Low Cost Solar Household Energy

January 29, 2020

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Introduction

This is a general purpose solar heater and drier which can be used for many different purposes. It is intended to be very inexpensive and versatile. A video covering this device is at

https://youtu.be/6Z6snha3uHE

The intention is that the device can serve many purposes, and the user would decide which function to use on a given day. The device can:

- Heat water to be used for washing (about 50°C).
- Heat water to be used for cooking (about 60°C or more).
- Heat drinking water to the pasteurization temperature (about 60-65°C).
- Heat large amounts of water for space heating.
- Dry wood to be used for firewood.
- Dry corn, beans, or other grains.
- Heat clothing to a temperature sufficient to kill insects and their eggs.

Observations and measurements in the developing world show that a significant amount of household energy goes into the heating of water, independent of cooking. In a typical West African village Johnson and Bryden (2012) measured 22.2% of wood going to wash water and 19.1% going for space heating.

The device is essentially the same for all purposes, and multiple purposes can be used at once, for example, some grain can be dried while wash water is being heated, while water for cooking is being heated.

The device is not useful for large drying tasks such as drying wet clothing. For these purposes it is better to spread out the clothing as on a clothesline to get better air circulation. Drying a large amount of firewood, such as a month's worth, would probably not work well for the same reason. A day or two of firewood works well, at the same time that other tasks are being done.

The Test Site-Climate and Solar Angles

This document contains a lot of test results, but something should be said about the climate at the test site. The tests were done at 40.1° N latitude over two summers, 2018 and 2019, mostly from mid-June to mid-August. In June the weather is rainy and warm, with few days available for testing. Starting about July 1, most days are sunny in the morning and partly to mostly cloudy in the afternoon. A few days are clear throughout most or all of the day. In the late summer the weather is more clear, but this is well after the solstice and the sun is lower in the sky.

The test site was in an open area and was windy. Very windy days affect the results considerably, ordinarily windy days less so. The test site is near the western edge of the Eastern time zone in the US, and with daylight savings time in effect the sun reaches a peak at about 1:25 pm. Most tests were started 4 hours before this and ended about 4 hours after. In a tropical region, the sun will typically be low in the sky 4 hours before and after noon, so the tests were limited to these hours.

One might ask whether a test site at 40° latitude near the summer solstice compares with a tropical test site at any time of the year. One way to compare the sites is to look at the average solar angle, specifically the average sine of the angle of the sun above the horizon. At solar noon on the equator on the equinox the sun is directly overhead and the sine of the angle is 1. At other times the sun will be lower in the sky and the sine of the angle will be less than 1. At the test site the sun is never directly overhead, but it doesn't approach the horizon as quickly in the morning and afternoon hours.

Solar angles can be calculated directly using methods given in Rapp (Rapp, 1981). On the summer solstice at 40.1° north latitude the average sine of the angle during the 4 hours before and after solar noon is 0.8367. On the equator on the equinox the average sine is 0.827, or 98.8% as much. At 40.1° latitude 30 days before or after the solstice the average sine of the angle is 0.8185, or 97.83% as much as on the solstice. On the equator 45 days before or after the equinox the average sine of the angle is 0.7917, or 94.62% as much as the solstice value. Thus, in the summer months the test site should be a reasonable approximation of tropical sun, if the tests are confined to the 8 hours around solar noon.

Building the Device

To build the device, select an open area of ground, generally flat. It is best to have few tall objects nearby. If the sky is clear, then most of the solar energy is direct, that is, in a straight line from the sun. In this case, it is important that there are no objects directly between the solar collector and the sun, but there can be tall objects around the collector.

If the weather is partly or mostly cloudy, then much of the solar energy is indirect, that is, it bounces off a cloud and then hits the collector. In this case, energy hits the collector from many angles, not just straight from the sun. In this case, it is important to have few tall objects near the collector. If the climate is such that most days are fully sunny then there can be tall objects around the collector. If the weather is partly to mostly cloudy, then there should be no tall objects around the collector. As a rule of thumb, if an object is a certain height and it is two times the height away from the collector, then it is far enough away that it doesn't affect the collector much.

For these tests the collector was in an open area and it performed nearly as well in partly cloudy weather as it did when the sky was clear. On mostly cloudy days the collector also performed well, though in rainy weather the performance is not good.

Once the location is selected the steps for building the collector are as follows.

Figure 1: The flat open area used for most of the tests described here.

Lay down an area of stray, grass, leaves, weeds, or other loose organic material, about 5 cm deep. The area for the test units was 2.4 m by 1.4 meters, but anything similar should be OK. Theory says it's slightly better to have the long axis running east-west, but the orientation probably makes little difference.

Figure 2: A layer of loose organic material is laid down about 5 cm deep, and about 2.4 m by 1.4 m.

Figure 3: Cover the organic material with a layer of black plastic or similar material. In the background is a wooden structure that was used in early tests, but is not part of the final design.

The loose organic material is covered with a black plastic sheet or other dark material. Other dark materials can be substituted if available.

The collector needs to have a “working space” inside, and one way to provide that space is to use 20-liter buckets. Water can be heated in the buckets, and either full buckets or nearly full buckets can be used. Empty buckets could be used, but if they are plastic they might get too hot and melt. If no water is needed, concrete blocks or wooden structures could substitute for the buckets to create the working space inside the collector.

The important factors are that the working space is deep enough that the top layer of plastic doesn’t touch the black layer, but that the working space is not deeper than it needs to be, as that leads to more heat loss and lower effectiveness.

Figure 4: Two buckets to be heated, one full and the other ¾ full. The buckets have temperature logging instruments for test purposes.

The buckets used in these experiments were all filled, except as noted when they are described as “3/4 full” or some similar description. The buckets were weighed, and the average net weight of the 6 test buckets was 20.1 kg, meaning they held about 20.3 liters of water. The full buckets were filled to a few cm from the top. Apparently, a bucket described as a 5-gallon bucket holds more than 5 gallons, and considerably more than 20 liters.

The top layer is added next, of clear or translucent plastic. This should be snug over the tops of the bucket. If the buckets have lids, the lids should not be used, so that solar energy can get down into the buckets. The top layer of plastic sheet is held down by bricks, rocks, or logs. There doesn’t need to be a full seal around the outer edges, but there should not be large gaps. The buckets should not have lids, but if lids are available they can be used to keep the water hot after it’s been taken out of the collector. Typically, in addition to rocks in all four corners of the plastic, I put one extra object on the short edges and about three extra objects on each of the long edges.

Figure 5: The finished system, on this day heating 6 full buckets of water. The edges of the top layer are held down by rocks, bricks, or logs, with a total of about 12 objects being used.

Figure 6: This shows the details of the plastic cover over the top of the open buckets. The plastic should be somewhat snug over the top of the bucket, but it does not need to form a perfect seal. It makes little difference whether the top plastic touches the water or not, the temperature of the white bucket was measured to be essentially the same as the orange and blue buckets.

The design evolved over the course of the summers of 2018 and 2019. On a given day two collectors were tested side by side, identical except for one design variable. The variable giving the best result could be easily chosen since both collectors were subject to the same weather condition. Often, the simpler of the two designs worked as well or better than the more complex design, and therefore later versions of this device were simpler than previous version. The design described above is for the optimized design, but some of the test results given below are for non-optimized designs, and some of the pictures show non-optimized design details. If the differences are significant, they are mentioned in the text.

Water Heating-Wash Water

One can use full or partially full containers, with the choice being based on ease of carrying, the amount of water needed, and the time when the water is needed. For example, if you want hot water at noon use a partially full container, if you want more water and are willing to wait until the end of the day, use a full container. Other water containers such as 10- or 20-liter jerrycans can also be used.

The device works partly by having the sunlight directly strike the object to be heated, but also by having the sunlight strike the black plastic and rapidly heating it. Then, heat is transferred from the black plastic to the object via both convection and radiation. Numerical modeling shows that as a rule of thumb, about 1/3 of the energy in the bucket is transferred from the black plastic by radiation, 1/3 by convection, and 1/3 from sunlight directly striking the bucket.

The figure below shows the surface temperature of the black plastic on both sunny and partly cloudy days. The effects of passing clouds is clearly seen. In some conditions the plastic can get even hotter than in Fig. 7, sometimes reaching 100°C.

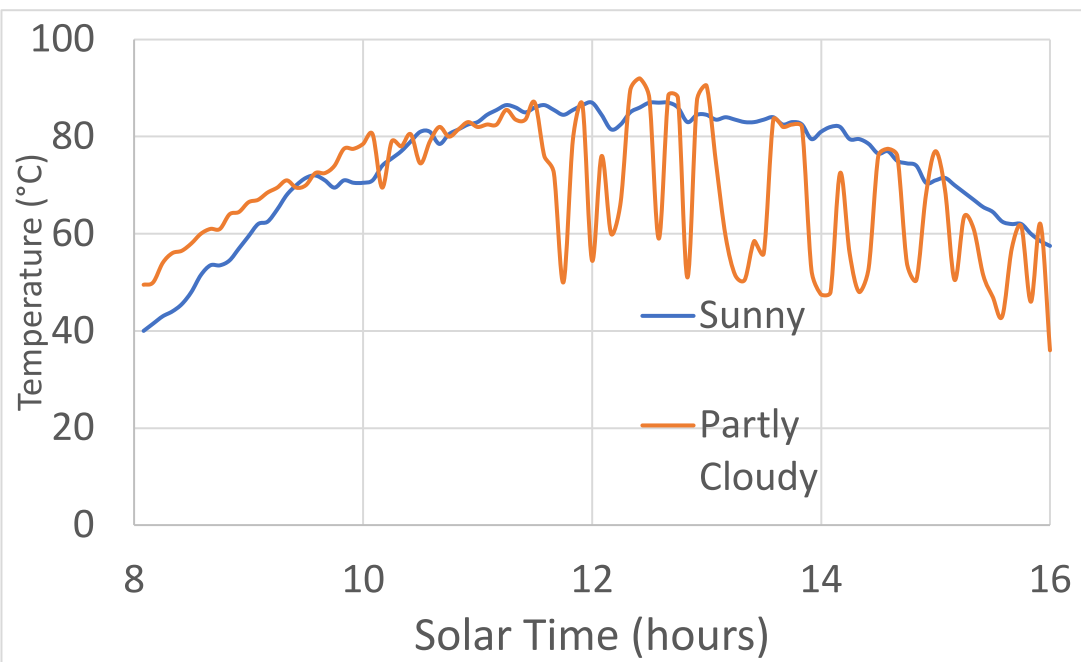

Figure 7: The black plastic surface temperature on sunny and partly cloudy days.

The following graph shows the temperatures of full and ¾ full buckets of water on a sunny day. The effect of a brief passing cloud between 13:00 and 14:00 can be seen. It can be seen that the non-full bucket heated up a good bit faster than the full bucket, but the peak temperature was not a lot different.

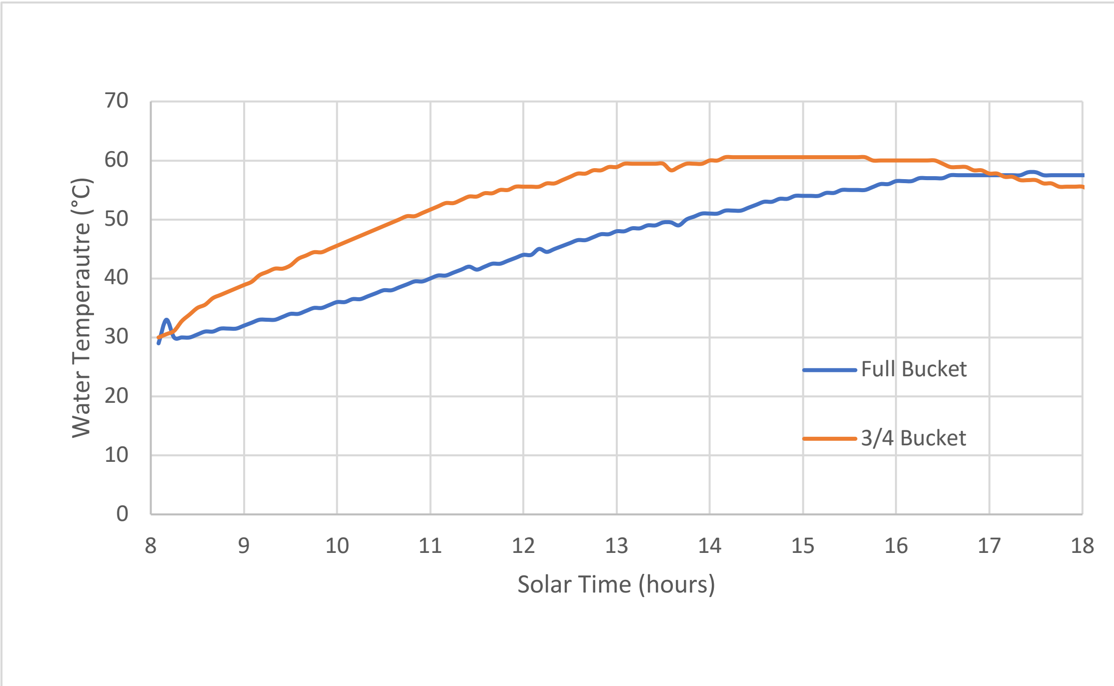

Figure 8: Time temperature traces for buckets of water on a sunny day. The situation is similar to the photo in Fig. 4.

Figure 9 below shows a Solar Household Energy Bank that was set up in less than an hour using materials that were available on site at an educational center just west of Nairobi, Kenya, latitude about 1° south. No test results are available from this site to date, but with the equatorial latitude, the device should work very well. For this device, the black plastic was not used, instead some dark color sheet steel that was left over from a previous construction project was used. There is grass insulation (some is seen in the background of the photo) under the sheet steel to provide insulation.

Figure 9: A Solar Household Energy Bank set up in the field using materials that were available. Inside the collector are two large buckets and a 10-liter jerrycan.

Water for Cooking

Water to be used for cooking can be preheated in the collector using the pot in which cooking will occur. The best arrangement is shown in Fig. 10. It is important that the pot have a lid, preferably a transparent one, or a layer of clear plastic can be placed over the top of the pot. There is a brick under the pot, allowing more heat to get to the bottom of the pot. The results are shown later in the graph in Fig. 13, but 70°C can be achieved.

(Figure 10 shows bricks under the buckets of water, and lids on the buckets. These were features of the non-optimal design that was used early in the design process, and are not needed.)

Figure 10: This photo shows the arrangement of a pot with 5 liters of water, to be used for cooking.

Space Heating

Many parts the developing world are far above sea level and the nights can get chilly. By heating a large amount of water and bringing the buckets inside the dwelling this device can serve as a space heater. The buckets would be taken out of the heater and the lids would be put on, and the buckets would be clustered together and covered with blankets until the temperature cools.

In a test with 6 buckets of water inside the collector, as seen in Fig. 5, the buckets were heated to an average temperature of 49.5°C. This was on a sunny and exceptionally hot day, with a high temperature of about 35°C. Typically, as the number of buckets in the collector goes up, the peak temperature goes down, but not by a lot. Thus, to collect the maximum amount of energy, the maximum number of buckets should be used.

The average net weight of the water in the bucket was 20.1 kg, and in cooling to 20°C the 6 buckets together will release almost 15 MJ of heat energy. This is the equivalent of 4.2 kW-hr of electricity, or about 15 cubic feet of natural gas. Of course, two collectors could be used to get even more energy.

Water Pasteurization

Pasteurization is the heating of a food or beverage, including drinking water, to a temperature sufficient to kill all pathogens. It is NOT necessary to boil the water as many people believe. Boiling is merely a convenient way to confirm that the water is hot enough.

Much microbiological research has shown that 65°C for a few minutes or 60°C for 30 minutes is sufficient to kill all pathogens. Most pathogens are killed by lower temperatures, and typically the more complex the life form, the lower the temperature required for killing. The hepatitis A virus, being a simple virus, requires the highest temperature (Parry and Mortimer, 1984). The larger water containers used in the wash water section are generally too large to reach pasteurization temperatures. Pasteurization is different from wash water heating in that the entire container to be pasteurized must reach the correct temperature, whereas with wash water it is mainly the average temperature that matters. In the data given on pasteurization, all temperatures given were measured at the bottom of the container.

Figure 11: This shows 3 sizes of bottles that can pasteurized. Glass or plastic can be used. The bottles must be angled, as the water at the bottom of the bottle will be significantly cooler than at the top. Painting the bottles black is best, but they work reasonably well in their natural color.

Small containers, up to 2 liters, can reach the pasteurization temperature. Small water containers of various types, sizes, materials, and colors, are commonly available in lesser developed countries. Seven different glass and plastic water containers of various sizes were tested in the heater/drier over the months. The following conclusions were reached:

- Water containers up to 2-liters can be pasteurized in good weather.
- Solar heated water heats and cools slowly, therefore 60° for 30 minutes is more often attained than 65° for a few minutes.
- Smaller containers don't particularly get hotter than larger containers, but they get hot faster. Thus, if the weather is sunny for part of the day and cloudy for part of the day, containers smaller than 2 liters may be needed.
- Dark colored containers work best, but clear containers are almost as good.
- Most bottles are tall, and tall containers will stratify, meaning the water on the bottom will be significantly cooler than the average. Bottles should be filled not quite full, and tilted as much as possible without spilling, as seen in Fig. 11.
- Plastic containers tend to shrink over time, thus, glass is the best material.
- As an added benefit to using smaller containers, using narrow-necked bottles also helps to keep the water from getting recontaminated.

The water can be confirmed to have reached the pasteurization temperature by using an inexpensive reusable pasteurization indicator, commonly known as a WAPI (for Water Pasteurization Indicator). These are available in a variety of designs, some of which fit into a narrow neck bottle. All of the common designs have a sealed transparent tube of glass or plastic containing a wax that melts at the pasteurization temperature. The photo below shows a WAPI containing green petroleum wax. The tube is on a bendable wire, and it goes into the bottle such that the wire is pushed to the bottom of the bottom where the coolest water is located, and such that the wax is in the high end of the tube as in the photo. If

Figure 12: This shows a WAPI (Water Pasteurization Indicator) about to go into the top of a small water bottle. The green wax is in the high end of the sealed glass tube. If the tube comes out later with the wax in the bottom end of the tube, then the water is pasteurized.

the wire is pulled out later and the wax is at the bottom end of the tube, then the pasteurization temperature was reached, even if the water has since cooled down. Pasteurization can often be achieved even if the WAPI doesn't register, as there are days when 60°C is attained for 30 minutes, but the melting temperature of the wax is not reached.

The WAPI can be reused by bending the wire such that the wax is again at the high end of the tube. Other types of WAPIs are available with larger plastic tubes and strings instead of wires. It is important that the WAPI is at or near the bottom of the water vessel where the water is coolest.

Figure 13 shows 3 types of water containers and the temperatures they achieved. These include the 2-liter bottle which reached 64°C, the pot which reached 70°C, and the full bucket which reached 51°C. For the bottle, since the goal was to pasteurize all of the water in the vessel, the temperature measurement was at the bottom of the bottle, the coolest part. The times when the thermocouples were inserted or removed can be seen as the rapid changes in temperature.

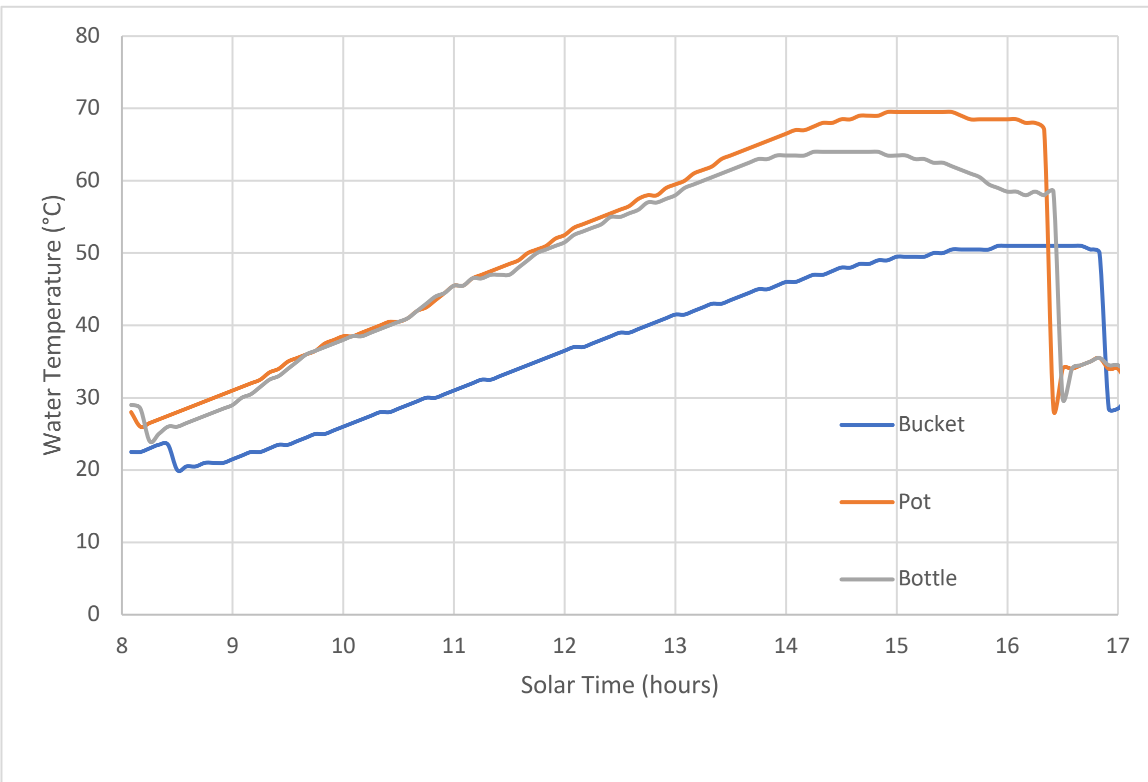

Figure 13: This shows the temperature vs. time curves for water containers of various sizes. For the bottle, the temperature loggers was near the bottom of the bottle, for the other containers it was more in the middle vertically. Data was taken on different days, but all with sunny weather.

Possible Shortcuts

The design shown above is the best design. Other simpler designs are possible, that is, shortcuts can be taken that reduce the effectiveness of the system, but might still be desirable.

The buckets were painted black in the tests given here, but they can be left unpainted, or smeared with mud. If the natural color of the buckets is not dark the performance penalty is on the order of 14%. If the buckets are smeared with mud, the performance penalty is about 4%.

The black plastic layer can be removed and the straw can be used as both absorber and insulator, absorbing the solar radiation, getting hot on the top layer, and insulating the hot top layer from the cooler ground below. The performance penalty for using just straw is about 17%. The results may be different if other insulators are used, and if wet substances are used, such as freshly cut grass, it may take some time to dry the grass, during which time the performance will be worse.

Most tests reported here are for a transparent top layer, but translucent plastic may be more readily available. This type of plastic usually has a whitish tint to it. Tests suggest that the performance of both types of plastic is similar.

Wood Drying

Wood fresh off a tree is very wet and burns poorly. This section is to give results for wood drying, particularly for the sizes of wood that might be used in cooking fires. All wood was hardwood crabapple, from the author's trees. In the author's experience, the ease of burning firewood is a strong function of moisture content, with about 0.18 moisture content (18%) being the upper limit for reasonable burning. Drier is better, but if wood can be dried to this level it should burn well.

Figure 14: The drying tests for unsplit wood are shown. Wood of 5 sizes was tested unsplit, with one size having two pieces, only one of which is given in the data. These were dried for 5 consecutive days.

The basic method of doing drying testing is to cut wood from a tree, cut it to the length and shape desired (that is split or unsplit) and measure its weight each day as the wood is dried. After these measurements are done the wood is dried fully in an oven and the dry weight is measured. At any previous time the moisture content at that time can be back-calculated from the difference between the weight at that time and the dry weight. All moisture contents given below are therefore on a wet basis.

Figure 14 shows some wood drying experiments with unsplit wood. The bucket in the collector is there to provide a working space, though it could be used to provide wash water as well.

It makes a large difference whether the wood is split lengthwise or not split. As would be expected, split wood dries much faster than unsplit wood. Looking first at the split wood, data is shown below in Fig. 15. This shows 4 sizes of wood and the progress of drying over several days. The wood was cut from the tree at about time 0. The legend gives the size of the original piece of wood before splitting.

For 3 of the sizes one piece of the split wood was dried inside the collector and the other half of the same piece was dried outside the collector, under cover but not in the sun. The pieces were not split very evenly, and in all cases the smaller half was the half that was dried outside the collector. These are the dashed lines in Fig. 15. The fact that the wood was not split evenly makes the smaller half dry faster than it would have if the pieces were split evenly. It is believed that the general trends still hold, regardless of differences in the sizes of the wood pieces.

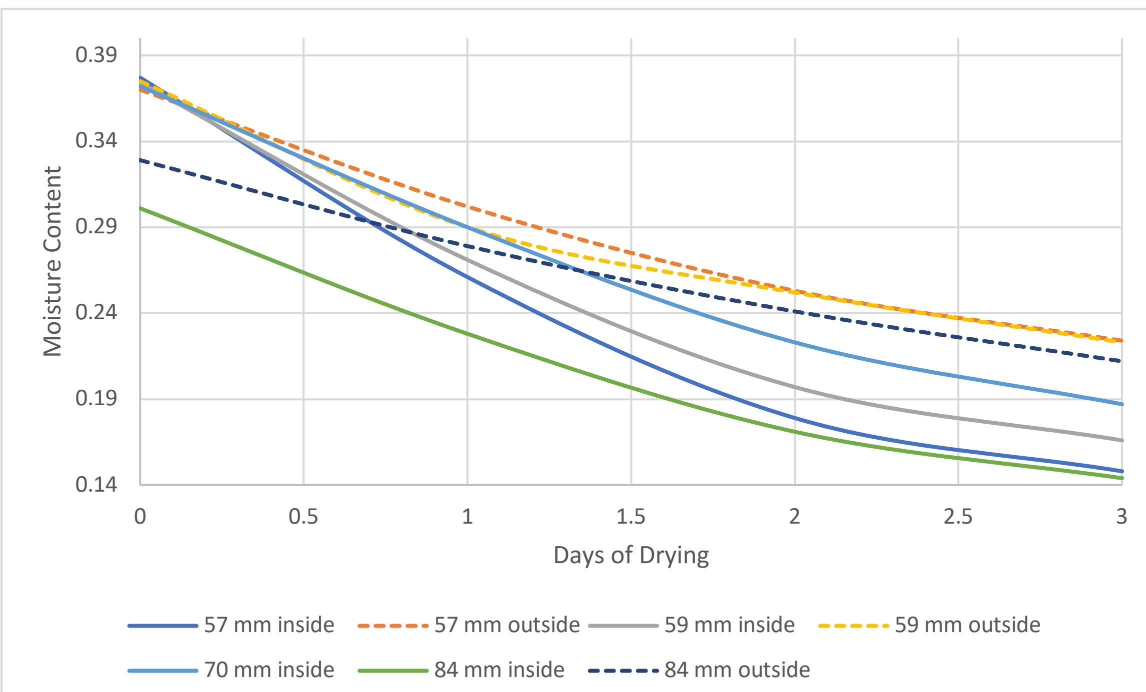

Figure 15: Moisture content vs. days of drying for 4 sizes of split wood.

It can be seen that the wood in the collector dried faster than the wood outside, but that all pieces dried considerably in 3 days. Depending on the needs of the user, it may or may not be an advantage to dry the wood in the collector. If the user has many days to let the wood dry before burning it, there is no need for the collector. If the user needs to burn the wood soon after it is taken from the tree, it will be an advantage to use the collector.

Except for the 70 mm piece, the tests here were done on 3 consecutive days and the weather on those days was mostly sunny. The 70 mm piece was tested earlier and dried on 3 consecutive days with strong sun on most of each day. The 70 mm piece therefore saw somewhat stronger sun that the other pieces.

The graph below shows moisture content for 5 pieces of unsplit wood of various sizes. The legend gives the approximate diameter of the wood pieces. The graph shows both the number of days of drying in the solar collector after 0, and the results of about 1.5 days of drying without being put into the collector before day 0. It can be seen that the moisture content drops by some amount during the 1.5 days after the wood was cut from the tree but before it was put into the collector, but dried faster when it was in the collector. As a rule of thumb, the drying rate was about 4 times faster in the collector as outside.

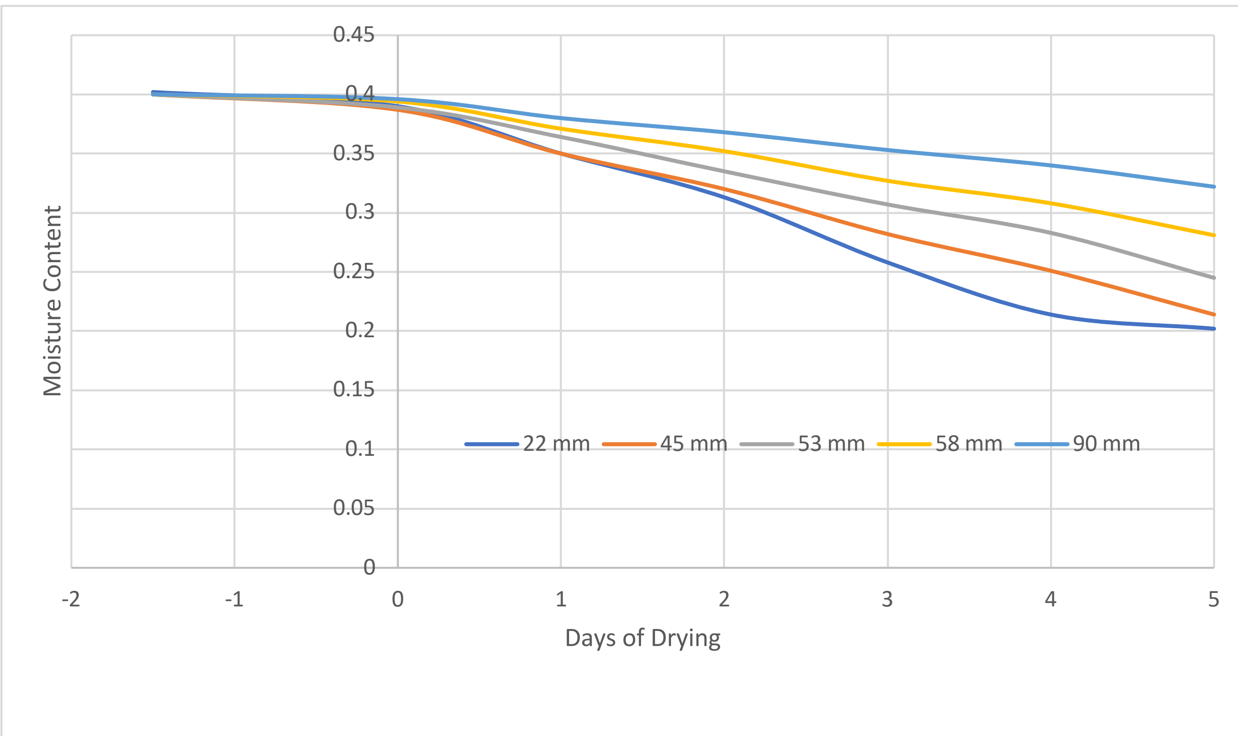

Figure 16: This shows the approximate moisture content of unsplit wood during the time after it was cut from the tree. The wood was in the collector for 5 days (after the 0 time) and it was off the tree for about 1.5 days before going into the collector. The legend shows the approximate diameter of the wood.

Since it was very difficult to dry the larger pieces of wood entirely, it was assumed that all pieces started out at the same moisture content as the measured moisture content of the smallest piece, which was 0.402, or 40.2%. All wood pieces were dried on the same days, and these were 5 consecutive days that were all partly cloudy. Any variations in weather would affect all pieces similarly. When not being dried in the collector the pieces were removed from the collector and covered, to protect them from rain or dew.

As expected, the larger wood pieces dry slower than the smaller ones. The unsplit wood dried much slower than the split pieces, although part of this difference would be a result of the less sunny weather seen on the days with the unsplit wood. As expected, the drying rate before going into the collector (the time before 0 days) was much slower than the drying rate after going into the collector (the time after 0 days). Even with the solar collector it takes considerable time to dry unsplit wood to 18% moisture.

It is useful to look at a single narrow size range. One might ask, is it more effective to split the wood and not put it in the collector, or leave the wood unsplit and put it in the collector? One could potentially save themselves the work of splitting the wood. The figure below shows data for the pieces in the 55-60 mm range.

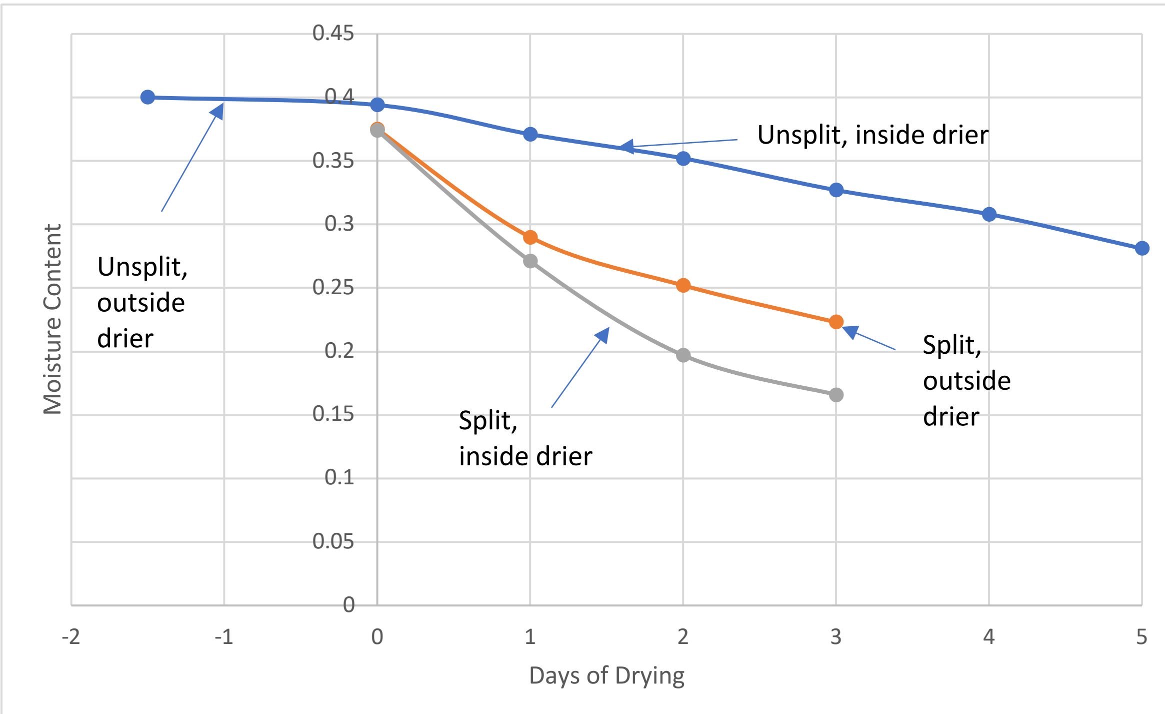

Figure 17: This shows the drying rates of pieces of wood of similar original size.

For the unsplit wood it can be seen that it dried little in the 1.5 days before going into the drier, then dried faster, about 5 times faster, inside the drier. The split wood dried faster whether it was inside or outside the drier, and fastest of all inside the drier. Thus, if one already has split wood it may not be necessary to dry it in the drier. If one has unsplit wood it is necessary to dry it as fast as possible. If one has the luxury of waiting 8-10 days to dry unsplit wood in the drier, one could do this instead of splitting the wood, saving themselves the work of splitting it.

Corn Drying

Beans, corn, and other grains are commonly dried by leaving them out in the sun for some time. The process can be accelerated by using the drying function of the device.

For a series of tests 3 kg of field corn, sold commercially as squirrel feed, was soaked in water, then spread out in a layer of about 1 cm depth. The corn was then dried on 3 consecutive days while other tasks were being done, primarily wash water heating. See Fig. 18. The corn was spread over a separate smaller black plastic layer on top of the main black plastic layer, so that the corn could be gathered up easily by gathering up the smaller layer.

Figure 18: This shows how 3 kg of corn can be dried while performing other tasks simultaneously. This photo shows an early design when bricks were still being used under the water buckets. Later designs omitted these bricks and improved the performance.

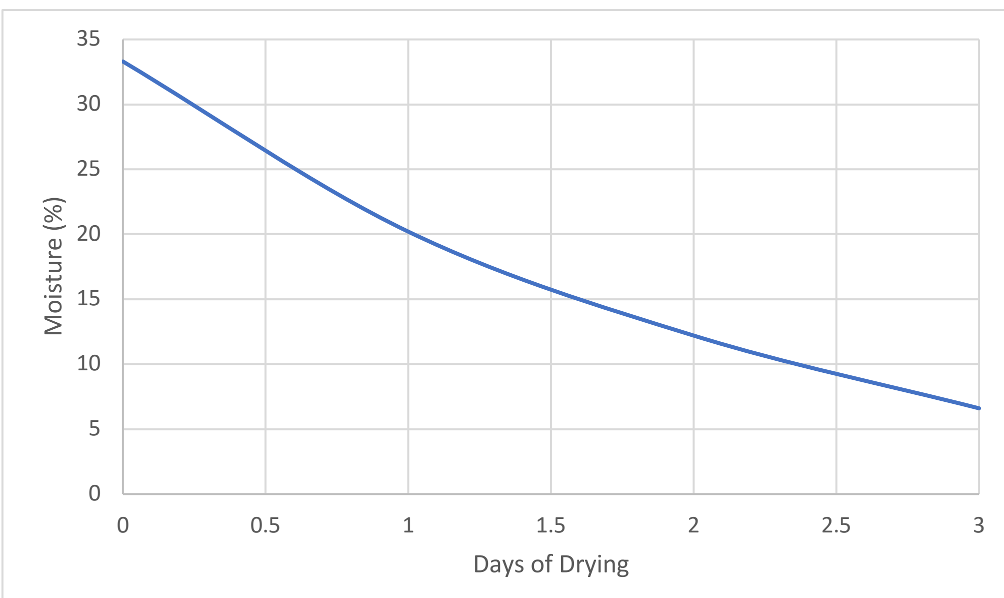

Figure 19: This shows the moisture content of the corn in % after the specified number of days of drying.

The drying results are shown in the figure above. As with the wood, after the drying was done in the solar collector, the grain was fully dried in an oven to get the dry weight. From this dry weight, plus the moist weight at any other time, the % moisture at that time can be back-calculated.

Insect Egg Killing

In some areas Putzi flies are common, which lay eggs in wet laundry while it is drying on a clothesline, then when the person puts on the clothes the eggs hatch and the flies bite the person. One solution is to iron every bit of laundry, a tedious and energy intensive process. In other areas, bed bugs are common.

Research has been done on the times and temperatures needed to kill worm eggs (Feachem, et. al., 1983). Hookworm and taenia eggs are killed by a few minutes at 60°C or 30 minutes at 55°C, and schistosoma eggs are killed by slightly lower temperatures. Ascaris (roundworm) eggs are notoriously heat-resistant, and require slightly longer times. The heater/drier can be used to heat clothing to this temperature after the clothing is dry. As described previously, the device does not work well as a clothing drier, therefore, the proper way to use this device is to heat and disinfect the clothing after it has been dried.

Figure 20 below shows how the items can be arranged. In the middle of the system is a bucket partially full of water, which is primarily to provide an air space but which could be used to provide wash water. On the right of the bucket is a towel folded into thirds, with a temperature logger under the towel. On the left are 3 pillowcases stacked, such that there are 6 layers of thin cloth above the temperature logger.

Preliminary testing showed that the laundry must be stacked such that there are minimal air gaps between the layers, as seen in Fig. 20. If the laundry is randomly piled there will be large air gaps and the lower layers don’t get hot enough.

Figure 20: Arrangement for using the heater to kill insect eggs. There is a temperature logger under each stack of clothing.

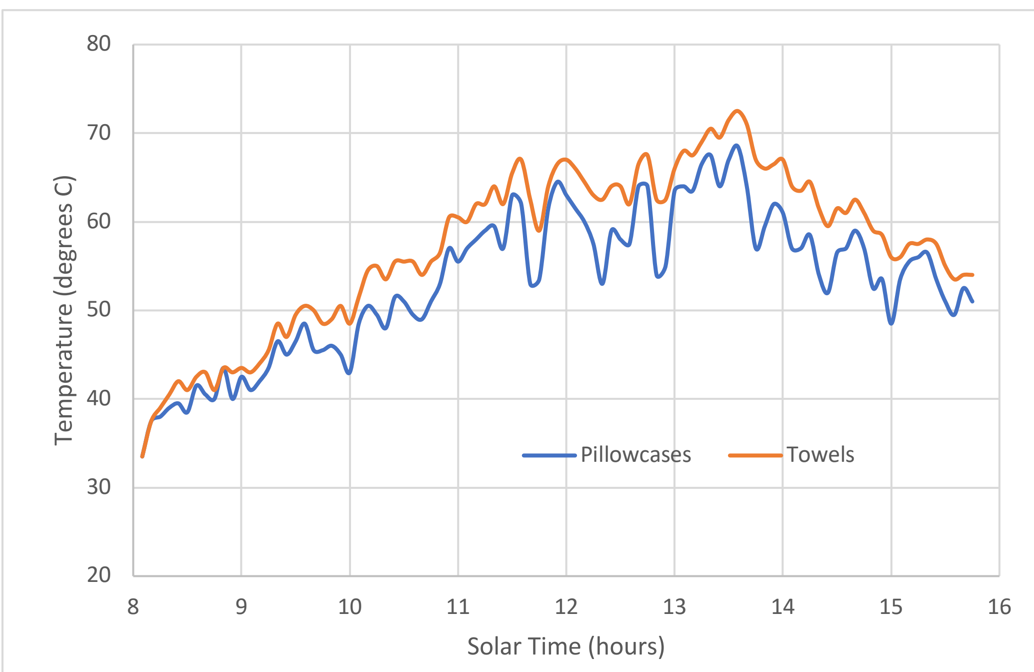

Figure 21: Temperatures at the bottom of a stack of two types of clothing. Weather for this test was mostly cloudy, hot, and windy.

With the laundry properly stacked as in Fig. 20, on both sides the temperatures far exceeded the 55° requirement, as seen in Fig. 21. On this day the weather was mostly cloudy, windy, and hot, with a high temperature of 33°C. Since the laundry heats up quickly it would achieve the required temperature after an hour or less near the middle of a day with reasonably good weather, that is, not too cool and not fully cloudy. Multiple sets of laundry could be disinfected on a good day. On days with cooler cloudier weather, it is likely that one set of laundry could still be effectively heated.

To register that adequate temperatures had been reached, one could potentially build a lower temperature version of the WAPI, one that registered at 60°C. This could be done with meltable wax or with one of the nickel-based memory alloys that change shape at a set temperature.

Longevity

While this device is inexpensive, it is made mostly of thin plastic that does break down over time with the combined effects of ultra-violet light and heat. The most vulnerable part of the system is the top clear layer. In some tests clear 0.8 mil plastic (0.0008 inches, or 0.02 mm) was used. This broke down in about a month and is not recommended. In other tests, 3 mil plastic (0.003 inches or 0.073 mm) was used that lasted about 3 months. UV stabilized plastic could be used that would last longer but be more expensive. The black plastic is not exposed to as much UV light as the clear, since it is somewhat protected by the clear plastic. Still, it gets hotter than the clear plastic and does break down also. The black plastic typically lasts 6 months.

The plastic can be used for other purposes after it is no longer useful on the collector.

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