Low Cost Solar Household Energy

October 29, 2019 (1st revision)

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Introduction

This document contains two major sections. The first section 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. The second section is about solar water heaters that are intended to be inexpensive, but not as inexpensive as the device in the first section. These are more special-purpose devices, they only heat water, and some pressure source is needed to make them work (in other words, piped water from a tank or tap). The two sections of this document are independent, one can study the first section or the second, without reading the other section.

A video covering both devices is at https://youtu.be/6Z6snha3uHE

Part I-The General Purpose Solar Heater/Drier

Introduction

Part I covers a general purpose solar heater and drier. 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 solar 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.

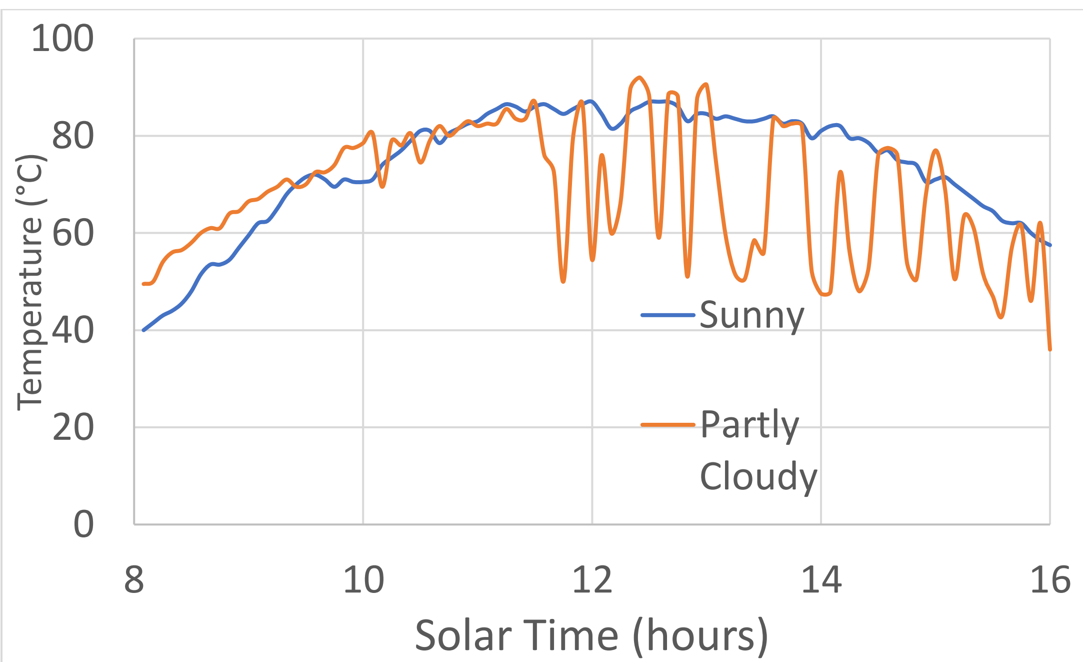

Figure 7: The black plastic surface temperature on sunny and partly cloudy days.

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.

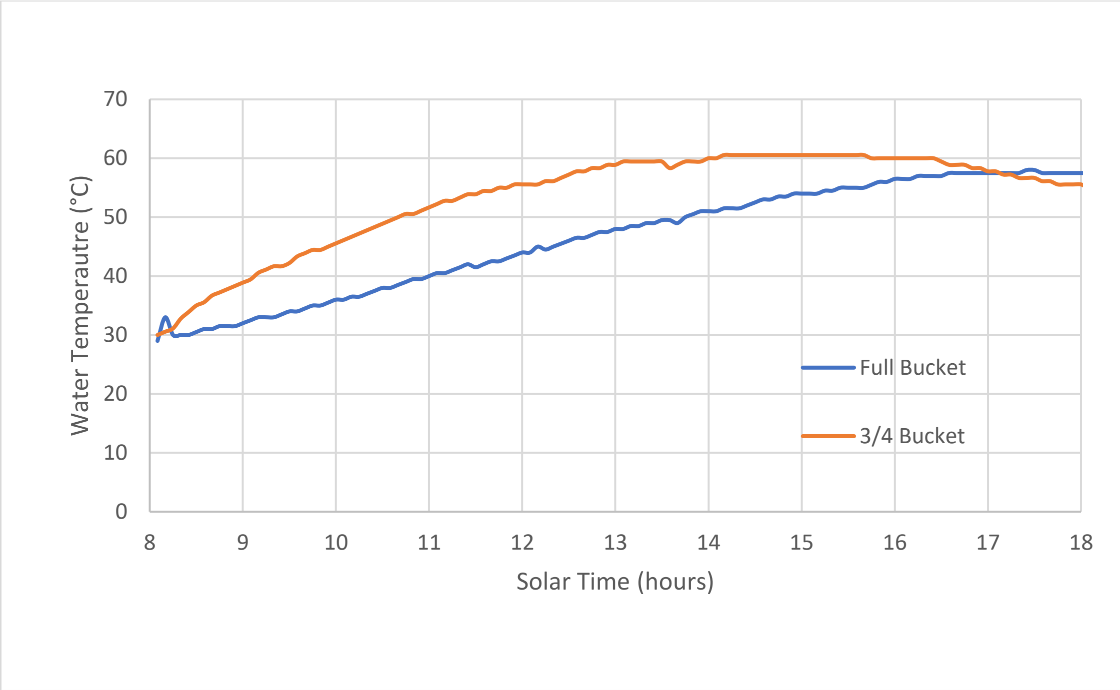

Figure 8: Time temperature traces for buckets of water on a sunny day. The situation is similar to the photo in Fig. 4.

Figure 9 below shows a solar heater/drier 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 heater/drier 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.

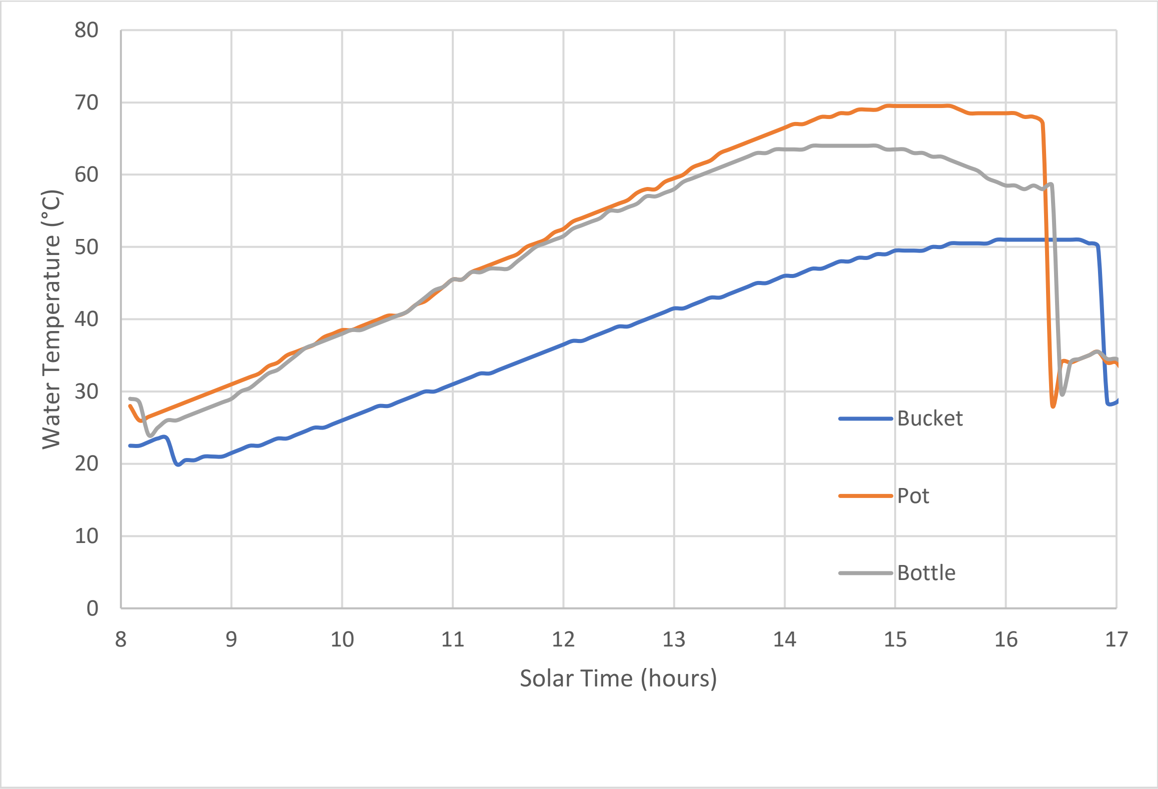

Figure 13: This shows the temperature vs. time curves for water containers of various sizes. For the bottle, the temperature loggers was near the bottom of the bottle, for the other containers it was more in the middle vertically. Data was taken on different days, but all with sunny weather.

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.

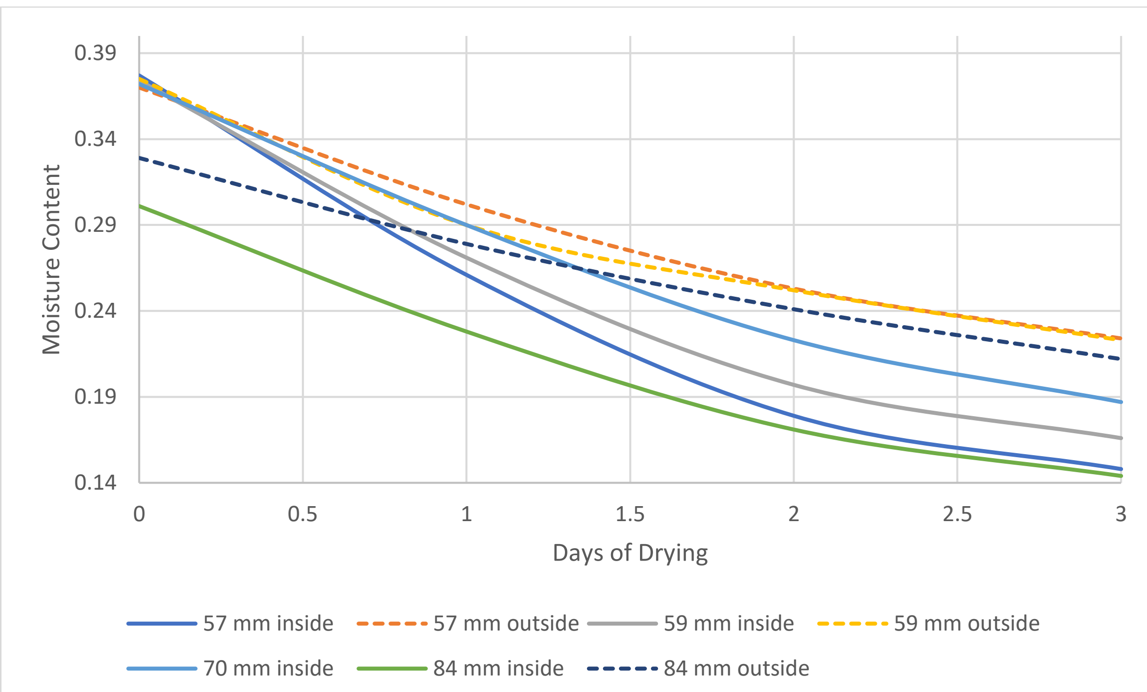

Figure 15: Moisture content vs. days of drying for 4 sizes of split wood.

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.

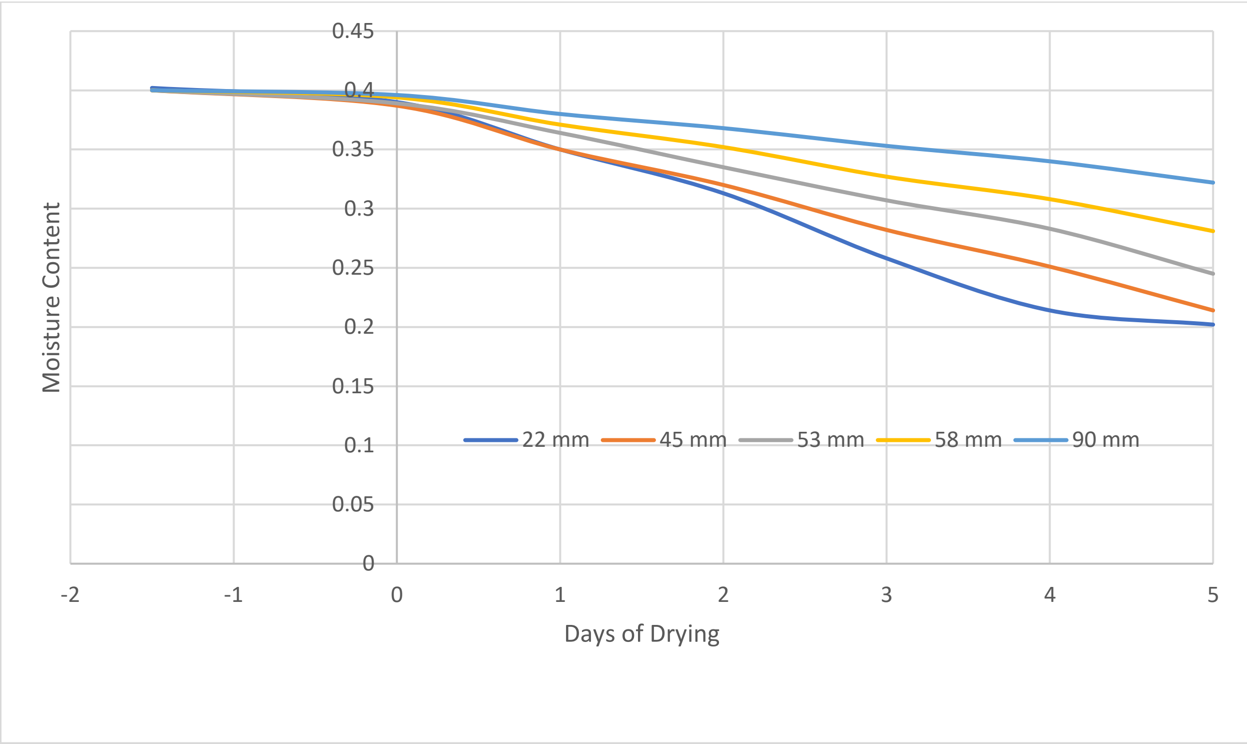

Figure 16: This shows the approximate moisture content of unsplit wood during the time after it was cut from the tree. The wood was in the collector for 5 days (after the 0 time) and it was off the tree for about 1.5 days before going into the collector. The legend shows the approximate diameter of the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

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 50-60 mm range, and shows that splitting the wood and leaving it outside the collector is more effective, by about a factor of 2, than leaving the wood unsplit and putting it in the collector. Wood lost 14% of its original weight when split and left outside the collector for 3 days, vs. about 7% when unsplit and in the collector for 3 days.

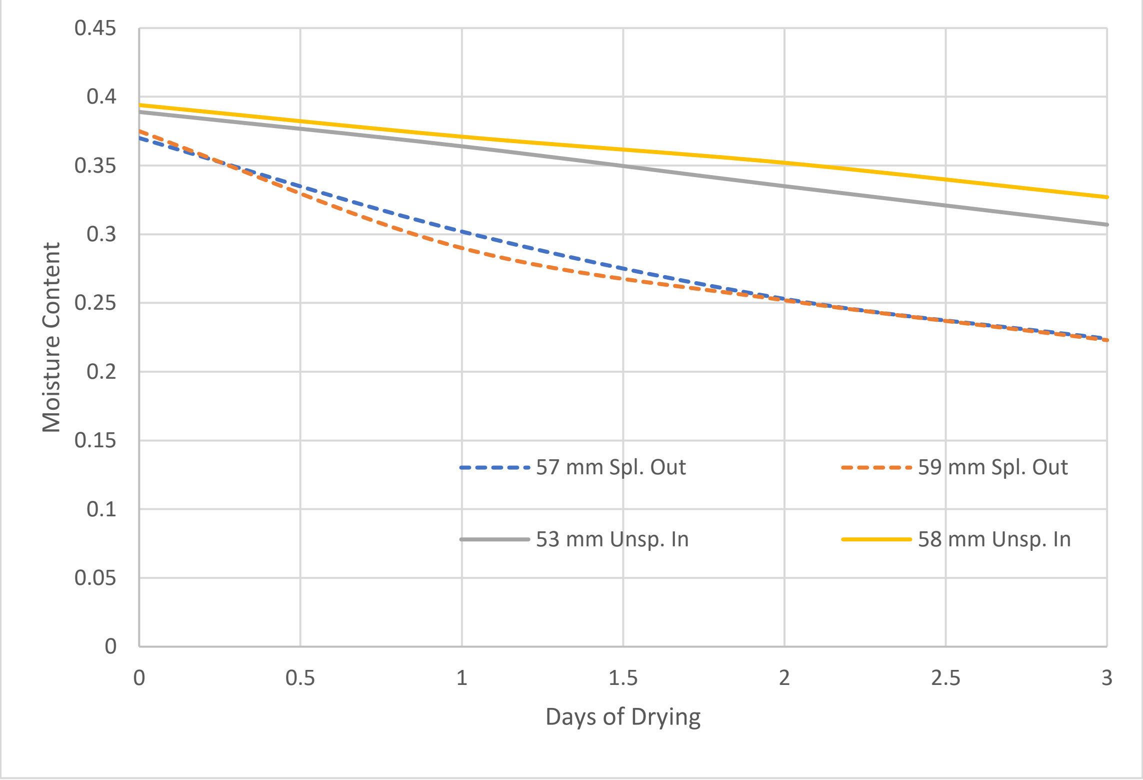

Figure 17: This shows the drying rates of 4 pieces of wood of similar original size.. Two of the pieces were split and left outside the collector, two pieces were unsplit and put into the collector.

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.

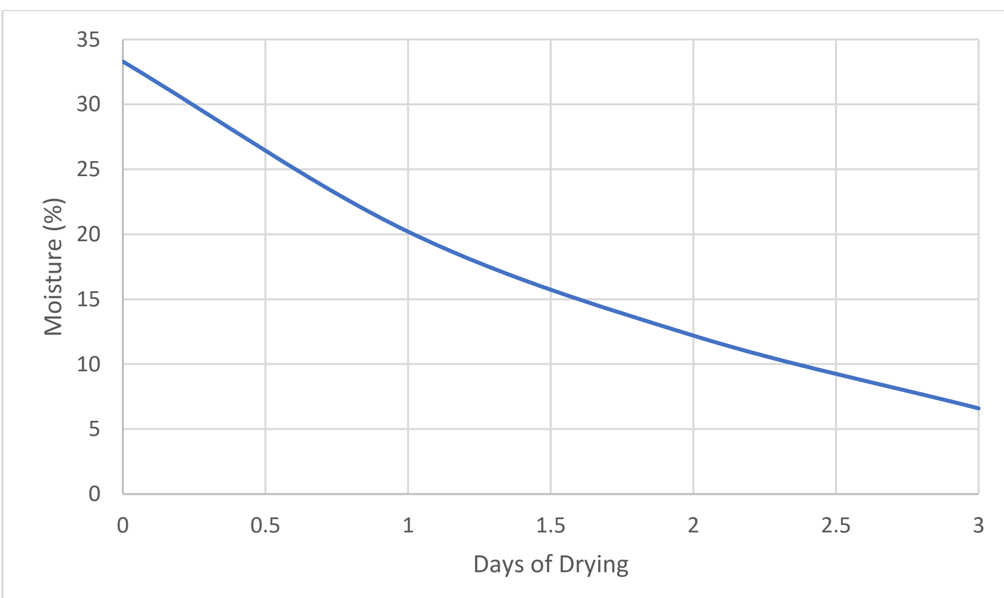

Figure 19: This shows the moisture content of the corn in % after the specified number of days of drying.

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.

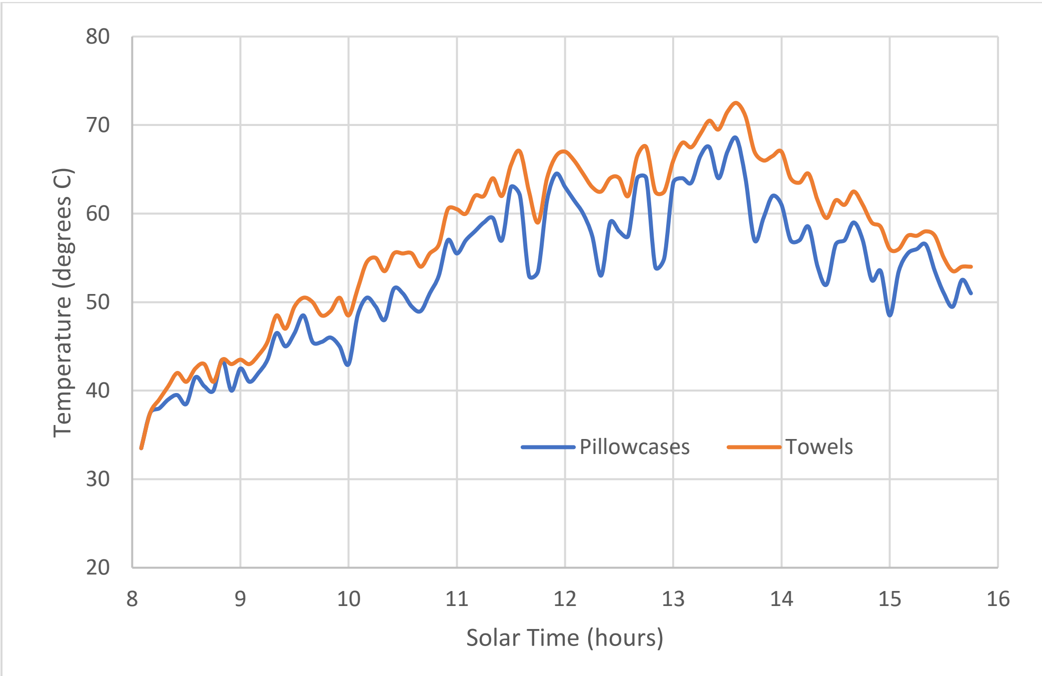

Figure 21: Temperatures at the bottom of a stack of two types of clothing. Weather for this test was mostly cloudy, hot, and windy.

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.

Part II-Two Types of Solar Water Heaters

Introduction

Part II of this document describes two variations on an idea for a low cost water heater than can provide piped hot water. These options are not as inexpensive as those described in Part I, they are more for people who have a little money to spend.

The problem to be solved here is that many good solar water heaters are available, and they are robust, efficient, and well-engineered, but very expensive. Figure 22 shows a typical water heater seen on many houses around Nairobi. The cost is typically about 115,000 Kenyan Shillings, or $1150.

Figure 22: A commercially available solar water heater of a type commonly seen around Nairobi, Kenya.

One possible application for the proposed water heater would be for a family that has piped cold water, and they want to have piped hot water. Another application would be for a hotel or lodge which currently has electric hot water, and they want to use solar energy to preheat the water going into the electric tank, so as to reduce their electric bill. In Africa, almost all hot water is heated by electricity.

The Solar Puddle, a Partial Solution

Some years ago I developed the solar puddle, a very low cost method of heating a lot of water (Andreatta, 2001). It is, more or less, a puddle in a greenhouse, insulated on the bottom to prevent heat loss into the ground, and with one or more air gaps on top to prevent heat loss into the atmosphere. The water puddle is formed by two plastic sheets, one of which must be black.

A cross section of a very simple form of a solar puddle is shown below.

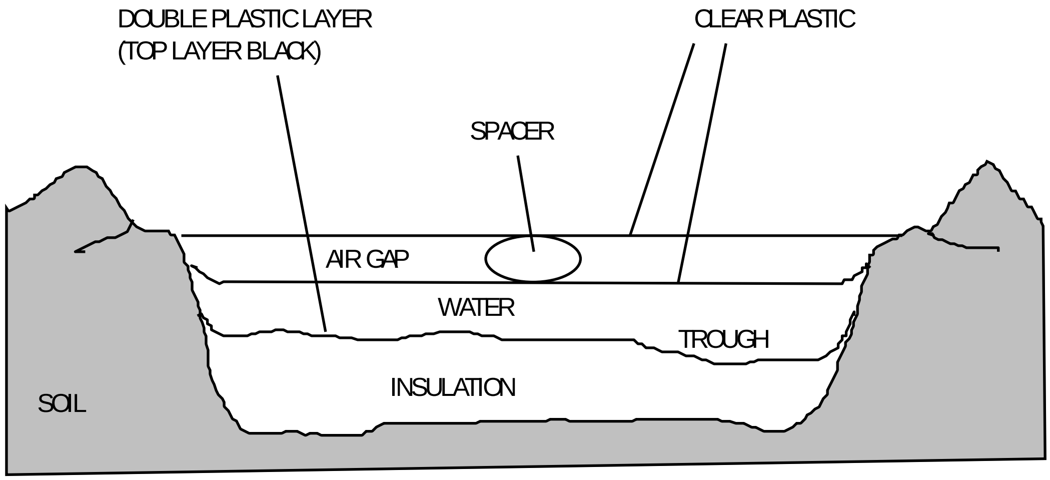

Figure 23: A cross section of a basic solar puddle built into the ground. Horizontal dimensions are compressed for clarity.

Some photos are below of the solar puddle (with wooden sides) used in these tests are shown below.

The amount of solar energy collected is proportional to puddle area, and so is the amount of water present. Thus, the temperature of the water is mostly determined by the depth of the water layer. If the water is 3 cm deep, 80°C can be achieved on a sunny day. If 5 cm, 60° can be achieved, if 10 cm, 50° can be achieved.

The problems with the puddle, and the likely reasons why it has never caught on, is that it is difficult to get the water out of the puddle, and also that the water tends to start growing heat-resistant algae after a while unless all the water is drained out. The two ideas presented here are means of working around these problems.

For both variations the puddle serves as a very low cost energy collector, then the question becomes how to get the heat from the puddle into the flowing water where the heat is needed.

Figure 24: The frame of the solar puddle. There is 19 mm of insulation. The area is 2 square meters.

Figure 25: The solar puddle with about 5 cm of water, but without the top layers of plastic. Two layers of plastic are used to line the frame, the top one is black and the lower one can be any color. The boards in the water will be used as spacers for the tube or tank, which will be described later.

The Puddle with Tube

A metal tube with cool pressurized water at its inlet is run through the puddle. The length of the metal tube is typically 6-18 meters. The water will come out of the tube significantly hotter than it went in. If the tube is long or if the water is only flowing slowly, the water will come out at essentially the puddle temperature. If the tube is short or if the water is flowing swiftly, the water will come out significantly warmed, but not as warm as the puddle. See photos below.

Figure 26: This shows the metal tube inserted in the puddle with fresh water and some wood spacers under the tube so that it is toward the top of the water layer. The tube has a length in contact with the water of about 5.8 m, much shorter than the optimum.

Figure 27: A layer of clear plastic has been placed over the water to prevent evaporation.

Figure 28: Wood spacers have been placed over the clear plastic layer.

Figure 29: The complete solar puddle with tube is shown here, with another layer of clear plastic placed over the spacers seen in the previous photo. Together, these form an air gap a few cm thick between the clear plastic layers. See also the cross section in Fig. 23.

Mathematical modelling of this system can and has been done. Most of the elements of the model are easy to calculate accurately, and the only item that is difficult to calculate beforehand is the heat transfer coefficient between the water in the puddle and the water in the metal tube. For this, experiments were done using the setup seen in Figs. 24 through 29. The purpose of these tests was twofold, first, to measure the heat transfer coefficient, and second to demonstrate the basic idea in a near-final arrangement. For each of the four experiments a value of the heat transfer coefficient was calculated. The four values agree with each other, with an average of 827.5 $W/m^2/°C$. This value was used in calculations of the overall system, to be described later.

Figure 30 shows a typical outlet water temperature trace, as well as the puddle temperature and the inlet water temperature. When the water was turned on at time 0 the first water to come out of the system was essentially at the puddle temperature as this water was sitting stagnant in the pipe for a long time, immersed in the hot puddle water. After about 100 seconds the outlet water reached a quasi-steady state where the outlet water was about halfway between the puddle temperature and the inlet temperature. This situation should continue indefinitely, with the puddle cooling as heat is pulled out of it by the flowing water. About 8 gallons (31 liters) of warm water was produced in about 4 minutes. Had the flow rate been lower or the copper tube been longer, the outlet water temperature would be closer to the puddle temperature. Had the flow rate been higher or the tube shorter, the outlet water temperature would be closer to the inlet temperature. The actual tube length, 5.8 m, was rather short in these quick proof-of-concept experiments, hence the outlet temperature is much lower than the puddle.

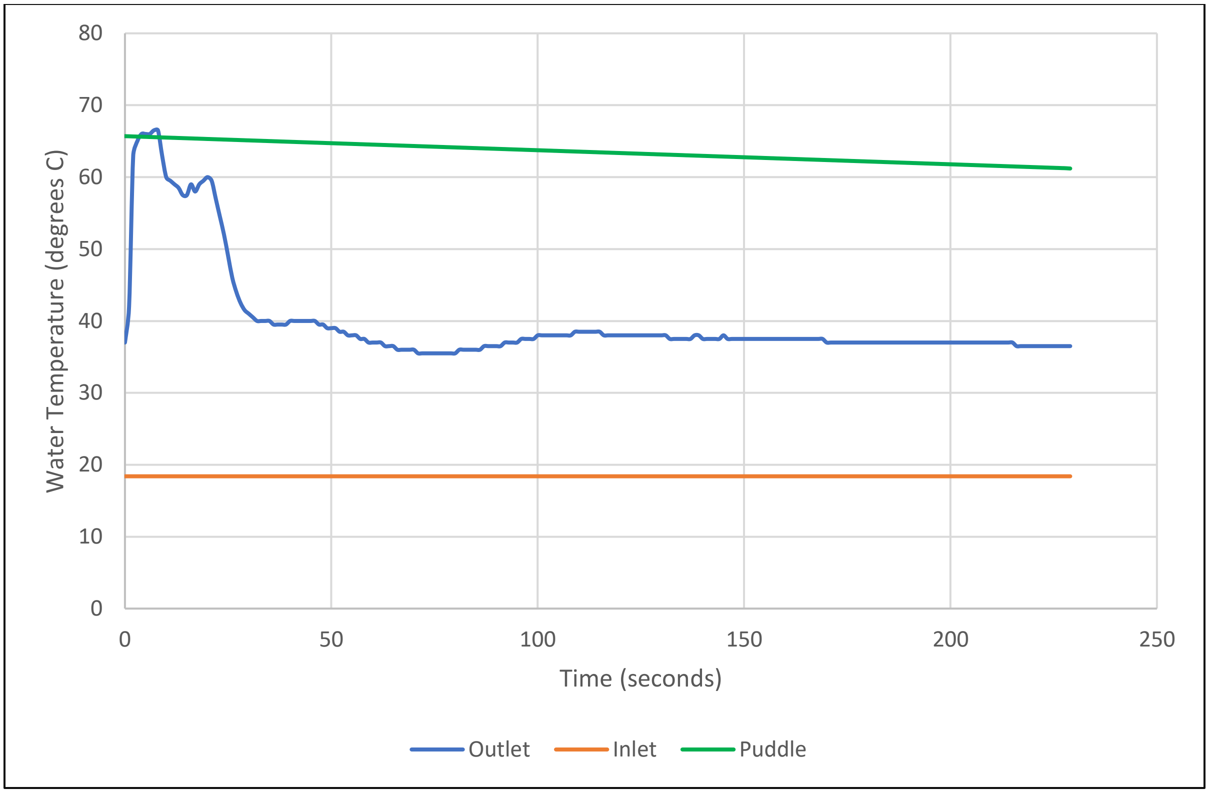

Figure 30: Water temperatures for the tube in puddle system. Time 0 is the time when the flow started. Water flow rate for this test was 120 g/sec, or about 2 gallons per minute. Other tests gave similar results.

Calculations can be done to optimize the design for a given requirement. For example, if the user uses most of the hot water during the day, the puddle can be made less deep so that it gets really hot, then a shorter metal tube can be used so that the outlet water is not scalding hot. Conversely, if you want hot water to be available into the evening hours, then a deeper puddle would be used, not getting as hot as a shallow puddle but staying hotter after the sun went down. A longer tube could be used, so that the water coming out would be almost as hot as the puddle. If the user wanted only a small amount of water but wanted it really hot, perhaps as preheated water for cooking, they could use a shallow puddle and a slow flowrate to get the hottest possible water.

Looking at some calculated results for the entire system, Fig. 31 shows the puddle temperature and outlet water temperature as a function of time through the day. Assumptions about system size and water usage were made that might be typical of a system for a small hotel. It is assumed that the weather is sunny, the area of the puddle is 3 square meters, the water flow rate is 120 g/sec (about 2 gallons per minute) when water is flowing, but that the tap is only open 10% of the time. The water inlet temperature, puddle starting temperature, and ground temperature are all 20°C, and the tube is 18 m long and 0.0156 m (5/8 inch) in outside diameter.

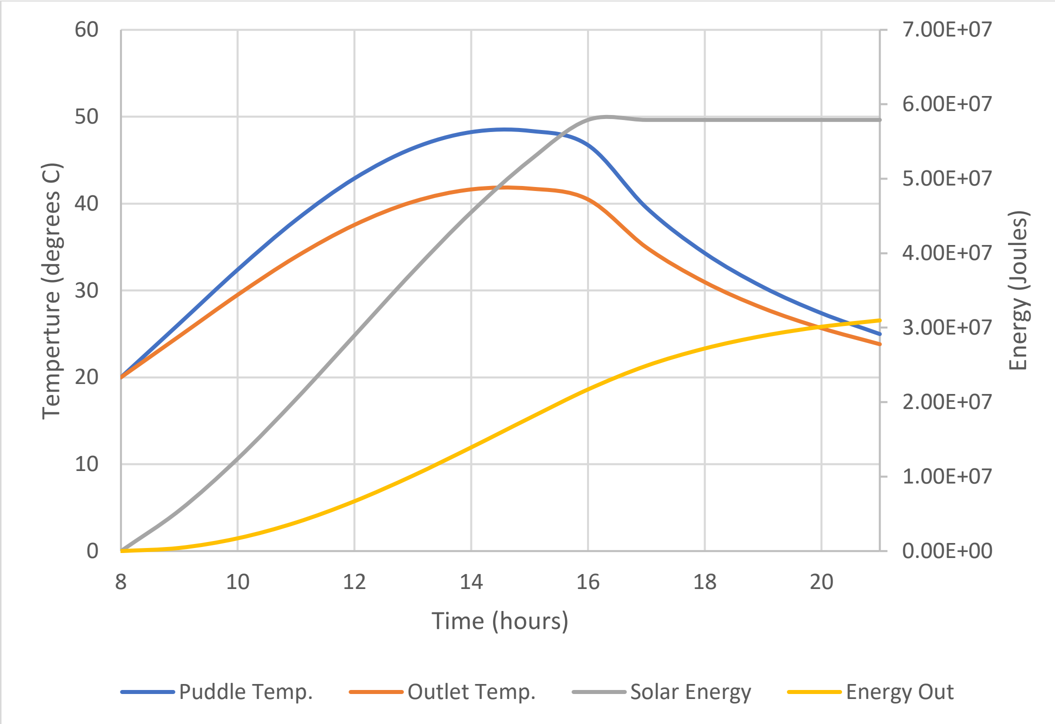

Figure 31: This shows calculated results for the solar puddle with tube water heater. The total solar energy received and the total energy output are shown using the right vertical axis, and the puddle and water outlet temperature are shown using the left axis. The sun is assumed to be too low in the sky before 8 am and after 4 pm to do any effective heating.

The figure also shows the total solar energy that has struck the system over the day, and the total energy that has gone into the flowing water. With the assumptions previously given, over the course of the day about 60 MJ of solar energy struck the puddle, 605 kg (617 liters or 160 gallons) of water flowed through the system, and 31 MJ (8.6 kW-hr) of energy ended up in the hot water to give an efficiency of 0.535. For a hotel, additional heat to the water would be supplied through an electric tank, and the solar system serves to reduce the electrical demand. These calculations, supported by the basic experiments as described, show that this very inexpensive system has potentially high energy transfer and high efficiency.

Africa has very limited fossil fuels, and almost all hot water is heated by electricity. At an electrical cost of $0.1524/kW-hr (Kenya retail price in 2016) $1.31 is saved in a day. The system will pay for itself very quickly. The idea could be used on the ground as in the photos above, or could be adapted to make a rooftop unit. Mass produced trays and covers could be made in kit form that would replace the solar puddle and could be easily transported and set up in a couple hours, not counting the additional plumbing to and from the building where the water will be used.

In Liberia, which had the highest electric rates in Africa in 2016, over 3 times the money would be saved. In places with economies that are generally less developed with businesses having slimmer resources, saving small amounts of money on the electric bill can be important to the success of a business.

The details of the calculations are available on request.

Puddle with Tank

A downside of the above system is that it does not store energy well. After the early part of the evening the puddle gets cool. It is possible to use a tank, through which the water to be heated flows, to store energy longer. The lower part of the tank is in contact with the water in the puddle, with the upper part of the tank insulated. During the day heat flows from the puddle to the lower part of the tank, heating the water and causing it to rise into the main part of the tank. When the puddle cools, the water in the lower part of the tank gets cool, but the water stratifies and the water in the bulk of the tank stays warm. Water is drawn from near the top of the tank, which is where the warmest water is located.

As with the tube system, the tank system is easy to model mathematically except for the heat transfer from the puddle to the tank. Basic experiments were done to measure these heat transfer rates. See photos below for the experiments. The tank must be metal for good heat transfer

Figures 32 and 33 show the experimental arrangement, beginning with the same solar puddle as seen in Fig. 25. The purpose of this rough experiment was to measure the heat transfer coefficient between the water in the puddle and the water in the barrel, not to test the system in final form. This is different from the tube in puddle tests, where the system was closer to its final form.

Figure 32: Solar puddle with the test tank. The barrel is full nearly up to the large hole, with about 125 kg of water in both the tank and in the puddle. The water is covered with bubble wrap, which forms a simple but reasonably effective translucent insulation.

Figure 33: This shows the final form of the tank experiment. The insulation around the tank keeps the tank warm and allows a more accurate measurement of the heat transfer coefficients.

The temperature rise of the tank is measured over time, as well as the temperature of the puddle over the same time. The average difference between the puddle temperature and the tank temperature can be calculated, along with the energy absorbed by the water in the tank. These items, along with the area of the tank in contact with the puddle water can be used to calculate an overall heat transfer coefficient. The average of the 3 tests that were done was 164 $W/m^2/°C$, and the values were consistent over the 3 tests.

Calculations can be done to optimize the system for the usage. For example, if the user used a lot of hot water then a deeper puddle and a larger tank would be in order. If only a little water was used, then a shallower puddle and a smaller tank could be used, or perhaps the tube system would be a better option.

Using the experimentally measured heat transfer coefficient, the results for the same inputs as previously used for the tube and puddle system are shown in the figure below. The assumptions about the weather, area and depth of the puddle, and usage rate of water are identical to the tube system, with the volume of the tank assumed to be 50 gallons (193 liters) the area of the tank in contact with the puddle assumed to be 0.343 square meters. The temperature of the tank and the puddle are given. Cool water passes into and through the tank, exiting at the tank temperature. The energy in the tank includes both the water that was warmed and passed through the tank, as well as the energy stored in the tank at a given time. By the end of the day, 25 MJ have been collected and the energy left in the tank is available for use during the night. Assuming no more hot water is used after 9 pm, the overall efficiency is 0.417.

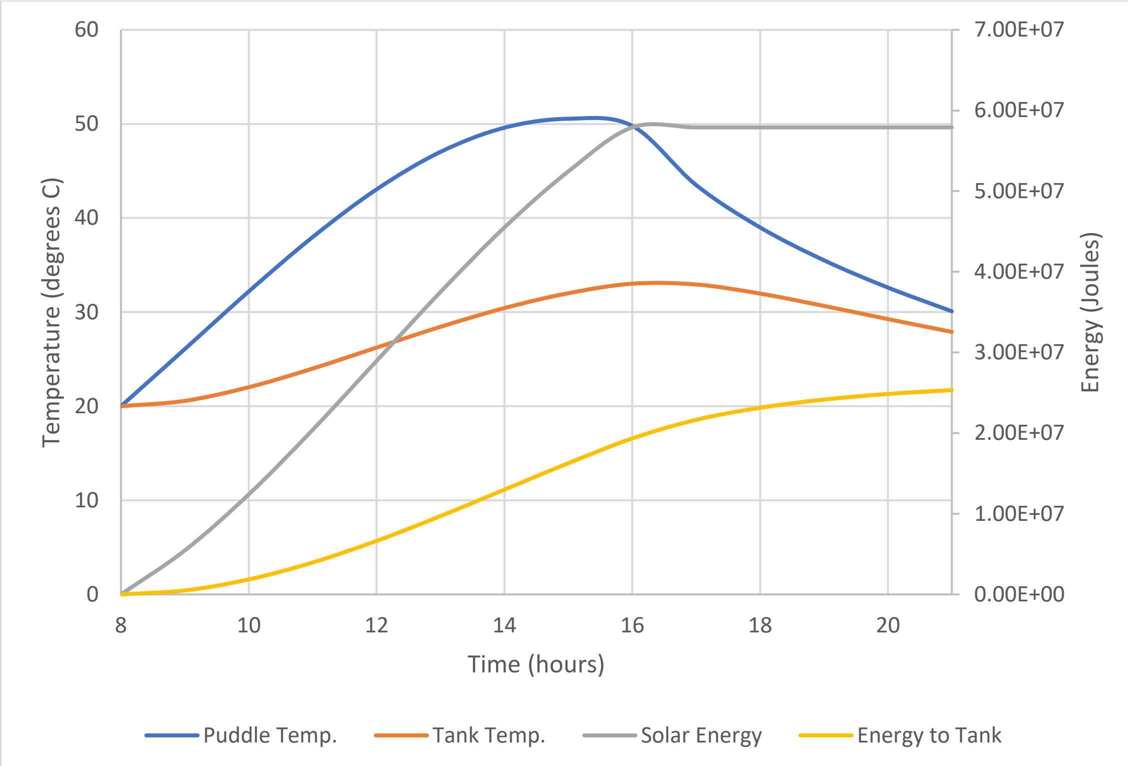

Figure 34: The results for the puddle and tank system using assumptions identical to those used to produce Fig. 31.

For these conditions the tube system is more efficient, however this is strongly dependent on how much water is used. The tank system has the advantage over the tube system that heat is being transferred from the puddle all the time, while for the tube system heat is transferred from the puddle only when water is flowing. If the water usage had been less, or the water flowing less frequently than 10% of the time, the tank would have been the more effective option.

Again, calculation details are available on request.

Future Work

Both versions of the solar water heater will be tested more extensively in the future using setups that are closer to final form.

In addition, an even simpler system will be tested using a barrel of water standing upright, but without the solar puddle. Rather, a larger version of the black plastic system similar to the systems in Part I of this document, will be used. A metal tube will run through the water in the barrel to transfer heat to the potable water. Before tests begin, modeling will the done to determine the optimum parameters and the likely performance.

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