Journal of Academia and Industrial Research (JAIR)
Volume 3, Issue 9 February 2015

ISSN: 2278-5213

REVIEW ARTICLE

Solar Cookers for Off-Sunshine Cooking

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Abstract

The increase in the level of green house gas emissions and the fuel prices are the main driving forces behind utilizing the various resources of renewable energy. Solar energy is one of the most promising renewable energy resource available to us in abundant. Cooking is the essential need of mankind all over the world accounts for a major share of energy consumption. A lot of research work has been carried out in recent years for the utilization of solar energy towards solar cooking. In this paper attempt has been made to provide systematic thorough review on solar cooking for off-sunshine cooking. This review provides an easy understanding of solar cookers and materials used for thermal energy storage for off-sunshine cooking.

Keywords: Solar cookers, solar energy, energy storage materials, phase change materials.

Introduction

Energy for cooking is the basic requirement of mankind all across the world. In developing countries like India, energy requirement for cooking is 36% of the primary energy consumption (Sharma *et al.,* 2009). In India, 70% of population is living in rural areas. More than 80% of this population is dependent on firewood, dung-cake and agricultural waste for fulfilling their energy requirements. While in urban area, people are dependent on firewood, LPG, Kerosene oil and electricity. In rural areas, the dung-cake, firewood, agricultural waste are available at free of cost but it requires a lot of effort in gathering these fuels and in urban areas the fuel is available at high cost. The fuel used by the population of India in rural or urban area is leading to deforestation and continuously polluting the environment. The fumes emitted by the burning of these fuels causes health concern such as burns, eye disorders and lung disorders. So, need of an alternative source of energy is required which overcomes the problem of pollution and is also economical. Solar energy is the most promising energy source among all the clean energy technologies, which is available to us, in abundant and at free of cost. In this paper, an organized and thorough review has been carried out on the solar cookers for off-sunshine cooking (evening cooking). The need for thermal storage in solar cookers and the various studies carried out with storage options are enumerated in detail.

Energy storage materials for solar cookers

Solar cookers are helpful in cooking at day time when sun is shining. Off-Sunshine/Evening or night cooking is not possible with them. This is the main limitation of solar cookers. Lot of research is going on in this direction to overcome this limitation.

Researchers suggested the use of energy storage materials for enabling cooking at evening or night time. Energy storage materials are the materials which stores solar energy in the form of thermal energy and this stored thermal energy is helpful in cooking at night. This section explains different types of energy storage materials. Energy storage materials are mainly of two types depending on the way it stores energy. These are: (a) Sensible/Specific heat storage materials, (b) Latent heat storage materials/phase change materials (PCMs).

Specific heat storage materials: Materials which stores energy in the form of specific heat are called specific heat storage materials. Initially researchers used these materials for storage of solar energy. The most probable specific heat storage materials used are sand, used engine oil, mineral oil, water, pebbles etc. This technique of storing solar energy in the form of thermal energy by specific heat storage material is not popular because the amount of energy stored by these materials is dependent on specific heat, temperature change and mass of the storage material. Large mass of material is required for storing solar energy if material has low specific heat; which makes the system bulkier. In addition, energy storage by these materials is also not able to cook the food efficiently and requires large time for cooking. So this technique is dropped and another alternate will be investigated.

Latent heat storage materials/phase change materials (PCMs): This section deals with the efficient and popular way of storing energy by phase change materials. These materials have advantage over the specific heat storage materials because they require small mass for storing large amount of energy. So these materials are helpful in making energy storage system compact.

Table 1. Thermo-physical properties of PCMs.

PCMs	Melting point (°C)	Heat of fusion (kJ/kg)	Specific heat solid/liquid (kJ/kg°C)	Density solid/liquid (kg/m^3)
Capric acid	30.1	150-158	1.95/1.60-1.72	-
Lauric acid	41-43	211.6	1.76/2.27	1007/862
Myristic acid	53.8	192	1.7/2.4	-
Pentadecane acid	52.5	158.6	-	-
Palmitic acid	59.9	197.9	1.9/2.8	-
Stearic acid	55.1	160	1.6/2.2	965/848
Acetamide	82	263	1.94/1.94	1159/998
Magnesium nitrate hexa-hydrate	89	162.8	1.84/2.51	1636/1550
Acetanilide	118.9	222	2/2	1210/1020
Erythritol	118	339.8	1.38/2.76	1480/1300

PCMs can be defined as the material, which change their phase by absorbing energy and regaining its initial state by releasing energy. The phase transition can be from solid-liquid, liquid-gas, solid-gas and vice-versa depending upon the application. But for cooking purpose generally solid-liquid phase transition is preferred because in liquid-gas, solid-gas transition the difficulty of handling large volume and leakage comes in picture (Sharma *et al.,* 2009). These materials are becoming popular for storing energy because of their efficient action. There are different types of PCMs available for storing energy and researchers have used many of them. The important PCMs which were used by researchers to store energy are: Erythritol, acetanilide, commercial grade stearic acid, commercial grade acetamide, pentaerythritol etc. The thermo-physical properties of important PCM are shown in Table 1. The mathematical expression of energy storage by PCM is given by:

$$Q_{PCM} = m_{PCM}\left[C_{PCM(solid)}(T_m - T_i) + L + C_{PCM(liquid)}(T_{PCM,max} - T_m)\right] \quad (1)$$

While selecting PCMs for a particular application; first of all its properties should be studied, whether it is fit for that application or not. It is not possible for any PCM to fulfill all the requirements for a particular application. But the most common desirable properties of PCM are listed and shown by Fig. 1; which helps in selecting the suitable PCM.

Fig. 1. Desirable properties of PCMs.

Desirable properties of PCMs used for solar cooking are (Abhat, 1981; Sharma *et al.,* 2005, 2009):

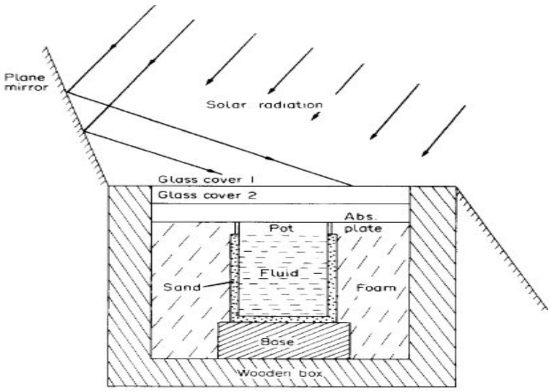
1. PCM should have suitable phase-transition temperature. The temperature at which material changes phase i.e. solid-liquid, liquid-gas, solid-gas and vice-versa. For cooking purpose, solid-liquid phase-transition is preferred and phase transition temperature should be around 100°C or more.
2. It should have high latent heat of fusion so that small amount of PCM should be required and heat storage system becomes compact, economical and easy to handle.
3. It should have good heat transfer property, so that uniform melting and efficient heat transfer between storage unit and cooking pot takes place.
4. It should have high energy density, small volume change and low vapor pressure. So that heat storage system becomes compact and there is no need of frequent inspection of the heat storage container.
5. It should have sufficient crystallization rate and free from super-cooling effect. Super-cooling effect is the phenomenon due to which the drop in transition temperature of PCM occurs during repeated cycles of solid-liquid and vice-versa phase transition. Due to super-cooling effect the efficiency of storage system decreases. The rate of heat transfer drops and efficient cooking of food is not possible.
6. It should have long-term chemical stability. Chemical stability means PCM doesn't get oxidized or break down into components during repeated solid-liquid and vice-versa transition.
7. It should have compatibility with materials of construction. The PCM used should have chemical stability with the materials of heat storage system.
8. It should be non-toxic, so that there is no adverse effect on the food during cooking and it remains edible. It should have no fire hazard.
9. It should be abundant, easily available and cost effective so the system becomes economical.

Solar cookers for off-sunshine cooking

Solar cookers are capable of cooking only in day time when sun is shining. Off-Sunshine/Evening and indoor cooking is not possible with these cookers.

Many researchers worked on this aspect of solar cookers and developed solar cookers with energy storage materials which are able to cook even in night time. Different types of materials are used for energy storage such as sand, engine oil but nowadays, phase change materials (PCMs) are most commonly used for energy storage. This section deals with listing the work of different researchers on solar cookers for off-sunshine cooking. Initially Ramadan *et al.* (1988) used sand to store solar energy of sun in the form of specific heat. They used sand because it is easily available and economical; in addition sand has high heat retention capability but it requires large volume to deal with. By using sand; cooker performance increased during the daytime and about 3hrs/day of indoor cooking was possible. It can also keep the food warm during night time as oven do. Same results are obtained when used engine oil is used for storing energy by Nahar (2003) in box type solar cooker. He used 5 kg of used engine oil for storing energy. Figure 2 shows the schematic of solar cooker used by Ramadan *et al*. (1988) at Tanta University, Egypt.

Fig. 2. Schematic diagram of solar cooker with sand as energy storage medium (Ramadan *et al*., 1988).



Schwarzer and Silva (2003) developed a flat-plate solar cooker with pebbles used as the energy storage medium. The vegetable oil was used as heat transfer medium, which was heated up in the collector by natural convection and transfer energy to the cooking unit. This work enhanced the possibility of indoor cooking. This system was able to keep food warm for longer period of time. Domanski *et al*. (1995) were the first who used PCM as the energy storage material. They used stearic acid and magnesium nitrate hexa-hydrate for energy storage in box type solar cooker. They experimentally evaluated the thermal performance of solar cooker for charging and discharging times of phase change materials. The overall efficiency of about 82% was achieved and maximum temperature inside the cooker was in between 78-84°C. The results obtained are satisfactory which opened the way for further research on PCMs.

Fig. 3. Schematic diagram of solar cooker used by Domanski *et al*. (1995).

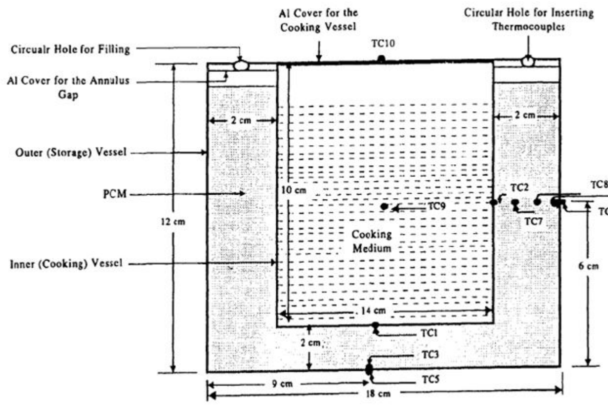
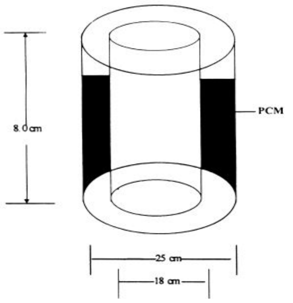


Figure 3 shows the schematic of solar cooker used by them. Bushnell (1988) developed a solar oven which used penta-erythritol as energy storage material. He calculated thermal performance of solar cooker with the help of first figure of merit. Nandwani (1997) studied a hot box solar cooker with polyethylene as phase change material. He tested the cooker under different operating conditions and at different loading times. He concluded that maximum temperature of 132°C was achieved by this cooker which was able to pasteurize 14-16 L of water and cooking food. Buddhi and Sahoo (1977) designed and experimentally tested the solar cooker with latent heat storage materials. They used commercial grade stearic acid (melting point=55.1°C, latent heat of fusion=160 kJ/kg) as PCM. They concluded that night cooking becomes possible by using stearic acid but the rate of cooking is very slow because melting point of stearic acid is low as compared to cooking temperature of food which is around 90°C. So to avoid such discrepancy, melting point of phase change material should be 100°C or more and latent heat of fusion should be high enough.

Sharma *et al.* (2000) designed, developed and calculated the thermal performance of box-type solar cooker having latent heat storage unit. They used commercial grade acetamide (melting point=82°C, latent heat of fusion =263 kJ/kg) as PCM. They designed concentric cylindrical vessel for energy storage unit. The void space was filled with PCM. They compared the performance of this cooker with the standard solar cooker. They tested it at different loading conditions. They evaluated that evening cooking was possible by this cooker. Figure 4 shows the schematic diagram of thermal storage unit used by them. Buddhi *et al*. (2003) calculated the thermal performance of box-type solar cooker with latent heat storage unit, having three reflectors. This time they used commercial grade acetanilide (melting point=118°C, latent of heat fusion=222 kJ/kg) as PCM for energy storage.

Fig. 4. Schematic diagram of thermal storage unit used by Sharma *et al.* (2000).



They experimentally tested the cooker under different loading conditions and loading times and concluded that it had much better thermal performance than their previously developed solar cooker. Sharma and Sagara (2005) designed and experimentally tested evacuated tube solar cooker having storage unit. They used erythritol (melting point=118°C, latent heat of fusion =339 kJ/kg) as PCM for energy storage. The insulated stainless steel tube was used to transfer hot water from evacuated tubes to the PCM storage unit. They concluded that erythritol achieved the temperature of 130°C and it was able to cook food twice a day easily. Figure 5 shows the schematic diagram of storage unit and solar cooker. Murty and Kanthed (2003) designed and tested box type solar cooker in which PCM was filled in between the glazing. The PCM used was lauric acid (melting point=42.2°C, latent heat of fusion=181 kJ/kg). Lauric acid acts as the transparent insulating material. They compared this solar cooker with standard cooker. They found that convection loss was minimized by using lauric acid in between glazing and its stagnation temperature was higher than standard cooker. It acted as a solar oven when it was closed.

Mettawee and Assassa (2006) studied a compact PCM solar collector. It acted as PCM container as well as absorber plate. They used paraffin wax as PCM which stored solar energy. PCM discharges this energy to water flowing in pipe which passed through paraffin wax. They studied behavior of PCM at different flow rate of water. They concluded that the heat transfer coefficient increases with increase in molten layer thickness during charging process and useful heat gain was increased during discharging process as mass flow rate increases. Hussein *et al*. (2008) experimentally tested indirect solar cooker with indoor PCM thermal storage unit. They used magnesium nitrate hexa-hydrate (melting point=89°C, latent heat of fusion=134 kJ/kg) as PCM. This system consists of flat plate collector with two reflectors. Solar cooker was of elliptical cross-section and wickless heat pipe was used. Experiments were conducted on solar cooker with no load and with different load at different loading times. The experimental results concluded that this cooker was able to cook different kinds of food at noon, after-noon, and evening times. It was also used for keeping food hot at night and early morning.

Fig. 5. a) Schematic diagram of evacuated tube solar cooker with PCM storage unit; b) Cross-sectional view of storage unit (Murty and Kanthed, 2003).

a

b

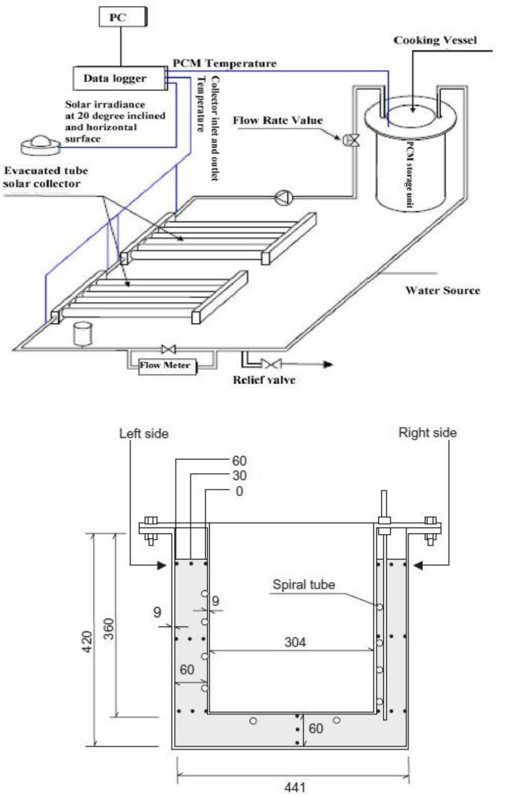
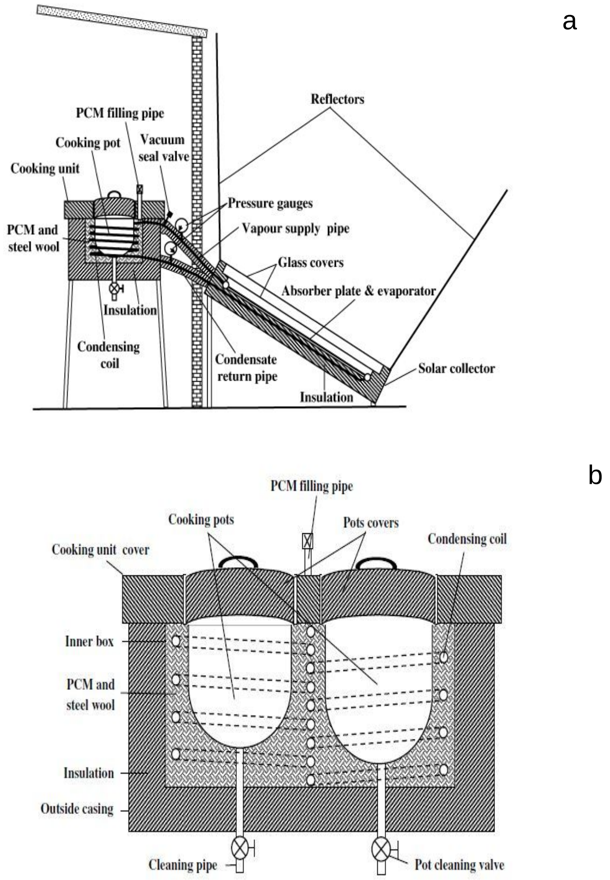


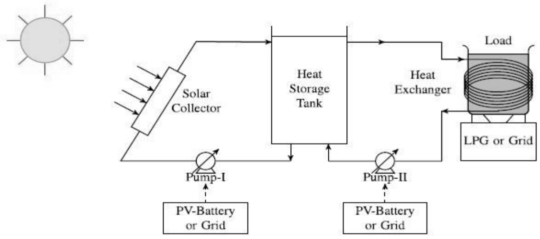
Figure 6 shows schematic diagram of this solar cooker and storage unit placed indoor. Storage unit consisted of integrated cooking pots around which PCM was filled. Condensing coils are used around them to transfer energy to PCM which stores it. Chen *et al*. (2008) investigated theoretically the box type solar cooker with different PCMs like magnesium nitrate hexa-hydrate, stearic acid, acetamide, acetanilide, and erythritol. They also used heat exchanger of different materials like glass, stainless steel, tin, aluminium and copper. They found that higher thermal conductivity of container material did not make significant contribution on melt fraction of PCM. Foong *et al*. (2011) investigated small scale double reflector solar concentrating system with mixture of nitrates as heat storage material. The mixture consists of $NaNO_3$ and KNO_3 in 60:40 mole percent ratios. Thermal behavior of salts was studied with differential scanning calorimeter (DSC). The melting temperature of mixture of salts was about 220°C; which was suitable for cooking and baking. They used cooper fins to enhance heat transfer from salts to top plate. Salts were completely melted within 2-2.5 hours. This system was simulated with the help of finite element method; simulation was based on effective heat capacity method. Muthusivagami *et al*. (2010) developed a solar cooker which used PCM A-164 as energy storage. This is synthetic energy storage material produced commercially.

Fig. 6. a) Schematic diagram of solar cooker with flat-plate collector; b) Cross-sectional diagram of storage unit (Hussein *et al.,* 2008).



In this arrangement a parabolic trough is used for concentrating solar energy on to tube which contains heat transfer fluid (thermic fluid). Heat transfer fluid transferred heat to the PCM unit kept inside which supply energy for cooking when desired. In this system, finned flat plate was used for cooking which attains temperature of 140-150°C easily and cook food efficiently. Mawire *et al.* (2010) performed the discharging simulations of a thermal energy storage system for an indirect solar cooker. They modeled indirect solar cooker having pebble bed as thermal energy storage unit and oil was used as heat transfer fluid. The results obtained from the simulation were validated by experimental results. The results of discharging simulations of thermal storage system were presented by adopting constant flow rate and varying flow rate techniques. In both the ways highest cooking temperature was maintained for the discharging process which is essential for cooking. El-Sebaii *et al.* (2009) investigated the suitability of acetanilide and magnesium chloride hexa-hydrate as energy storage material for indoor solar cooking. They tested above mentioned PCM in thermal storage unit of solar cooker having container made up of aluminium and stainless steel. They performed five hundred cycles of melting/solidification of PCMs and concluded that acetanilide was the most favorable PCM among the two, which was compatible with aluminum and stainless steel container also. On the other side, magnesium chloride hexa-hydrate was not stable during the cycling due to phase segregation problem and it was not compatible either with aluminum or stainless steel container.

Fig. 7. Block diagram of hybrid solar cooking unit (Prasanna and Umanand, 2011).

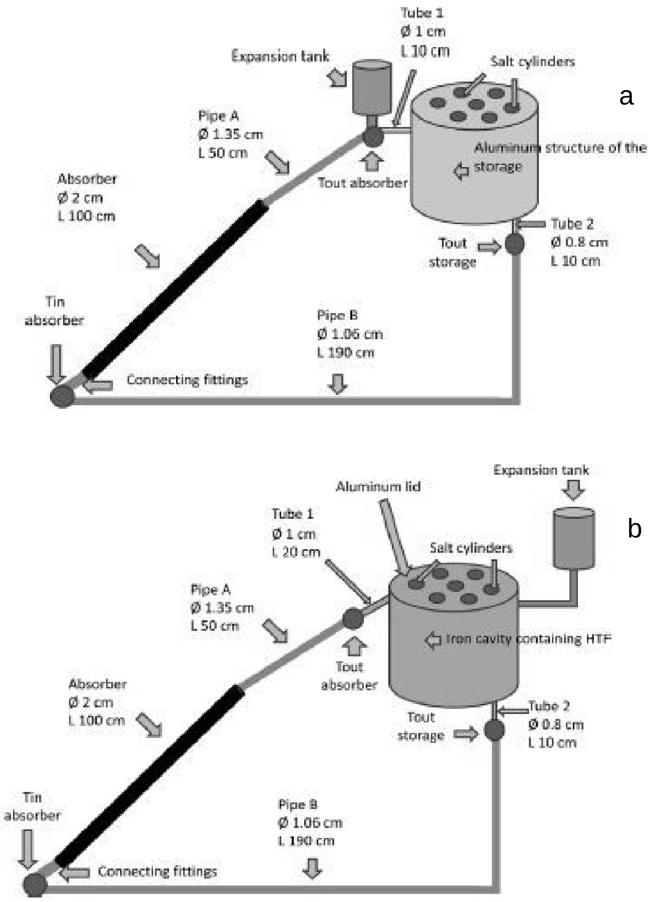


Prasanna and Umanand (2001) modeled and designed a hybrid solar cooking unit (Fig. 7). This cooking unit consists of parabolic trough collector, thermal storage tank, heat exchanger respectively. The heat was supplied by heat transfer fluid (servo-thermo oil) to thermal storage unit by natural convection process. In this system supply of energy was two way, firstly energy supplied by the heat transfer fluid to the cooking pot and secondly energy supplied by LPG. This system provides the facility of using LPG and solar energy according to situation. The hybrid cooking unit was very useful and had great advantage. The performance of this cooking unit was controlled by varying the fluid flow rate from collector to thermal storage unit and from thermal storage unit to the heat exchanger. The performance of this unit also depends on the diameter of pipes containing heat transfer fluid. The whole system was modeled with the help of bond graph approach.

Chaudhary *et al.* (2013) designed and experimentally evaluated thermal performance of parabolic dish type solar cooker with latent heat storage unit. They used acetanilide (melting point=118°C, latent of heat fusion =222 kJ/kg) as PCM for energy storage. They consider three cases for enhancing thermal performance of solar cooker. These cases were: ordinary solar cooker, solar cooker with outer surface painted black and solar cooker with outer surface painted black with glazing. They found that solar cooker with outer surface painted black with glazing was the most efficient and stored 32.3% more heat in contrast to PCM in ordinary solar cooker. Lecuona *et al.* (2013) experimentally and theoretically worked on portable parabolic type solar cooker (Fig. 8) incorporating phase change material. They used technical grade paraffin and erythritol as PCMs. They designed a thermal storage unit consisting of two concentric cylinders having gap between them which was filled with PCM. They concluded that cooking lunch on this cooker was possible simultaneously with heat storage. The heat retained by PCM was able to cook food at evening also when the thermal storage unit was kept in insulated box after storing solar energy.

Fig. 8. Photograph of parabolic dish type solar cooker with PCM (Lecuona *et al.,* 2013).

Fig. 9. a) Schematic view of aluminium based; b) Schematic view of oil based storage unit (Mussard and Nydal, 2013).



The high melting point and thermal conductivity of erythritol helps in efficient and fast indoor cooking. The system was simulated by developing one dimensional thermal model. Mussard and Nydal (2013) tested oil and aluminium based heat storage unit used for solar cooking. They compared results of both storage units. They used small scale parabolic trough for charging storage units. They used mixture of nitrate slats for storing energy having melting point around 210-220°C. Duratherm FG was used as heat transfer fluid. They heated it with help of electrical coil which was simulating the sun. Figure 9 shows schematic diagram of aluminium and oil based storages. They investigated that oil based storage unit has much better performance than that of aluminium based. They modeled the system by dividing it in 43 cells; each cell having 10cm length. From the findings by different researchers on solar cookers with phase change materials as energy storage medium, it was concluded that PCMs having melting point above 80°C are suitable for off sun-shine cooking.

Conclusion

From this review on solar cooking technology, it may be concluded that solar cookers are beneficial to the community. This study covers solar cookers for off-sunshine cooking and energy storage materials for storage units. Solar energy is the most gifted energy source and solar cooking is one of the convenient and important techniques of harnessing solar energy. The main conclusions of this review are:

1. Solar cookers are helpful in minimizing CO_2 emissions, conserving conventional fuels and helpful in making the environment green.
2. The cylindrical storage unit is preferred over rectangular storage unit.
3. Off-Sunshine/Evening cooking is possible with solar cooker using PCMs as energy storage medium.
4. PCMs having melting point above or close to 100°C are more promising for the storage unit of solar cookers.

In coming future due to depletion of non renewable energy resources solar energy is becoming more and more accepted in developing and developed countries due to its sustainable nature. Lot of work has to be performed on solar cookers from research point of view for meeting demands of society. Some important work have to be done in future are listed below

1. Research should be carried out for reducing the cost and increasing the efficiency of solar cooker.
2. Work should be performed in designing more compact and efficient thermal storage unit.
3. Work should be carried out to minimize thermal losses in order to make solar cookers more efficient.
4. Solar cooker should be designed for low temperature hilly and isolated areas.
5. High energy density PCMs should be developed for storage unit.
6. Research should be carried out in developing highly efficient hybrid solar cooking unit so that it could cook food uninterruptedly during the complete diffusion of energy from the storage unit.

These are the probable areas of interest on which work can be carried out in future for making the system more efficient, easy to handle, available at low cost and commercially viable for each and every household. In brief, the upcoming era is of renewable energy resources and solar energy is one of them.

Nomenclature

Q_{PCM}	Energy stored by PCM
m_{PCM}	Mass of PCM
$C_{PCM(solid)}$	Specific heat of PCM at solid state
T_m	Melting temperature of PCM
T_i	Initial temperature of PCM
L	Latent heat of fusion of PCM
$C_{PCM(liquid)}$	Specific heat of PCM at liquid state
$T_{PCM,max.}$	Maximum temperature of PCM

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