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Independent Study – PHYS 400 with Dr. Peter Schwartz during Winter 2019

Objective:

In our target region (Africa) most residents currently cook over a fire. Replacing a fire with solar PV powered cooking can be inferior (due to lack of power) for many high-power cooking methods, such as frying, making PV powered cooking much less likely to catch on. However, solar PV is superior when baking (which requires very little power), due to the increased temperature control achievable with low-cost electronics. The objective of independent study this quarter was to develop a solar PV powered oven that was able to bake food. Additionally, there was an intent to evaluate the oven's ability to function as a multi-method cooker (for example, a cooker that can bake, fry, and boil). Deliverables included two prototypes with testing for efficiency in drawing power from a panel and cooking speed, plus a list of improvements for each round.

Hardware:

The solar panel used is an 85W flexible polycrystalline panel (Figure 1) with V_{oc} = 21.6V and I_{sc} = 5.8A. For the heating element (Figure 2), which is directly wired to the solar panel, several diodes and a single temperature switch are soldered in series, with copper lead wires used as needed. The diodes used are 1N5408 silicon rectifier diodes. The temperature switch is a 160C bimetallic switch. The copper wire is insulated 16 gage multistrand. For both ovens, an enamel coated 6qt steel bean pot with a lid (Figure 3) was used. While cooking, this pot was placed inside of a styrofoam box (Figure 4) insulated further with fiberglass insulation (Figure 3). The same box was used for both ovens.

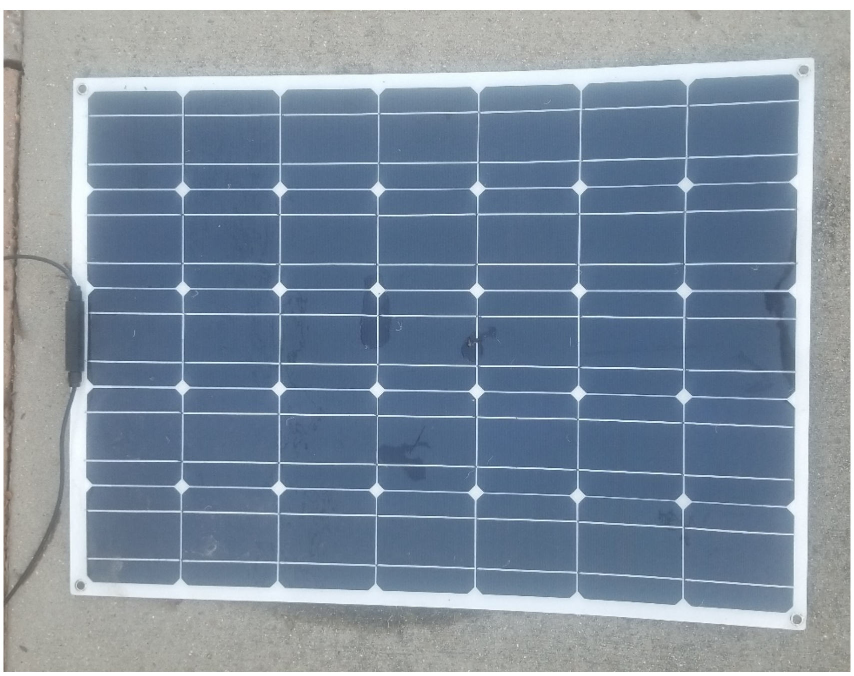

Figure 1. Generic 85 W flexible polycrystalline solar panel.

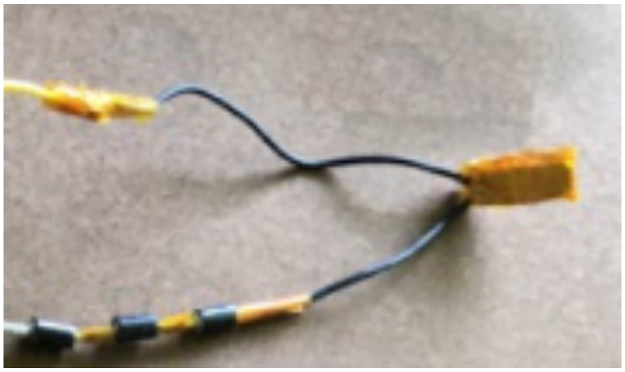

Figure 2. A portion of the heating element including the switch, some of the diodes, and wire.

Figure 3. Steel bean pot surrounded by fiberglass insulation inside of the styrofoam box.

Figure 4. Styrofoam box enclosure.

Peak Power Efficiency:

Here peak power efficiency is measure by the heating elements ability to draw power. On the first oven, 20 diodes are used for the heating element, which was able to draw 75 watts (4.65A at 16.10V) from the 85-watt panel at peak power, corresponding to an 88% efficiency in drawing power from the panel. On the second oven 22 diodes are used for the heating element which was able to draw 76 watts (4.88A at 15.60V) from the 85-watt panel, corresponding to an 89% efficiency at peak power.

Cooking Speed:

The cooking speed was measured by the rate that the diode heaters heat water. Both ovens used the same exact insulation cavity, so the rate of heat loss is the same. However, cooking speed is different from Peak Power Efficiency for two main reasons. The first is that the diodes drop in voltage as their temperature increases, which increases the amount of current the panel can provide them. The rate that each heating element drops in voltage differs based on the number of diodes in the element. The elements are designed purposefully to initially turn on at a higher voltage than the panel will provide peak power at, then drop in voltage to operate at steady state (while hot) around the peak power voltage of the panel. Second, each heating element includes a temperature control switch that turns off when the temperature of the switch itself reaches approximately 160 C and turns back on at 100 C. The time it takes for the switch to reach this temperature depends on a few things including how far the switch is placed from the diodes and how long it takes for the diodes to drop their voltage and begin drawing peak power. An ideal heating element would operate at peak power voltage while at steady state, have diodes operating at 220C, and have the switch just far enough away from the diodes so that the switch remains right below 160C, therefore it still protects the diodes from damage if their temperature rises over 220C.

Oven 1 boiled one liter of water (starting at 20 C) in 76 minutes. We assume the specific heat of water to be 4.184 kJ/kg*C. Therefore, Oven 1 delivered an average of 73 watts to the water. We assume 1 watt is lost to the environment through the insulating box, so Oven 1 pulled an average of 74 watts from the panel. Oven 2 boiled one liter of water (starting at 20 C) in 86 minutes. Therefore, Oven 2 delivered an average of 65 watts to the water and pulled an average of 66 watts from the panel. Oven 1 is 12% faster for boiling than Oven 2. This test demonstrates that when you optimize a cooker for baking, it will take some hits in the efficiency of the boil & simmer cooking method. Since oil fryers operate at higher temperatures than boiling water, baking and frying may be a better combo for a multi-use cooker.

Temperature Distribution - Oven 1:

A test was run to investigate the temperature profile of the ovens. Thermocouples were placed in 5 different spots from top to bottom of the oven. The thermocouples start at the hottest point (the diodes) and are evenly spaced up or down the side of the pot. This setup is displayed in Figure 5, and the results in Figure 6. Prior to the test, we noticed that there is not a significant difference in the temperature distribution with or without food in the pot. Therefore, for consistency and simplicity we ran the tests without food in the pots. Before running the test, we assumed the profile for Oven 1 would be linear, as conduction is the main method of heat transfer from the top of the oven to the bottom. In a linear model, the distance between data sets on the Y-axis of Figure 2 would remain constant. However, this was not reflected by the results, which indicated that in reality, there is a smaller temperature difference between the bottom two points than the top two.

The issues with Oven 1 showed in separate cooking tests too, as food would not reach the desired temperature and not be golden brown or crispy. This was attempted with a small frozen pizza over the course of 2.5 hours.

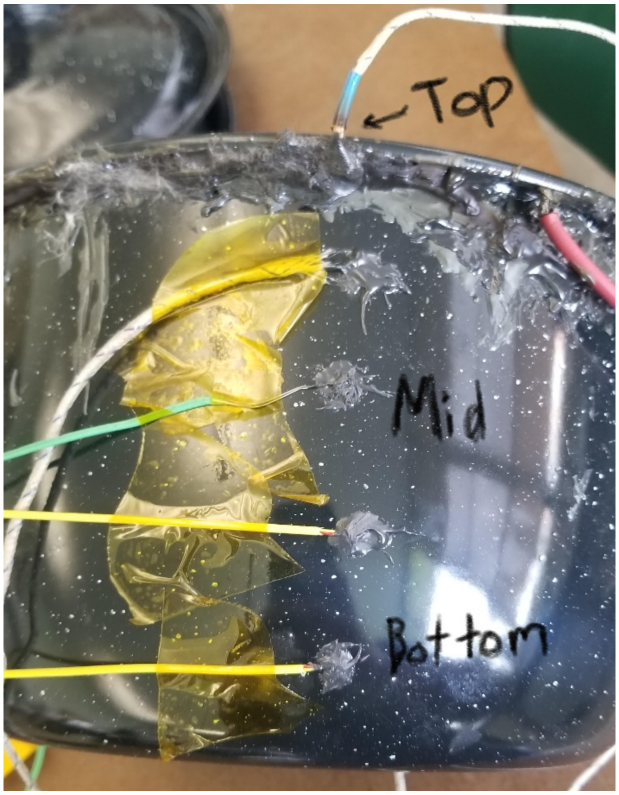

Figure 5. Oven 1 setup.

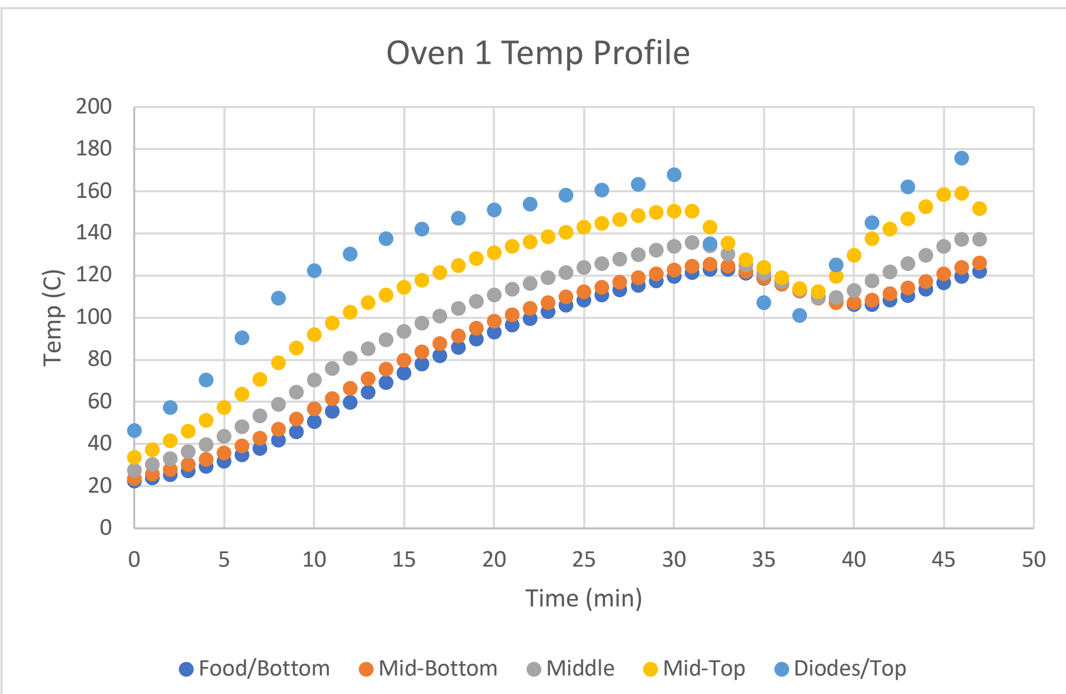

Figure 6. Oven 1 Temperature Profile test results. Note: drop at 30 minutes followed by rise at 37 minutes is a result of the temperature switch opening and then closing the circuit, respectively.

Improvements from Oven 1:

Using the results in Figure 6, we can predit the temperature at different points in the oven. This allows us to figure out how far to put the diodes away from the food, and how far to put the temperature switch from the diodes. In Oven 2, we needed the diodes to reach a higher temperature. We also needed the food to reach nearly the same temperature as the diodes. In Oven 1, the switch was placed 25mm below the diodes, and the diodes were placed at the top of the pot. In Oven 2, the temperature switch was moved further away from the diodes to a distance of 30mm above to allow them to reach the optimal temperature of 220 C. Additionally, since 220C is the recommended baking temperature for most foods, the diodes were moved towards the bottom of the pot so that the food will be at about the same temperature as the diodes. This can be seen in Figure 7. Lastly, in Oven 1 20 diodes were used. In Oven 2, 22 diodes were used to compare the efficiency of each elements cooking speed and peak power efficiency.

Temperature Profile - Oven 2:

As expected, Oven 2 took slightly longer to reach peak power (usually occurs at peak temperature), which can be seen in Figure 8 by the fact that it shuts off (shown by the sharp decrease in temperature, caused by the temperature swtich opening the circuit) at 33 minutes where Oven 1 shut off at 30 minutes. Oven 2 also displayed a vastly different temperature profile. Since the food was right near the diodes, barely any heat was conducted upwards, leading to a large temperature difference between the diodes and the bottom/middle thermocouples, but a very small temperature difference between the other three thermocouples. The improvements between ovens did help, as Oven 2 did not shut off until it reached the perfect baking temperature of 220 C.

When cooking food (separate from this test), the biscuits in Figure 9 turned out perfectly golden brown and crispy, taking about 45 minutes to cook.

Figure 7. Oven 2 setup. Note: after this photo was taken, the thermocouples were glued down to the side of the pot.

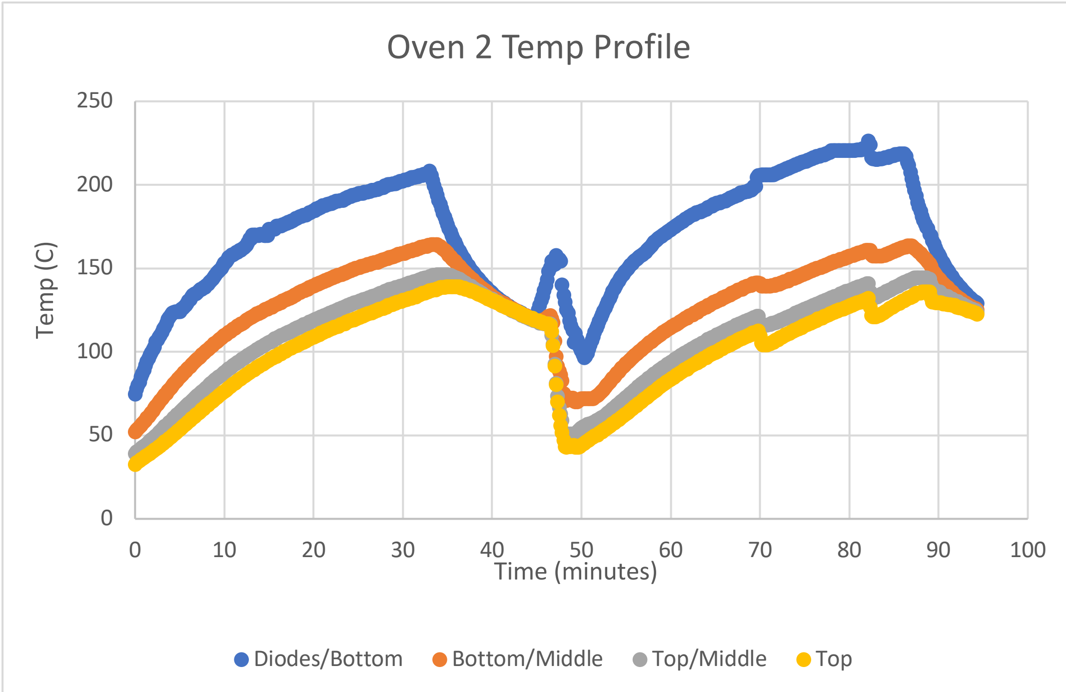

Figure 8. Oven 2 Temperature Profile test results. Note: Drops at 33 and 86 minutes are from the temperature switch opening the circuit. At 45 minutes the switch closed the circuit, causing the rise. The drop around 48 minutes was due to opening of the pot to check on a strange odor.

Figure 9. Biscuits cooked in 45 minutes while at Pismo Beach.

Improvements for future:

Several improvements can be made in future studies. For convenience they will be placed below in a list.

1. Re-run cooking speed with thermocouples to measure temperature, use an ammeter/voltmeter combo to measure current and voltage and find power. This will give us a hint as to how to strike the perfect balance between optimizing the baking and optimizing the other cooking methods.
2. Try frying in one of these ovens.
3. Test these setups with more power, such as 200W. This may require parallel diode chains and resistors at the beginning or end of each chain to balance current across parallel chains. Additionally, as power is added, another temperature profile should be assessed to find the optimal place to glue the diodes and switch to the pot.
4. Use a dial to create variable amounts of power by adding and removing diodes as you turn the dial. With an oven, it is beneficial to reduce the power once the desired temperature is reached. With boiling or frying, you may want to reduce the number of diodes in the chain, which can lower the voltage and cause the device to operate closer to peak power.
5. Use a cast iron cooking pot. This is much thicker metal, so more conduction occurs, lessening the temperature difference between the top and bottom of the pot.
6. Use flat rectifier diodes. These can handle at least 20A and are better thermally anchored to the pot. The voltage drops across each diode are the same. This will allow for the use of more power and lead to a lower temperature difference between the diodes and the food.
7. Connecting diodes as a necklace rather than twisting can be beneficial for some applications. This allows the maker to place the diodes in the desired spot, glue them down and move them around as they please. Soldering is the last step. This configuration can be seen in Figure 10.

Figure 10. Diodes connected as a necklace rather than twisted into a fixed shape.

8. Fiberglass insulation is unacceptable – it is unsafe, unhealthy, uncomfortable, expensive, and not environmentally friendly. Additionally, as it gets warm it emits a strange scent. Some better options are wool blankets or old couch cushions.

Conclusions:

Baking in a solar cooker is highly feasible. Not only that, but it is a superior method to the current common method of cooking in our area of interest – Africa. Cooking over a fire provides little opportunity for temperature control whereas temperature switches and diodes pair with solar panels to make a well-functioning oven and multicooker for under $100. This is likely to catch on.