Passive Solar System to Store Heat for Cooking

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Abstract

A passive solar heat storage system for cooking is constructed and tested. The system is designed to convert excess electricity to high temperature heat (about 240 degrees C) and store it for cooking applications at times when needed. When electrical batteries are full, the Photo Voltaic (PV) power is directed to a heat storage. Wind and hydro turbines can provide excess electricity in the same manner, through a diversion controller for a battery. For the AC case, the heat storage can replace dump loads which are used to provide a constant load for hydro or wind generators. The current tests are made with power from PV panels directly, without batteries, using a dedicated load controller for the heating elements.

The system is based on oil as both a heat transfer and a storage medium. Care has been taken to make it as simple as possible, in order for it to be produced and maintained in small work shops. The flow is gravity driven and a mechanical thermostat valve controls the storage temperature. A prototype system and some cooking tests are presented. The system is scalable and the main purpose of the prototype system is to replace fire wood with solar energy for cooking at rural, off-grid locations (schools etc).

Keywords: solar heat storage, solar cooking, heat batteries, PV to heat, dump loading to cooking heat

1. Introduction

The number of people getting access to electricity is increasing, but the grid extension in rural areas of the African continent will still take time (UNDP, 2018 and IEA, 2017). The slower electrification rate compared with other regions is generally due to remoteness of locations, lack of infrastructure and non-economical grid expansions (Chmiel and Bhattacharyya, 2015).

The International Energy Agency has reported in a forecast, that over half of the additional electricity demand needed to meet the target of universal energy access, is expected to be provided through off-grid systems (Mandelli et al. 2016a). Others have estimated that 2/3 of those gaining energy access in rural areas will do so through an off-grid system powered by either hydro, wind, solar or a hybrid system (Mandelli at al. 2016b).

Electrical batteries, charged by Photo Voltaic (PV) panels, can provide power for households for low power applications (light, refrigeration, cell phone charging etc), solar water heaters can provide hot water but power for cooking is lacking for off grid households. Rural areas rely heavily on biomass for cooking (UNDP 2018, Karekezi and Kithyoma, 2002), where wood and charcoal are the most commonly used fuels. The number of people depending on biomass for cooking is also estimated to increase over the next 25 years (Cuce, 2013 and Hammond, 2010).

Direct solar cookers, where a cooking device (concentrators, box cookers) is placed in the sun, have not gained wide spread use. Heat storage technology for cookers is still largely missing, see the reviews by Mawire (2015), Nkhonjera et al. (2017) and Sharma et al. (2009).

A long term university collaboration between several African universities and the Norwegian University of Science and Technology has included development and testing of several methods for solar heat storage, such

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that cooking can be made after sunshine hours. Direct collection of solar heat with concentrators (parabolic dish or troughs) is more energy efficient than indirect collection using PV panels and heating elements (PV efficiencies are typically 10-15%). However, solar concentrators for delivering useful heat at about 240 degrees C require solar tracking and a heat transfer loop between the absorber at the focal point and the heat storage. This involves some precision in the construction of reflectors, solar trackers, controllers and pumps or fans for both charging and discharging of the heat storage.

An indirect solar heat collection and storage system is presented here, where electrical power is converted and stored as heat for cooking. The system which is tested is without electrical batteries, but the heat storage can be just as well interfaced with general off grid power systems, both AC and DC systems. The heat storage then offers an energy storage option such that excess power, from PV panels or from hydro or wind dump load controllers, can be accumulated in the form of cooking heat.

2. System

A system has been designed and constructed under the following main requirement specifications:

- The system should be robust and simple, requiring minimal maintenance and operational concerns.
- The storage and cooking system should be fully mechanical, without sensors, pumps, motors, batteries, controllers etc.
- The system should be affordable and possible to produce locally in small work shops.
- The system should be operationally safe and without environmental risks.
- The system should be scalable.
- The storage system should be possible to interface with PV systems (stand alone or with batteries) as well as with hydro and wind dump load controllers.

The system is schematically shown in Figure 1 and has three main parts:

- Heat Storage Unit
- Heating Module
- Cooker Unit

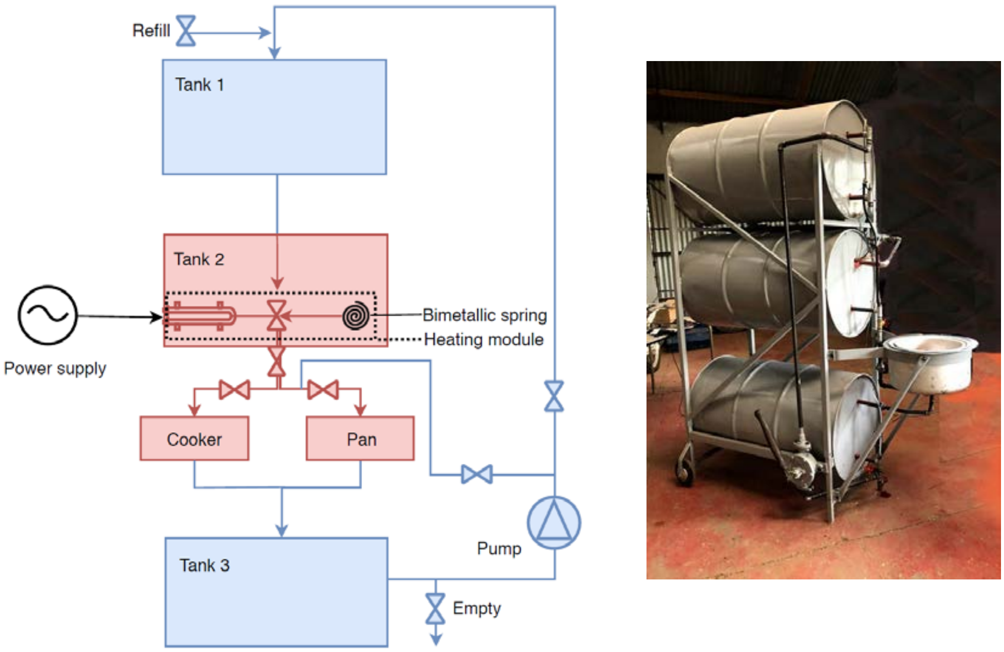

Fig. 1 Schematic layout and picture of the solar heat storage system

Concept

Three tanks are stacked on top of each other. Each tank has an inner tank, with insulation between the inner and the outer tank. The top tank holds cold oil and is connected to the middle tank which contains heating elements. The flow from the top to the middle tank is governed by a mechanical thermostat immersed in the hot oil. As the hot oil temperature reaches a threshold temperature, the thermostat valve opens for cold oil to enter the middle tank. During the day, the hot oil level in the middle tank rises and keeps the threshold temperature (typically 240 degrees C).

Several applications can be positioned between the middle and the lower tank. The test system has a single cooker, with about 10 liters capacity. Opening a valve gives a gravity driven hot oil flow through the cooker and the residual oil ends up in the lower tank. The flow rate determines the power given to the cooking pot. The prototype system has a cooker attached to the rack, but the cooker could also be located indoors, with oil pipes through the wall.

At the start of the next day, or during the day if the cooker is in use, the residual oil in the lower tank is hand pumped to the top tank, and ready to feed the middle tank according to the power on the heating elements.

Heat Storage Unit

The middle tank is the heat storage unit, containing high temperature oil. Palm oil was used in the test system, but as the palm oil would tend to solidify at low temperatures, in particular after thermal cyclings, a synthetic heat transfer oil would be preferable. Other edible oils have also been tested for high temperatures by Mawire et al. (2014).

A constant temperature heat storage is desirable for cooking applications. This can be achieved by using a latent heat system (Phase Change Material, PCM) and the “Solar Salt” nitrate mixture has a suitable melting point of 220 degrees C. A liquid sensible heat storage method can also be designed to give a constant outlet temperature if a thermocline can be maintained in the storage. If hot oil is entering at the top of a vertical container, cold oil will leave at the bottom. With careful operation, the top part remains separated from the cold part by a thermal front. Hot oil similar to the inlet oil temperature can then be recovered by reversing the flow.

As it can be difficult to maintain a sharp thermocline layer, and as a pump was to be avoided, we designed a batch system based on separate storage tanks for the hot and cold oil.

Heating Module

The heating module consist of heating elements inserted into the middle storage tank and a mechanical thermostat which opens for cold flow at a given pre-set temperature. The mechanical thermostat is based on a bi-metal spring which expands with the temperature.

The heating elements must be designed according to the available power source. In the present tests, PV panels were used for powering the heating elements directly. If a battery system is used, with an inverter to provide constant AC voltage, then a single heating element can be applied, as the voltage level is fixed. For the case with direct heating from PV panels, several heating elements with a load controller is useful, as the PV voltage will drop during cloudy periods. Two heating elements were applied in the current tests, and Figure 2 shows the power arrangements, including also power for an Arduino data logging module. The logging module is not needed for the operation of the system but was included to monitor the system by logging temperature sensors to a memory card.

The Power box includes the main switch and Mosfet power switches for the two heating elements, as controlled by voltage set points in the Controller box. When the power produced from the PV panels pass a certain threshold value, both heating elements are turned on by the controller board in order to utilize the available capacity. In the same way, to obtain as much heat collection as possible, one of the heating elements was turned off when the level dropped below the adjustable threshold voltage value.

6 PV panels were used in the test setup, giving two types of benefits. One is that voltage reaches values such that standard 220 V heating elements could be used. The second is that the total power from the panels (up to about 1.8kW) is sufficient to allow for immediate cooking, without the need to wait for hot oil accumulation in the heat storage tank. The heat storage acts as a buffer, absorbing the excess cooking power in the form of a rising hot oil level.

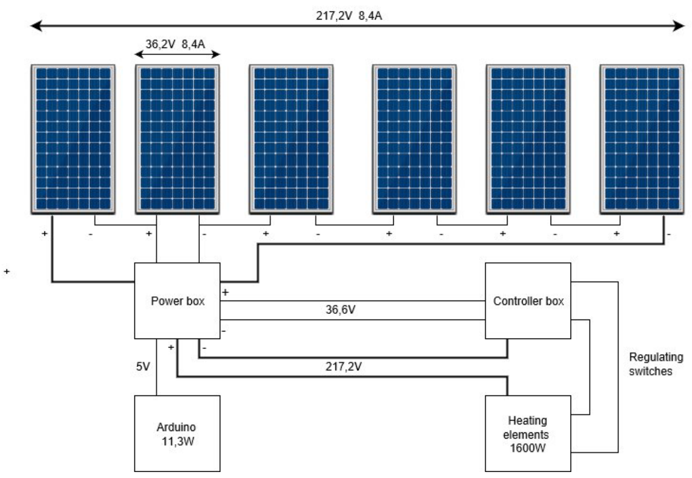

Figure 2 PV power module for the heating elements

Cooker Unit

The heat storage tank is designed to supply hot oil for both a cooker and a frying pan. In the current protoype, only a cooker was installed.

In order to achieve an efficient heat transfer rate, the cooker was designed such that the cooking pan is in contact with the hot oil coming from the hot oil tank, see Figure 3. This allows also the use of bulky cooking pots. Hot oil comes from below and flows past the cooking pot from the centre and up some distance on the walls before leaving over an overflow and into an annulus draining slot.

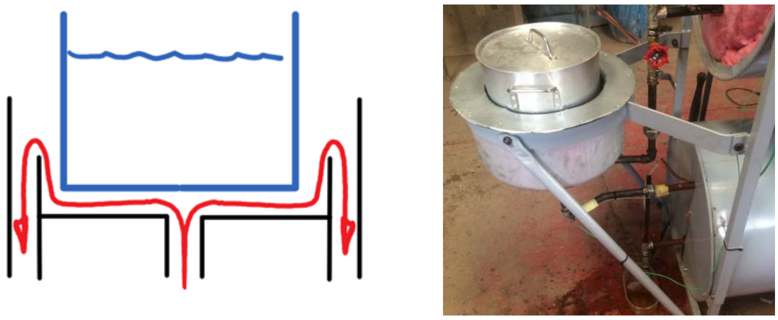

Figure 3 Principle and picture of cooker with the flow of hot oil

3. Tests

PV Power on a cloudy day

Some tests were made in both full sun shine and in partly cloudy conditions. Figure 4 shows the recorded power from the PV panels to the heating elements on a cloudy day. The fact that the power levels were significant even without full sunshine also illustrated one benefit of using PV panels instead of solar concentrators; a concentrator would give close to no power in the absence of direct sunshine.

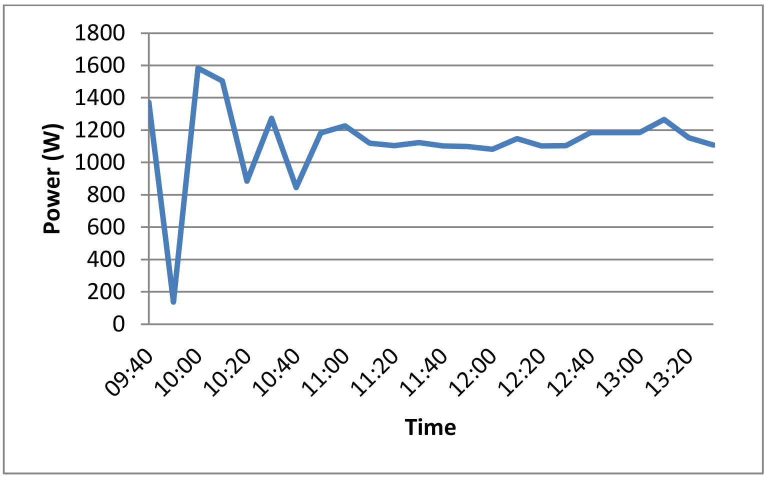

Figure 4 Recorded power from PV panels on a partly cloudy day

Boiling water

Figure 5 shows the temperature recordings during heating of 10 liters of water to the boiling point. The boiling point was reached after about 13 minutes. This was made with a high oil flow rate, giving a high heat transfer rate but also a high temperature of the oil leaving the cooker (about 150 degrees C). 2 liters of water was likewise brought to cooking in 3.5 minutes, which was faster than an electrical boiler (7 minutes).

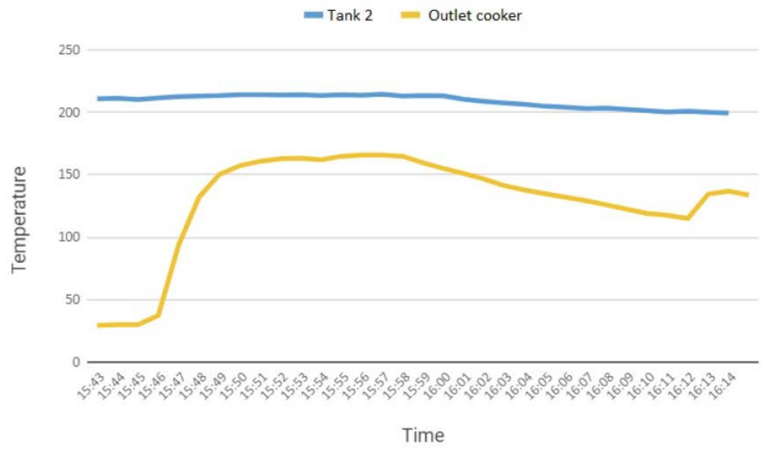

Figure 5 Temperature recordings during heating of 10 liters of water to the boiling point

Cooking rice

Figure 6 shows the recording during cooking of 1 kg rice (about 10 portions). The rice was brought to boiling at a higher oil flow rate, then the flow rate was adjusted to a minimum to keep the rice just simmering during the cooking. The oil temperature in the storage tank was about 220 degrees C. During cooking, the oil leaves the cooker with a temperature close to the boiling point, and ends up in the lower tank with slightly less temperature due to thermal losses in the pipes and the lower tank.

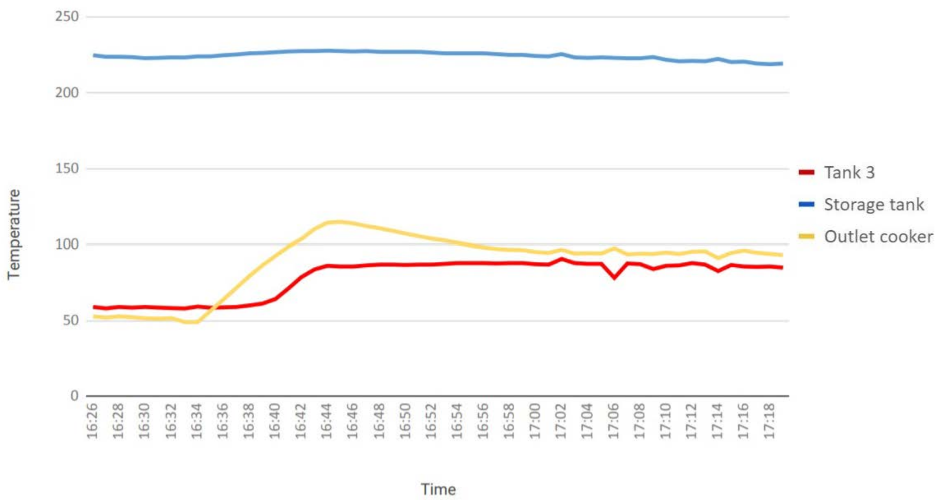

Figure 6 Temperature recordings during cooking of 1kg rice

About 12 litres of oil was used for the boiling of the rice. The rice was over cooked, but nevertheless did not stick to the bottom of the pan. The residual 12 liters of oil in the lower tank reduced its temperature from about 80 degrees C to about 45 degrees C during the night period. Figure 7 shows pictures of the cooking. The thermal picture shows also high temperatures in the gap between the pot and the cooker wall.

Figure 7 Pictures of cooking 1 kg rice

4. Conclusions

A solar energy system to store and provide solar cooking heat when needed has been built and tested in Arusha, Tanzania. Palm oil was successfully used as both heat transfer medium and heat storage medium, but a synthetic heat transfer fluid is expected to have better cycling behaviour. The oil was heated by directly connecting PV panels to two heating elements in the oil, without the use of electrical batteries. A load controller successfully routed the PV power to one or two elements according to the sun intensity.

A mechanical thermostat valve is able to control the accumulation of hot oil (about 240 degrees C) in a storage tank. A gravity driven flow through a cooking unit was sufficient for controlling the time for heating of water and for coking of rice. The cooker responds very quickly to the change in the hot oil flow rate.

The use of firewood or charcoal for cooking is discouraged in Tanzania, and the presented solar system can provide a robust and affordable alternative. The system is mechanically simple and should be possible to be produced and maintained by local workshops. The system is scalable and suitable for implementation at institutions which have to provide daily cooking for many people (schools, hospitals, restaurants etc).

5. Acknowledgments

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