibility of solar cooker data and we hope will encourage others to follow similar practices.

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 assemble instrumentation and use it to raise the quality and quantity of cookstove performance measurements. No longer do people need to rely on crude bimetallic strip oven thermometers.

Repeatability must be established first, before further tests are conducted. We have learned that to be repeatable, heating experiments must be conducted in a careful and meticulous way. Full documentation of the measurement conditions (including photographs, date and time, ambient temperature data, wind speed data and other variables) should be reported. (A sample experiment form is shown in Appendix A below).

Solar Household Energy, Inc. designed and produced a solar cooker, the “HotPot”. We reported heating experiments with this device and documented the results in several Technical Notes. 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.

The lid gap issue

In low-power solar cookers, such as panel cookers like the CooKit or the HotPot, food is cooked slowly, and hence their efficiency is strongly influenced by heat losses, especially from small air gaps between the lid and the cooking pot. The same issue occurs with electric-powered slow cookers (i.e. the “CrockPot®”) in kitchens. Users are advised not to lift the lid on the cooker, which releases a significant amount of heat and slows the cooking process. Conversely, for maximum performance, the cooking pot lid could be completely sealed to prevent convective heat loss. However, this is not feasible due to a buildup of pressure while heating that could be dangerous (unless the pot is designed to be a pressure cooker). Or, after food has cooled, the partial vacuum could tightly seal the pot to make it impossible for a person to remove the lid!

In practice, electric slow cookers are designed with three or four very small gaps around the pot lid to serve as steam vents and to equalize the internal pressure. The same approach should be applied to pots used for solar cookers.

The temperature measurement challenge

A tight seal is also not feasible for measurements because it prevents the wire of a thermometer from entering the pot. Therefore a tradeoff must be made: the cooking pot can have a partial seal, but not a complete one.

In earlier experiments with Lascar temperature probes, the probe wires were passed over the lid, which created a gap of about 2 mm. This could create a significant source of heat loss and reduced performance in a low-power solar cooker. Technical Report TR-04 describes the effect of such gaps on repeatability of measurements of the HotPot. Strategies for reducing the influence of sensor wires were investigated.

Maxim self-contained sensors

One way to prevent excessive lid gaps is to use a recording instrument that is completely self-contained within the pot being heated. But this introduces other requirements: the device must be much smaller in mass than the food being cooked; and the device must record accurate readings at high temperatures.

One such device that is marketed to measure internal temperatures is the Maxim iButton sensor/data logger. It contains a small sealed microprocessor that records temperature readings from its built-in sensor. Here is a photo of an iButton next to a penny:

Figure 1. Maxim iButton sensor and penny.

The specifications for the iButton sensor are:
Temperature range 15 to 140 deg. C.
8192 readings; minimum interval is 1 minute.
1 s. to 273 hours range.
+/- 1.5 deg. C accuracy from 110 - 140 deg.
Resolution selectable 8-bit or 11 bit
part number DS1922E-F5#
The pricing for 1 - 24 pcs is $161.13 each.
The iButton must be made waterproof with part no. DS9107 capsule, $64.35 each.

The product appears to be intended for large industrial companies. However, it is small and affordable. For reading the data logger, the iButton is placed in an adapter which can be plugged into a USB port on a PC computer. Software and documentation are free from the Maxim web site. As with the Lascar data logger, the data can be downloaded as a table of csv (comma-separated-values) file for plotting in Excel.

For cooking measurement purposes the main limitation of this sensor/data logger is its maximum temperature of 140 deg. C, which is on the low end of what is desired for cookstove heating measurements. For measurements of water-based foods in cooking pots, the iButton can be a practical solution. But in the case of frying or baking, cookstove temperatures can easily exceed 140 deg. C. It would be highly desirable to have instrumentation that does not limit the temperature range that is achieved in real cookstoves. Unfortunately, semiconductor electronic devices such as the iButton will melt at these high temperatures.

Onset Computer self-contained data loggers

Hanna Rolland measured internal temperatures using HOBO Stainless Temperature Data Loggers, model U12-015. A glass votive candle holder was used to suspend the probe in the middle of the water within the HotPot, as shown below.

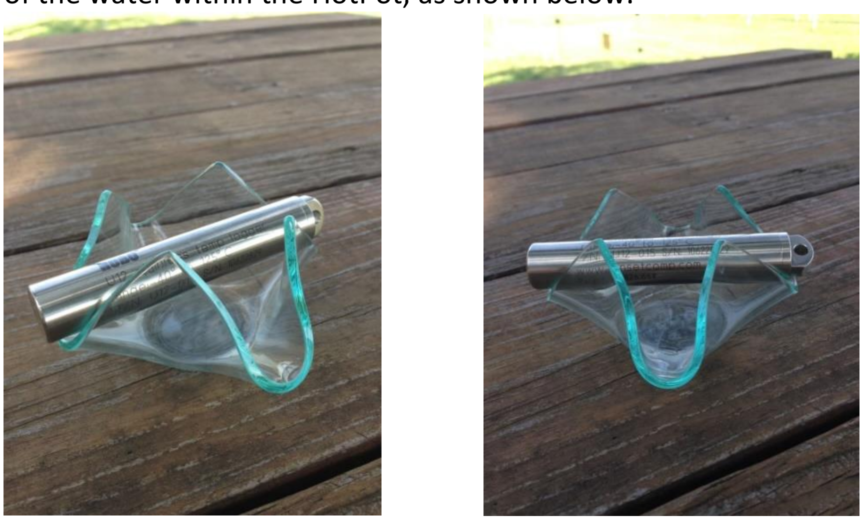

Figure 2. Onset Computer data logger and holder.

The Onset self-contained data logger has the following specifications:
Measurement range: -40° to 125°C (-40° to 257°F)
Accuracy: ± 0.25°C from 0° to 50°C
Response time in water: < 3.5 minutes, typical to 90%
Construction: Food-grade 316 Series Stainless Steel
Logger dimensions: 17.5 x 101.6 mm (0.69 x 4.00 inches)
Weight: 72 g (2.5 oz)
Price: $272

These self-contained sensors may be adequate for measurements in water up to boiling. For higher temperature measurements, it is necessary to use a sensor with external electronics and hence a wire has to be introduced into the pot. This can be done either with a wire that crosses the lid of the pot, or a small hole can be drilled in the lid or the pot to accommodate the thermocouple wire. (Omega thermocouple wires have a cross section of about 1mm x 2 mm, so a minimum lid gap of 1 mm is required.)

Drilling a hole in metal cooking pots

For his preliminary research in developing the solar cooker standard, Dr. Paul Funk drilled small holes in the sides of metal cooking pots, inserted a sensor wire and sealed the hole with silicone sealant. This is a simple way to avoid the lid gap problem when using metal cooking vessels.

Drilling a hole in the HotPot lid

The HotPot cooking vessel is completely surrounded by glass, so to avoid placing sensor wires over the lid, a hole was drilled in the lid of a HotPot. First we examined the lid with polarized light to ensure that there were not stress concentrations at the drill point.

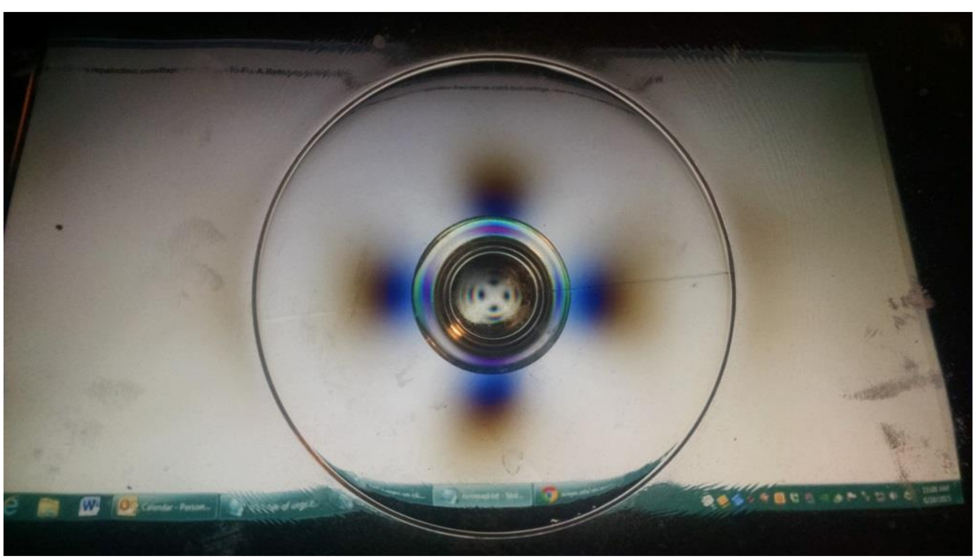

Figure 3. Stress pattern in annealed glass of the HotPot lid.

The image showed strong stress around the center but not at the periphery, so a hole was drilled at a position in the clear area. A carbide 3/16-in. bit was used. Drilling the hole was fairly straightforward. But ten minutes later, as the lid was being carefully cleaned by hand, it spontaneously shattered.

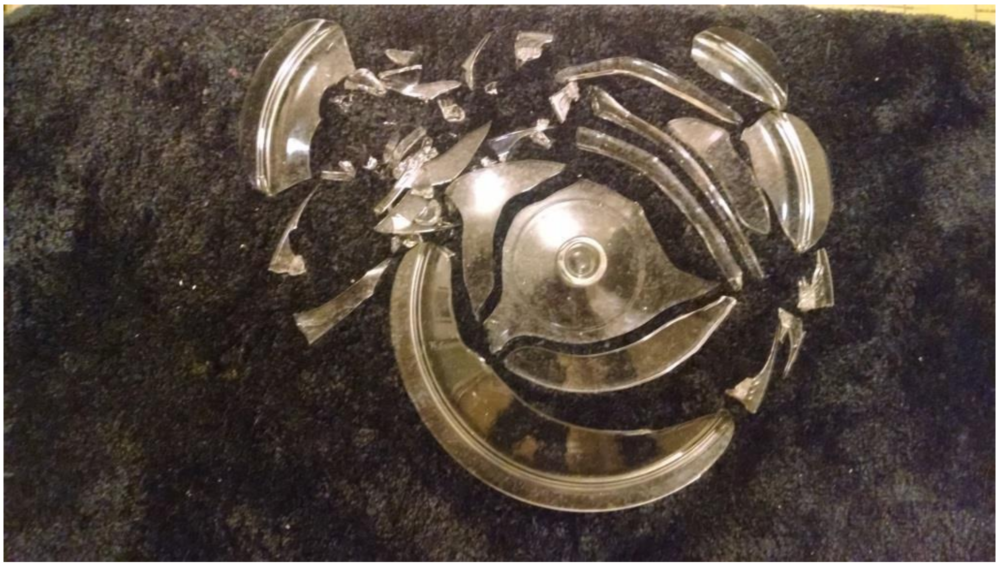

Figure 4. Shattered lid of the HotPot after drilling.

The lid is made of glass that has been annealed. This is a heat treatment process that hardens the glass and makes it less vulnerable to breakage if dropped. It creates a thin, hard surface layer. But if that layer is penetrated, it acts like a water balloon – the whole thing breaks to pieces. So this idea was abandoned.

Hence, for measuring temperatures above 140 deg. C, a thermometer probe with a wire is required, which brings with it the need for a small lid gap. Of course wires can be made very thin; little current is involved, so it would even be possible to convert the original 2 mm wire to a flat wire lead less than 1 mm thick. In any case, we have to accept the fact that some air gap is necessary for pressure release in any pot or cookstove, although for small cookstoves the air gap can be small. In larger devices, a *steam vent* is commonly used; these release pressure while reducing heat loss compared to a simple air gap.

Placement of sensors within the cooking pot

Experiments were conducted to determine whether placement of the sensor within the cooking pot is a significant source of variability. For all experiments, the pot is loaded with either water or cooking oil. When heated, convective mixing occurs and ensures uniform temperatures throughout the liquid. This was confirmed in many experiments when two sensors were placed at different positions, and their readings were very nearly the same. The exception was when a sensor is either exposed above the liquid, or touching the side or bottom of the pot. To prevent touching the pot, the thermometer probe was supported by a wire guard, as pictured in Figure 5. (It is recommended that this wire be made of stainless steel to avoid possible chemical reactions in boiling water.)

Figure 5. Thermometer probe guard.

When in later experiments thermocouples were used as the sensors, their stiff leads were bent in a U-shape to prevent touching the pot surfaces. Other than this precaution, placement in the cooking pot was found to be not significant.

If the load were a thick food such as stew or polenta, convective mixing is limited and we would expect a thermal gradient to be established in the pot. In such experiments, it will be important to measure temperatures at the center of the food, so some type of support structure will be needed to maintain the position of the sensor(s).

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