A Review of Solar Cooker Technology

Solar Thermal Energy Design

Caitlin Trethewy z3241063

Session 2, 2011

1 INTRODUCTION

Solar cookers are defined as devices that capture the Sun's energy and use it to cook food. Solar cookers were first developed in the 18th century and although they are a relatively simple application of solar thermal technology, interest in the area has continued into the 21st century. This interest is driven by the potential for widespread application of solar cookers in developing countries. These devices offer users a clean alternative to traditional biomass. The intended application of solar cookers is driving the development of low cost, low maintenance and easy to use devices. Within the area of solar cookers there are many devices based on different design and operating principles. The two main categories are solar cookers with storage and those without however within these categories there are numerous sub categories. The design and operating principles of each category of solar cooker will be discussed and newer cutting edge technology will be included in the discussion of the category that it falls under. In recent years research has been focused on developing large-scale solar cookers that could be used on community buildings and developing solar cookers with heat storage that could be used at night or in cloudy conditions.

2 HISTORICAL DEVELOPMENT

In ancient times people developed many ways to harness the Sun's power. Ancient Greeks, Romans and Chinese were all known to have used curved mirrors to concentrate the Sun's rays however they were primarily interested in its military applications [1]. Around 1860 Napoleon III Emperor of France commissioned the development of solar cookers for his troops stationed in Africa. These cookers used parabolic reflectors to concentrate beam radiation into a cooking pot and were a forerunner to today's concentrating solar cookers [2].

In the sixteenth century glass became sufficiently inexpensive to be widely used to keep tropical plants alive in European greenhouses. Using this knowledge of the greenhouse effect Horace de Saussure built the first solar cooker in 1767 and continued to experiment with the technology throughout his life [1-3]. Over the following years others followed his lead and began to use plane mirrors to increase the amount of solar radiation incident on the cooking vessel [1, 3]. However throughout the centuries following Saussure's invention interest in solar cookers repeatedly dropped when cheaper alternative fuels such as coal became available and spiked again when those fuels became more expensive [1].

Contemporary applications of solar cooking were pioneered in the 1950s by Maria Telkes, a scientist working at the Massachusetts Institute of Technology (MIT) [1]. In 1959 she constructed a solar oven with four main reflectors, between which there were four smaller triangular reflectors (Figure

1). This oven could reach a temperature of 225°C and is widely considered the forerunner of today's box type solar cookers [3]. During the latter half of the 20th century governments began investing in solar cooking technology in response to oil shocks, energy shortages and growing populations in India and China. In 1981 the Chinese Government began to distribute subsidized solar cookers [1]. Research into solar cookers is now being undertaken by various groups all over the world.

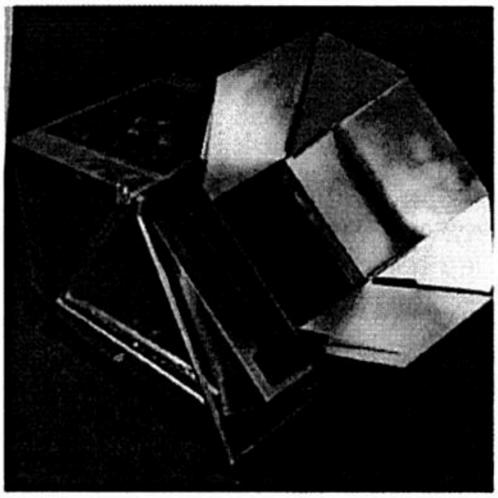

Figure 1 the pot stove developed by Maria Telkes [2]

3 DRIVERS AND BARRIERS

Contemporary interest in solar cookers is largely driven by their potential for application in the developing world. At present, more than three billion people use traditional forms of biomass such as fuel wood, animal dung, and coal as their major sources of energy for cooking [4]. This usage has harmful health, ecological and social impacts that could be greatly reduced through the adoption of solar cookers. Cooking represents a large portion of developing countries' primary energy consumption; it accounts for 36% of India's primary energy consumption [5]. If this energy were derived from a renewable resource such as solar, it would have significant environmental benefits.

Cooking with traditional biomass causes indoor air pollution (IAP) which is known to have serious health effects, particularly to women and children who are often responsible for cooking [6]. The World Health Organisation estimates that in 2002, 1.5 billion people died from diseases caused by IAP [4]. The use of traditional cooking fuels also has harmful ecological impacts as growing demand for fuel wood is leading to deforestation and soil erosion [7, 8]. Moreover, burning these fuels produces greenhouse gas emissions and destroys trees that would otherwise be sequestering carbon dioxide [4]. Likewise, the use of animal dung as a cooking fuel means that it is not used as a fertilizer and useful organic nutrients are lost [7]. The collection of traditional fuels places an enormous burden on women and children who often have to travel very far in order to collect fuel [3, 6], as forest deplete further these journeys become longer and the price of fuel increases [7].

Solar cookers present a viable solution to the problems posed by traditional methods of cooking in the developing world. They are clean and have a minimal impact on the local environment. They have virtually no running costs [3] and their usage is likely to free up the time women and children would have spent collecting fuel. This would allow them to pursue other activities such as work or education. It is for these reasons that there is enormous international interest in the promotion of solar cookers as an alternative to traditional energy sources.

Despite the many benefits attributed to solar cookers there remain barriers to their wide scale deployment. Studies have found that very few of those who purchase a solar cooker continue to use it over a long time period [9]. The sunny space required by the solar cooker can be a barrier [3, 9], particularly to its usage in the urban areas of the developing world that are typically characterized by high population density. Solar cooking can also take a long time, particularly using box style cookers which may take 2-4 hours to cook a meal [9] although solar cookers are advantageous in that they do not need to be attended at all times. For many users readjusting their cooking routine to cater for the solar cooker is a challenge and inconvenience [9]. One of the largest barriers is that solar cookers cannot be used at night or in low solar radiation conditions. Significant research has gone into developing solar cookers with built in storage and several prototypes have been developed that will be discussed in Section 4.

2 DESIGN AND OPERATING PRINCIPLES

The largest markets for solar cookers are people living in the developing world, this is a very diverse market and hence there is a need to develop many different models of solar cooker. A well designed solar cooker should be suited to the specific climate, culinary customs and economic situation of its intended market [10]. The different solar cookers available fall into the following broad design categories identified by Muthusivagami et al. (2010) and given below;

- Solar cookers without storage
  - Direct cookers
    - Box type cookers
    - Concentrating cookers
  - Indirect cookers
- Solar cookers with storage
  - Sensible heat storage
  - Latent heat storage

As outlined the principle application for solar cookers is as an alternative to traditional solid fuels in the developing world. The intended market for this product plays a large role in determining the features of a successful solar cooker design. Sharma (2004) outlines the key factors in determining the success of a design: (1) cost, (2) safety, (3) heating and cooking capacity, (4) convenience, (5) durability, (6) ease of maintenance, (7) stability in the wind, and (8) operating instructions on the use of the cooker [6]. As the market is less affluent people in developing countries i.e. those who cannot afford gas or electric stoves, it is imperative that the device is affordable. It must also be safe and easy to use as it is to be operated with minimal instruction. The device should be convenient to use and appropriate to the life style of the owner, it must also have the heating and cooking capacity to address their needs e.g. if they have a large family, a large solar cooker should be available. If it does not meet their cooking needs it is unlikely to be adopted. The solar cooker must also be durable and easy to maintain as there is limited access to technical maintenance services in developing countries [6]. Part of maintaining durability is ensuring that it is stable in the wind; if the solar cooker were to fall it may break rendering it useless to the owner. When providing operating instructions consideration should be given to the intended market. As literacy rates are low in developing countries and many dialects are spoken, it would be good practice to provide instructions in pictorial form [6].

4.1 SOLAR COOKERS WITHOUT STORAGE

Solar cookers without storage are heavily dependent on the instantaneous quality of the solar resource. They are divided into two categories; direct (containing concentrating and box type cookers) and indirect type cookers as shown in Figure 2. This classification is based on the heat transfer mechanism deployed, direct type cookers use solar radiation instant on the cooking vessel to cook food while indirect type cookers use the solar collector to heat a fluid which transfers heat to the cooking vessel [3].

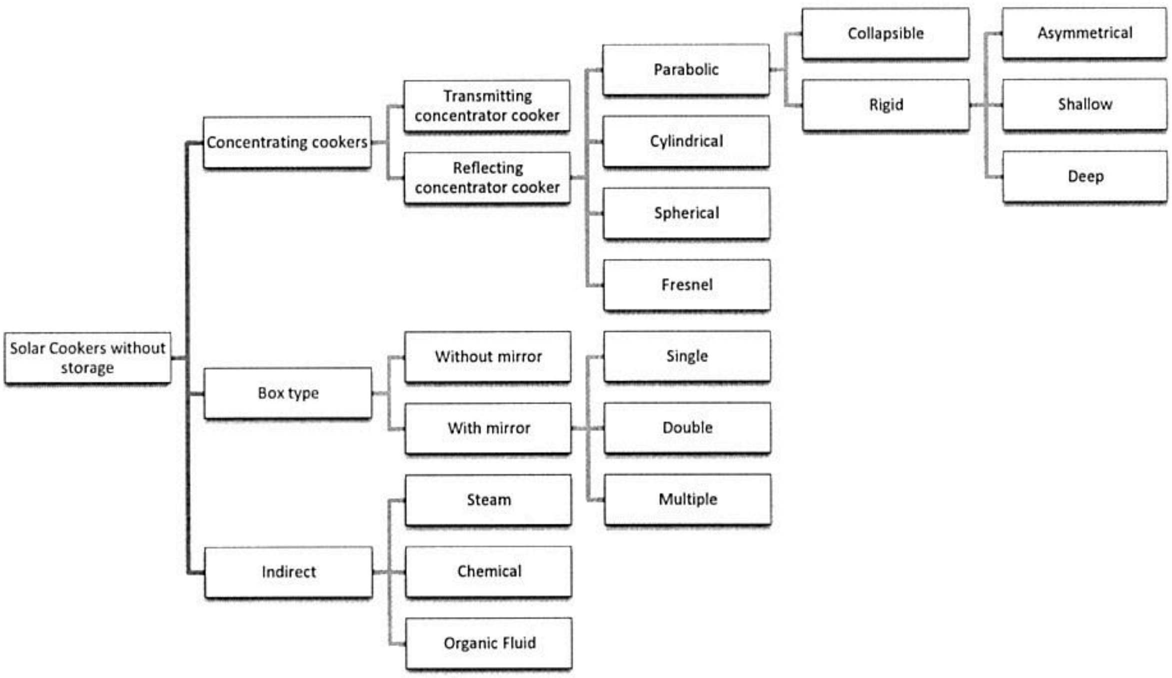

Figure 2 Types of solar cookers without storage [6]

4.1.1 DIRECT COOKERS

Direct type cookers are divided into two key categories; box type and concentrating cookers. These technologies are very different and each has their own unique advantages and disadvantages.

BOX TYPE COOKERS

Box type cookers are the oldest and most common type of solar cooker [10]. They utilize the greenhouse effect, they allow short wave radiation into the enclosure but block the long wave radiation that is re-emitted from the cooking food from exiting the enclosure [3, 6]. They typically consist of an insulated box covered by a transparent glass or plastic sheet; the transmission properties of the cover are important in determining the effectiveness of the cooker in trapping long wave radiation. In some models one or multiple plane mirrors are attached to the box to increase the amount of sunlight incident on the cooker and hence increase the operating temperature[6].

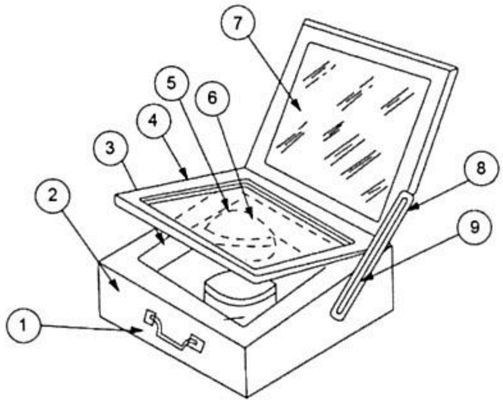

Figure 3 Box type solar cooker (1) Handle; (2) outer box; (3) insulation material (glass wall); (4) cover; (5) glass sheet; (6) cooking container; (7) plane mirror; (8) mirror support; and (9) hinged adjustor and guide [6]

Advantages of this technology are that it is light weight, low cost and operates at a lower temperature so that food is unlikely to burn and the risk of burn injuries are low [6]. They are reasonably easy to use; minimal attendance is required during cooking unless the design includes multiple mirrors that require adjustment throughout the day [5]. Box type cookers work well with diffuse radiation and in windy conditions where they continue to operate and remain stable [2, 3, 10].

The disadvantages of this technology are generally related to its operating temperature, this is the cooker's stagnation temperature where the heat transfer losses are equal to the gains. Box type cookers typically operate at around 100°C, they are therefore appropriate for boiling but not for frying, roasting or baking [6]. Although an extensive range of food can be cooked by boiling, when introducing this technology it is worth considering the traditional foods of the target market and whether or not they can be cooked using a box type solar cooker [9]. Preparing a meal with a box type cooker can take a very long time (sometimes several hours) and if solar insolation is poor for an extended period of time then the food remains half cooked and then get wasted as it cannot be re-cooked, this is even know to be a problem for box type cookers with mirrors [3].

CONCENTRATING COOKERS

Concentrating cookers rely on reflective surfaces to concentrate beam radiation onto a point where the food container is located. The power output of the cooker depends on the size of the reflective dish, the intensity of radiation and the reflectivity of the material used [6]. Concentrating cookers require direct beam radiation and hence need to be constantly tracking; more often than not this is done manually [2]. There are many different models of concentrating cooker available. Parabolic dishes (Figure 4d) are commonly used however the fabrication of a parabolic dish can be difficult so there are also models available with spherical dishes (Figure 4c). Other common reflector geometries include Fresnel reflectors that consist of reflective rings arranged in a concentric Fresnel geometry (Figure 4e). These have been developed as a solution to the difficulties of manufacturing parabolic cookers however these are difficult to design which has inhibited their progress [2, 5]. Plane reflectors use different configurations of plane mirrors to focus beam radiation on the cooking vessel (Figure 4a) and have the advantage of being easier to manufacture than a parabolic dish however they tend to be quite large and bulky [2,5]. Cylindro-parabolic concentrators (Figure 4f) focus beam radiation onto an insulated box in which the cooking vessels are placed [2, 5].

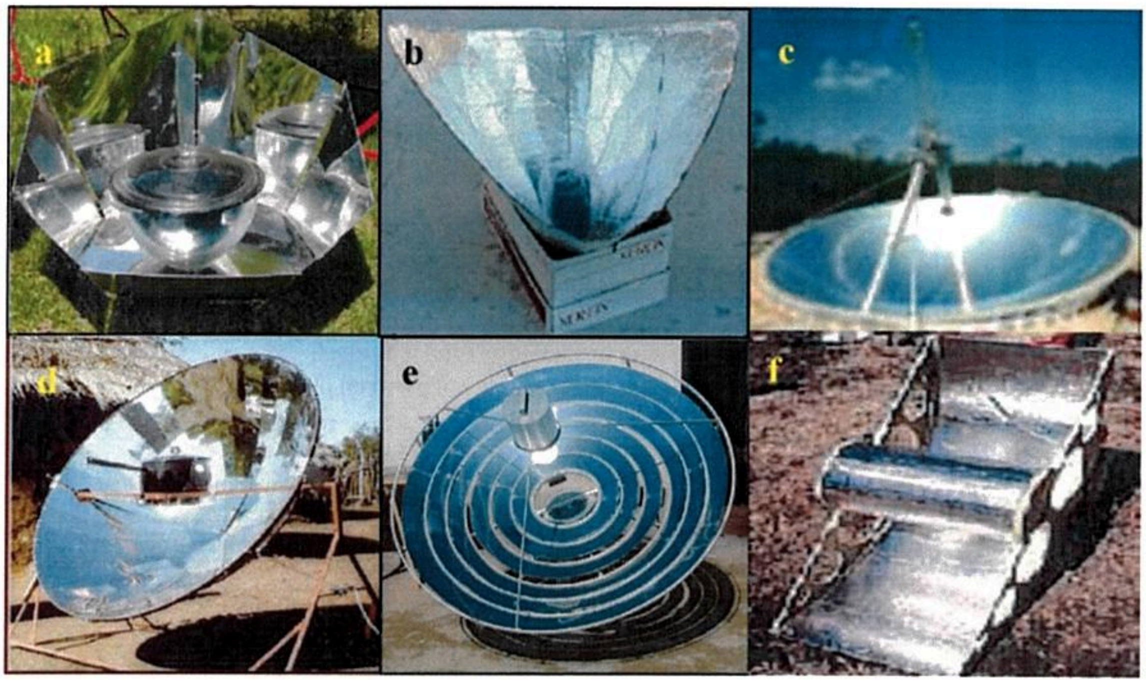

Figure 4 Concentrating cooker: (a) panel cooker, (b) funnel cooker, (c) spherical cooker, (d) parabolic reflector, (e) Fresnel concentrator and (f) cylindro-parabolic concentrator. [3]

A key difference between designs is whether or not the dish is 'deep' or 'shallow'; for deep cookers the focal point of the concentrator is within the rim of the dish (Figure 5 and Figure 4b) whereas for shallow cookers it is outside the rim of the dish. Deep cookers include funnel cookers (Figure 6c) and deep parabolic cookers (Figure 5) and tend to be less popular than shallow cookers because they are difficult to use [2, 5]. Asymmetrical cookers try to get around this problem; some parts of the dish are deep while others are shallow and so allow the user easy access to the cooking vessel [6]. Transporting bulky solar cookers is a problem so some solar cookers have been developed with a folding reflective dish that is easy to fold up and carry, however such reflectors have found to be fairly unstable and have poor focus so rigid dishes have remained the most popular [6].

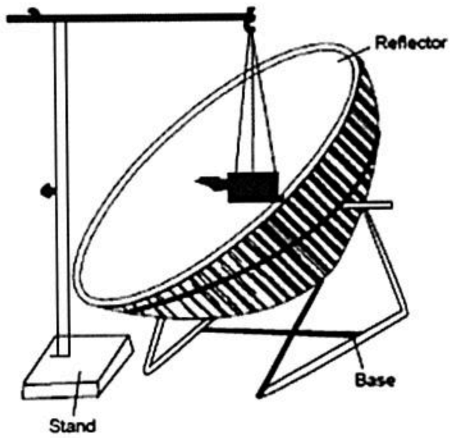

Figure 5 Deep parabolic cooker [6]

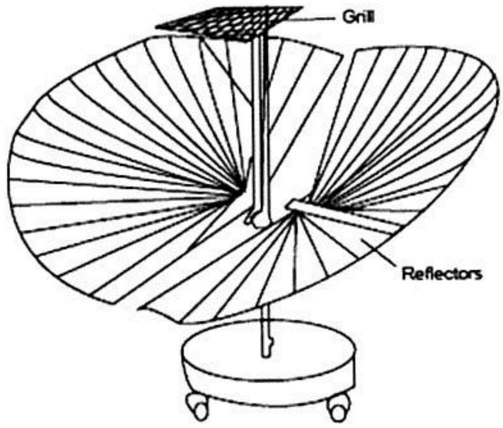

Figure 6 Collapsible parabolic cooker [6]

Solar cookers that use lenses to transmit and concentrate sunlight also fall under this category. Sharma (2004) describes two such solar cookers. The water lens cooker uses concave sheets made of plastic or glass that are fill with liquid (typically water or alcohol) to concentrate radiation [2]. Dome lens cookers operate using a similar principle however they are quite difficult to manufacturer, a dome is placed over a number of cooking vessels in order to concentrate radiation [2]. Transparent Fresnel lenses have been suggested however they have several significant drawbacks; they require constant tracking, they are expensive to manufacture and plastic will deteriorate fast in the outdoor environment [2].

The key advantage of concentrating cookers is that they are able to reach higher temperatures than box type cookers; this makes them appropriate for frying and roasting food [6]. The higher temperature also decreases the cooking time of food. They are quick to heat up however they are not well insulated so cool down quickly if conditions deteriorate, this is a sharp contrast to box type cookers which are slow to heat up but hold heat for hours [10]. Concentrating cookers require direct beam radiation and hence they must be constantly tracked which generally requires that the user be there for the entire cooking process [3]

4.1.2 INDIRECT COOKERS

Indirect type cookers are very useful as the cooking vessel can be physically separated from the collector; this allows the user to cook indoors however they are also more expensive than direct type cookers [10, 11]. A medium is required to transfer heat to the cooking vessel; organic fluids, chemicals and steam are commonly used fluids [2]. Most indirect type cookers use a flat-plate solar collector to transfer heat to the fluid [10] however in recent years evacuated tube collectors and concentrating collectors have also been used [3]. Indirect solar cookers are of particular interest because they have the scope to be applied on a larger-scale, for instance collectors could be placed on the roof of a building and heat transferred to the kitchen. Several large-scale systems have been designed and deployed.

Schwarzer et al. (2003) developed a flat-plate collector that used oil as the heat transfer fluid. Thermal storage and reflectors to increase the amount of solar radiation incident on the absorber were also incorporated [3, 11]. One of the key advantages of using oil was that it moved by natural flow and so a pump was not required, valves were installed that could be operated manually to control the flow of oil [11]. Disadvantages of this system were that it had high fabrication costs and required materials that are not readily available in developing countries [11].

The Scheffler community cooker uses a concentrating parabolic collector. A first reflector is located outside and reflects beam radiation through a hole in the wall onto a second reflector. This secondary reflector concentrates beam radiation onto a cooking vessel. Just like direct concentrating cookers, the first reflector requires tracking [2].

4.2 SOLAR COOKERS WITH ENERGY STORAGE

Solar cookers with energy storage respond to one of the key drawbacks of solar cookers; that they cannot be used for cooking when the Sun is not shining i.e. at night or during cloudy weather [5]. A medium is used to store heat for when it is required and can be used to supply additional heat when the demand exceeds the instantaneous supply of the solar cooker [5]. This category of solar cookers is still in the development stage. The literature on solar cookers shows there to be many promising prototype designs however none are in the commercialization and deployment stage as yet. Prominent work in the field will be described in this section.

4.2.1 SENSIBLE HEAT STORAGE

Sensible heat storage involves raising the temperature of a liquid or solid medium in order to store thermal energy [5]. There are many ways to achieve this outcome. Box type cookers have been modified so that their inner box is double walled, the space between the walls can be filled with a storage medium such as oil and sealed. Nahar (2003) developed such a cooker using engine oil as a storage medium, the cooker achieved the same stagnation temperature during the day as a similar box type cooker without storage however between 5pm and midnight its temperature was 23°C higher [3, 12]. Oil can also be used as a storage medium in indirect solar cookers such as the one designed by Schwarzer et al. (2003).

Ramadan et al. (1998) developed a solar cooker that uses a solid medium (sand) as a storage medium and a copper absorbing flat plate with two glass covers [3, 13]. They found that the optimal and most economic performance was achieved by making a 5mm jacket of sand around the vessel [3, 5, 13]. this device was able to cook indoors for 3 hours per day and has an overall energy conversion efficiency of 28.4%[3].

4.2.2 LATENT HEAT STORAGE

Latent heat storage is an emerging technology within the solar cooking field. It has many benefits and has generated a lot of interest in recent years. It involves storing energy in a phase change and uses phase change materials (PCMs) to do so [3]. As they absorb energy solid-to-liquid PCMs liquefy and as they release that energy they solidify [5]. During this process they maintain a fairly constant temperature and can store a great deal of energy [3, 5]. One of their key advantages is their high storage density making them compact [3].

Sharma et al. (2008) outline the requisite properties for a solid-to-liquid PCM to be appropriate for use in a solar cooker (Table 1). The PCM needs to be non-toxic and chemically inert because of its proximity to food. Abundance, availability and cost effectiveness are essential if it is to be mass produced and affordable for people living in developing countries. Salt hydrates, paraffin, paraffin waxes and fatty acids are among the compounds thought to be appropriate for this application [5]. Solar cookers have been designed using stearic acid, magnesium nitrate hexahydrate, acetamide, acetanilide and erythritol [3, 5].

Table 1 Main desirable properties of phase change materials [5]

Thermal properties	Physical properties	Kinetic properties	Chemical properties	Economics
Suitable phase-transition temperature	Favorable phase equilibrium	No super cooling	Long-term chemical stability	Abundant
High latent heat of transition	High density	Sufficient crystallization rate	Compatibility with materials of construction	Available
Good heat transfer	Small volume change		No toxicity	Cost effective
	Low vapor pressure		No fire hazard	

The use of PCMs in solar cookers is a fairly new field however there are several designs that have been proposed. Domanski et al. (1995) developed an experimental solar cooker using latent heat storage. The solar cooker consisted of two concentric cylindrical aluminum vessels, the gap between the vessel is filled with the PCM (either 1.1kg of stearic acid or 2kg of magnesium nitrate hexahydrate) [5, 14, 15]. This solar cooker was fairly compact; the outer aluminum vessel was 0.18m in diameter and 0.12m tall. It was painted black to improve its absorption of solar radiation [16]. They concluded that the solar irradiance, mass of food and thermo physical properties of the PCM affected the performance [5, 16]. This model took a long time to cook a meal using the stored energy because the rate of heat transfer between the PCM and the cooking vessel was slow [3, 5, 16].

Sharma et al. (2000) developed a box type solar cooker using commercial-grade acetamide as a PCM [15]. They developed a cylindrical PCM storage unit which would surround the cooking vessel similar to that developed by Domanski et al. (1995) [5, 15]. The cylindrical design allowed for a large surface area of contact between the PCM and the cooking vessel which increased the conductive heat transfer [5]. Aluminum fins were attached to the inner wall of the PCM container to increase heat transfer. This design was able to cook three batches of food during summer and two during winter [5]. Sharma et al. (2000) also found that storage does not affect the performance of the solar cooker at noon [15].

Sharma and Sagara (2004) and Sharma et al. (2004 and 2005) developed a prototype for an indirect solar cooker using an evacuated tube solar collector as shown in Figure 7 [5, 14, 15, 17]. The collector transfers heat to water which is then pumped through a heat exchanger. The heat exchanger is wrapped around the cooking vessel and heat is transferred from the water to the PCM [5]. The PCM storage unit consists of two concentric aluminum cylinders; 45kg of commercial grade erythritol (the PCM) is located in the gap between the cylinders and the cooking vessel is inside the inner cylinder. This device was able to cook two meals a day and cooked the evening meal faster than the noon meal [5].

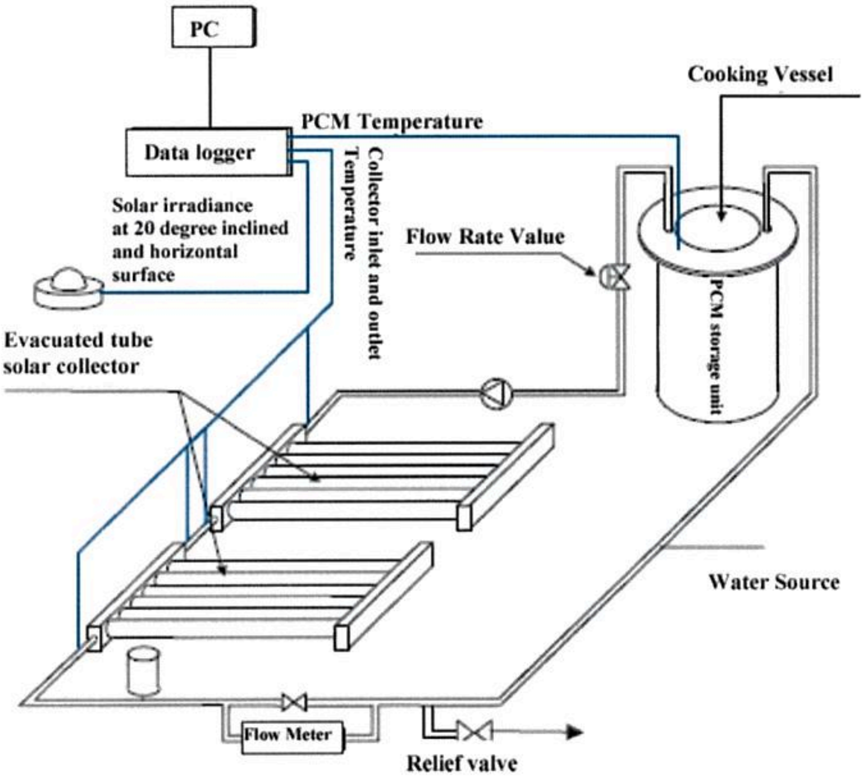

Figure 7 Outline of the prototype solar cooker based on evacuated tube solar cooker with PCM storage unit [5]

6 CONCLUDING REMARKS

The field of solar cooking is diverse and many dramatically different designs of solar cookers are available. This variety is important; if solar cookers are to be considered an appropriate technology for people living in the developing world then they must be able to meet the unique needs of their intended market. In addition to being suited to the typical solar radiation conditions of the given location, they should also be inexpensive, safe, easy to use and maintain, durable and stable in the wind. Further development of large-scale solar cookers is required to meet the needs of communities as a whole rather than just catering for individual families. Although there are many solar cookers used throughout the world there remains barriers to their widespread dissemination. One such barrier is that the solar cooker cannot be used when conditions are poor or at night time. Storage in the form of sensible or latent heat is currently being developed in an attempt to address this problem however it is still in the prototype phases. Latent heat storage in phase change materials (PCMs) appears most promising as PCMs are compact and can maintain a fairly consistent temperature. Such improvements are important in ensuring the uptake of solar cookers. Into the future solar cookers are likely to play an important role in improving the lives of those living in developing countries by offering them a clean and safe alternative to conventional biomass.

REFERENCES

1. Knudson, B., *State of the Art of Solar Cooking: A Global Survey of Practices and Promotion Programs*. 2004, Solar Household Energy.

2. Telkes, M., *Solar cooking ovens*. Solar Energy, 1959. **3**(1): p. 1-11.

3. Muthusivagami, R.M., R. Velraj, and R. Sethumadhavan, *Solar cookers with and without thermal storage--A review*. Renewable and Sustainable Energy Reviews, 2010. **14**(2): p. 691-701.

4. Rehfuess, E., *Fuel for life : household energy and health*. 2006, World Health Organisation.

5. Sharma, A., et al., *Solar cooker with latent heat storage systems: A review*. Renewable and Sustainable Energy Reviews, 2008. **13**(6-7): p. 1599-1605.

6. Sharma, S.K., *Solar Cookers*, in *Encyclopedia of Energy*, J.C. Cutler, Editor. 2004, Elsevier: New York. p. 559-574.

7. Shyam S, N., *Solar cookers—cheap technology with high ecological benefits*. Ecological Economics, 1996. **17**(2): p. 73-81.

8. Schwarzer, K. and M.E.V. da Silva, *Characterisation and design methods of solar cookers*. Solar Energy, 2008. **82**(2): p. 157-163.

9. Bashir, A., *Users and disusers of box solar cookers in urban India—: Implications for solar cooking projects*. Solar Energy, 2001. **69, Supplement 6**(0): p. 209-215.

10. Funk, P.A. and D.L. Larson, *Parametric model of solar cooker performance*. Solar Energy, 1998. **62**(1): p. 63-68.

11. Schwarzer, K. and M.E. Vieira da Silva, *Solar cooking system with or without heat storage for families and institutions*. Solar Energy, 2003. **75**(1): p. 35-41.

12. Nahar, N., *Performance and testing of a hot box storage solar cooker*. Energy Conversion and Management, 2003. **44**: p. 1323-1331.

13. Ramadan, M., S. Aboul-Enein, and E.-S. AA, *A model of an improved low cost indoor solar cooker in Tanta*. Solar and Wind Technology, 1998. **5**: p. 397-393.

14. Sharma, S., et al., *Experimental results of evacuated tube solar collector for use in solar cooking with latent heat storage*. Proceedings of the EM4 indoor workshop IEA ECES 1A annex 17, April 21-24, 2004.

15. Sharma, S.D., et al., *Design, development and performance evaluation of a latent heat storage unit for evening cooking in a solar cooker*. Energy Conversion and Management, 2000. **41**(14): p. 1497-1508.

16. Domanski, R., A.A. El-Sebaii, and M. Jaworski, *Cooking during off-sunshine hours using PCMs as storage media*. Energy, 1995. **20**(7): p. 607-616.

17. Sharma, S., et al., *Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit*. Solar Energy, 2005. **78**(3): p. 416-426.

* Very good report!

10/10