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Performance Assessment of Solar Reflector Supported Steam Generator for Cooking of Meals under Different Climatic Conditions

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ABSTRACT

Solar energy is gaining enormous attention from researchers, environmentalists, government agencies and stake holders due to its inexhaustible availability, environmental friendly and easy to tap. This experiment was designed to evaluate the efficiency and cooking performance of a solar reflector with steam generator under different climatic conditions and the results were compared with the traditional method of cooking. In summer season, the temperature of concentrated light beam on receiver was observed to be 460 ± 31 ^{o}C and generated maximum steam pressure of 7.4 kg/cm^2 followed by 353 ± 13 ^{o}C and 5.1 kg/cm^2, respectively in post winter and 311 ± 26 ^{o}C and 4 kg/cm^2, respectively in rainy season. The reflector efficiency was calculated to be 30 ± 1% during whole experiment. High specific energy in steam at 1.5 kg/cm^2 pressure resulted in excellent cooking and consumed only 7 min to prepare 1 kg of rice, which was significantly lower as compared to the time consumed (27 min) in traditional system. The whole assembly would be free of cost after 8.7 years of operation and therefore it is imperative to state that this cutting edge technology would uplift the social economy along with conserving the basic structure of environment.

Highlights

- Solar reflector-cum-steam generator was evaluated under different climatic conditions.
- The efficiency of reflector and header assembly was found to be 30% and 93%, respectively.
- As compared to the traditional method of cocking solar system was found highly efficient.

Keywords: Energy source, meal preparation, steam, sunlight, solar reflector

Recently, shortage in conventional energy reserves and world-wide environmental issues has become global hot topic of debate, for instance Kyoto Protocol 1992 and Paris agreement 2017. Interestingly, these two overwhelming concerns can be efficiently solved by single solution i.e. advancement in green energy or renewable energy sources (Jacobson 2009). The present and the decade before have seen substantial development in the existing devices or invention of new devices to harness energy from the naturally available energy sources such as sun, water, wind and waste items (Dincer 2000). Various bifunctional devices, as for example microbial fuel cells (Noori *et al.* 2016; Noori *et al.* 2017; Tiwari *et al.* 2016) biogas plants (Bhunia and Ghangrekar, 2008; Thirugnanasambandham, 2014) have been commissioned to provide off-grid energy along with reduction in pollution threats.

Although, the gap between energy demand and production is still big, especially in developing countries such as India, where large portion of population resides in villages. The distribution of energy to the geographically remote location is also a challenging issue apart from the other concerning problems related to daily needs. Thus, promotion of self-sustainable energy resources remains only solution to fill the gap of energy need to uplift the life style and social economy of villages (Akella *et al.* 2009; Wüstenhagen *et al.* 2007). According to the literature and reports, solar energy and biogas has been advocated as best source to be used in rural areas due to abundant availability of sunshine-days and waste materials in most of the part of the country. However, fabrication of biogas plants is capitally intensive and large quantity of waste organic material is required to start-up the plant, which therefore make it unfeasible for single household with less number of family members. On the other hand, cooking of daily meals consumes high energy in traditional "*chulhas*" with production of air polluting gasses, for example CO, CO_2, SO_2 etc., which enflames both temporary and permanent diseases or disorders in human body (Kampa and Castanas 2008). Thus, to seek sustainable solution of these prodigious problems, collection and utilization of solar radiation in the form of direct energy or secondary energy generation in the form of electricity has been advised by researchers (Carlson and Wronski 1976). Solar panels, however, has been profoundly used in various part of the country but the less conversion efficiency makes difficult to comply its use for cooking purpose rather operating small electric appliances and LED bulbs (Green *et al.* 2015).

The solar reflector, on the other hand was found to be efficient for collecting low intensity solar radiation to beam as high energy light in an enclosed surface, which further can boil water or dry items efficiently (Kaushik *et al.* 1995). Substantial research has been carried out in past few decades to enhance the efficiency of the reflectors by employing advanced tracking system and efficient glasses (Kaushik *et al.* 1995; Baccoli *et al.* 2015; Kancevica *et al.* 2012). Solar driers, water heater are the distinctive examples of solar collectors/reflectors, which were applied in various community based places, hotels and restaurants. However, still limited research is available to understand its effectiveness of using this cutting edge technology as primary low cost sustainable solution for individual families in this country. Therefore, the primary objective and aim of this present research was encircled to appraise a low budget solar reflector in association with a boiler to cook different types of traditional meals, for example "*Kheer* (milk rice)", "Cooked rice" and "*Dal* (pulses). Cooking time of different recipes prepared with solar reflector cum steam generator was compared with time required in the traditional "*Chulhas*". In addition, cost analysis was performed to validate its community acceptance.

MATERIALS AND METHODS

Geographical location and climatic condition of experimental site

Experiments were carried out in college of agricultural engineering, PUSA, Bihar having geographical location as follows: latitude of 88° 48′ east and an altitude 25° 22′ north and 52.92 m above the mean sea level. The maximum temperature during the hottest month of June goes up to 40 °C. Whole experiment was performed in three climatic conditions viz. summer (June – July), monsoon (August – September) and post winter (October – November) to evaluate the climatic effect on the performance of the system.

Solar reflector and steam generator assembly

The solar reflector system was made by assembling different individual components such as parabolic solar reflector, receiver, header assembly and a cooking vessel. The parabolic solar reflector was made with multiple flat mirrors having total projected surface area of 16 m^2 and was coupled with semi-automatic solar tracking system.

Fig. 1: Digital image of solar system and individual components

The receiver was an empty cylinder both side closed of diameter 37 cm and length of 50 cm made with mild steel. The vessel was properly insulated to avoid any heat loss accept the beam facing side, which had thickness of 2 cm with thermal conductivity of 20 W/mK. The header assembly was a cylindrical vessel of 1.8 m long and 30 cm diameter with 10 cm insulation from inside connected with the receiver vessel for collection of steam and equipped with a pressure gauge. The specific heat capacity of header assembly was around 0.49 kJ/kgK. A cooking vessel of capacity of 0.05 m^3 was attached via high strength insulated pipes with the header assembly to utilize steam for cooking different recipes. A digital image of the whole system and its components is shown Fig. 1 for better understanding.

Experimental variables

Experiments were performed using different variables such as climate, types of recipe and weight of materials to be cooked. Table 1 shows composition of recipes and other parameters taken into consideration for evaluation of performance of the system. The weight of rice and pulses for meal preparation under this experiment was chosen based on family size (single or multiple families with 5 person to maximum of 25 persons) and community gathering supposed to have maximum member of 50. Each experiment was replicated at least three times to have good precision in data. It is worth to mention here that the cooking stuffs were soaked into the water at least for 1 h to make it structurally soft for quick cooking.

Table 1: Experimental recipes and corresponding notations

Recipe	Weight	Notations	Composition
Rice	1	R_1	Rice + Water
	5	R_2	
	10	R_3	
Dal	1	D_1	Pulses + Water + Spices + Salt
	2.5	D_2	
	5	D_3	
Kheer (milk Rice)	1	K_1	Rice + Milk + Sugar
	2	K_2	
	3	K_3	

Operation and maintenance of the system

Before sunrise, reflector and the receiver assembly was washed carefully to remove possible dust particles. The header assembly was washed and filled with tap water suitable for cooking purpose. Cooking experiments were started after getting suitable steam pressure in the header assembly. Time required for cooking of each recipe using solar system was noted and compared with the traditional method of cooking.

Data analysis and calculation

Solar radiation near reflector was recorded using Mastech Digital Luxmeter (MS6610, China) in the interval of 1 hour from dawn to dusk throughout the experiment period. A digital thermometer (Thermotech Instruments (P) Ltd. India) was used for measuring the temperature on the surface of the receiver assembly and water. Efficiency of the reflector (η_R) and the header assembly (η_H) was calculated according to equation 1 and 2, respectively (El Ouederni *et al.* 2009).

$$\eta_R = \frac{q_c}{\theta_{inc}} \quad \ldots(1)$$

where, q_c = Concentrated solar flux; W/m^2

θ_{inc} = Incident solar flux; W/m^2

q_c = Energy required to increase temperature of water + Energy required to increase temperature of header pipe in 11 to 12 h,

$$q_c = \frac{\text{Mw Cp w(dT/dt)+Ms Cps (dT/dt)}}{S_r}$$

where,

M_w = Mass of water in header pipe; kg

M_s = Mass of header pipe; kg

C_{PW} = Specific heat capacity of water; kJ/kg.K (4.18)

C_{PS} = Specific heat capacity of carbon steel; kJ/kg.K (0.49)

S_r = Surface area of receiver; m^2

$$\eta_H = 100\% - \text{Total loss of heat} \quad \ldots(2)$$

where, Total loss of heat% = Leakage loss% + Radiation loss% + Manufacturer loss %

RESULTS AND DISCUSSION

System performance under various climatic conditions

The performance of the solar reflector cum steam generator was evaluated based on reflector efficiency and the header assembly efficiency under three different climatic conditions. A perfect solar reflector should concentrate incident solar radiation to high energy light beam on receiver in order to get proficient results (El Ouederni *et al.* 2009; Kussul *et al.* 2008). The temperature of light beam on receiver certainly will be dependent on energy content in incident solar radiation and thus should vary with respect to the climate temperature and availability of sunshine hour. As shown in Fig. 2a, the highest receiver temperature of 460 ± 31 °C was obtained during the month of June – July, which clearly evidenced the hot climatic condition during this month had ample amount of energy in the incident sunlight. During the rainy season i.e. August – September in which many days were evinced lack of clear sun due to cloud cover, received absurdly fluctuating temperature of 311 ± 26 °C at receiver side and was noted least average value of temperature among tested climatic conditions. Second highest temperature of 353 ± 13 °C was obtained for post winter season i.e. October-November months and least variation in average value of temperature suggests uniform sunlight throughout the experiment duration.

However, it would be worth to mention here that the obtained results contains a single calendar year data of a confined place, thus can change with climatic conditions and place of testing. The efficiency of the reflector was calculated to be 30.3 ± 1.9%, which was found in coherence with the efficiency of 27% obtained with parabolic solar concentrator as reported in previous literature (El Ouederni *et al.* 2009).

The results suggesting it as an excellent low-cost device for harnessing natural renewable energy. In addition, the efficiency of the reflector was found almost independent of the climatic conditions. As far as the header assembly is concerned, the efficiency was found to be 93% considering leakage loss, radiation loss and manufacture loss of around 5%, 1.5% and 0.4%, respectively. The radiation loss and manufacture loss are the involuntary action, which cannot be controlled, hence the maximum efficiency would always less than 98%.

Steam pressure collected in the header assembly is an important parameter, which eventually offers energy for cooking meals. Rise in temperature in receiver side due to focused energy beam from reflector allows to boil water in the receiver container. The heat conducts through receiver surface to the solid-water interface. Boiling water at high temperature evaporates and converts to high temperature and pressure steam. High temperature rise on receiver in the months of June– July, facilitated quick boiling of water, which resulted in advancement of steam pressure quickly as compared to the other tested climatic conditions (Fig. 2b). Steam pressure consistently increased from 9:00 h to 16:00 h and the gauge recorded a highest

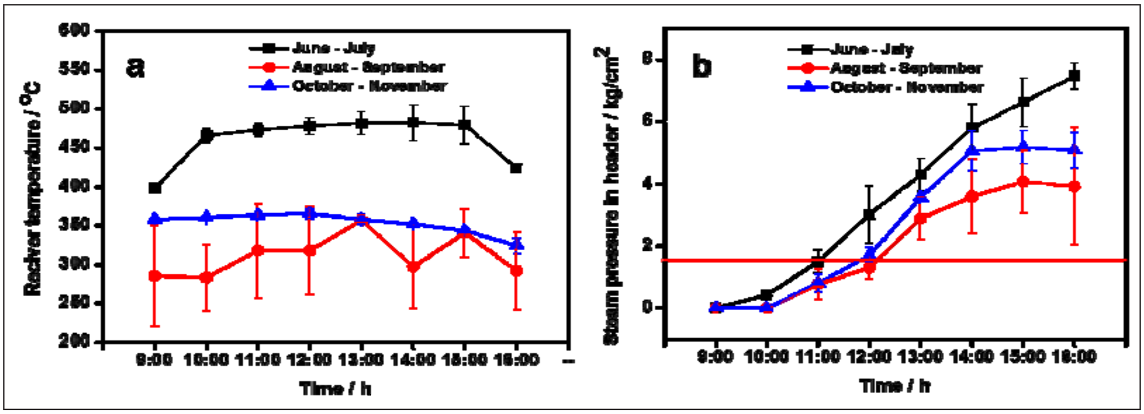

Fig. 2: (a) Receiver surface temperature profile and **(b)** Steam pressure profile on header assembly with time

Note: *1. Here temperature and steam pressure values at particular time are average for corresponding entire season, 2. The red line denotes an arbitrary chosen pressure (1.5 kg/cm²) at which the meal preparation experiments was carried out.*

pressure of 7.4 kg/cm^2 in summer. On the other hand, maximum steam pressure of 4 kg/cm^2 for August – September and 5.1 kg/cm^2 for October – November was recorded. The line traced on Fig. 2b, cutting Y-axes shows steam pressure of 1.5 kg/cm^2 at which the cooking programme was performed. It is to be noted that the required pressure in all the cases was attained between 12:00 to 13:00 h of steam formation.

Preparation of meals using traditional and solar steam cooking system

Tradition cooking in open "*Chulhas*" is most common practice in India, which has low heat conversion efficiency and at the same time exhales harmful greenhouse gases (Pohekar *et al.* 2005; Hanbar and Karve 2002). Fig. 3a shows a typical example of traditional cooking system using "*Chulha*" and wood logs, which clearly visualize the amount of wastage of heat from the side and therefore has less conversion efficiency. On contrary, the solar reflector cum steam generation system compel heat from sunlight for generation of steam and the compressed steam at high temperature directly cooks the food in a closed container, which makes this system a cost effective sustainable solution (Fig. 3b).

A minimum pressure and suitable time in Indian context at which most of the people make food for lunch was chosen to run the experiment trials. As discussed above, during 12:00 – 13:00 h, steam pressure in header assembly was noted about 1.5 kg/cm^2 (~ 21 psi) in all the cases, corresponding to the steam temperature of 126 ^{o}C, thus the time can be considered suitable for cooking. According to the results obtained from both of the cooking practices, cooking time of 9.3 ± 1.5 min to prepare 1 kg of rice was found significantly lower as compared to the traditional method, which took 27.5 ± 3.2 min with total consumption of 2 kg wood log. Similarly, solar system consumed less time of 8.6 ± 2.0 min and 7.8 ± 1.1 min, respectively for cooking 1 kg pulse and 1 kg rice in the form of *kheer* as compared to time required for traditional method (32.2 ± 1.7 and 29.6 ± 2.5 min, respectively). As the weight of the substances increased, an obvious increase in the time consumption was witnessed in all the cases. Detailed observation is given in the Table 2. Nevertheless, the solar system was found exceptionally better than traditional cooking method in terms of processing time and wastage.

Table 2: Consumption of time for preparation of different recipes with varying weight using traditional and solar system

Recipe	Variables	Time consumed	
		Traditional	Solar system
Rice	R1	27.5 ± 3.2	9.3 ± 1.5
	R2	37.3 ± 2.7	12.6 ± 2.5
	R3	41.6 ± 2.0	18.0 ± 2.0
Dal	D1	32.2 ± 1.7	8.6 ± 2.0
	D2	48.7 ± 2.9	15.2 ± 1.7
	D3	60.3 ± 3.0	21.0 ± 1.0
Kheer	K1	29.6 ± 2.5	7.8 ± 1.1
	K2	45.0 ± 2.0	13.3 ± 1.5
	K3	54.1 ± 3.3	17.6 ± 1.5

In addition, the cooking time was not observed to be dependent on the climatic factors, since the

Fig. 3: Digital image of **(a)** traditional cooking practice showing a mud "*chulha*" and **(b)** Cooking experiment on solar system; in inset: prepared *dal*

pressure and steam temperature was constant in all the cases. After meal preparation, rest of the steam can be used for other useful purposes, as for example to drive pump or DC generator as an additional benefit. In terms of operation and maintenance, this system was found to be very reliable that can be operated by any person but care must be taken while approaching to the receiver side and children mandatorily should keep away from the system. Concentrated solar beam with high energy at receiver side can cause severe burn. From above results, it is authoritative to conclude that the chosen solar reflector cum steam generator was able to facilitate required steam for cooking purposes irrespective of climatic conditions. The clean approach of this technology has potential to replace most practising traditional method of cooking for smaller family to larger scale community.

Cost analysis

An advanced technology in any form should qualify certain constraints before presenting it for social and commercial utilization and these are cost effectiveness, easy to maintenance and user friendly. The present solar system used in this experiment could qualify in operation and maintenance constraints as discussed above. It is a debating issue in present on the capital investment for installation of solar energy harvesters (solar panel, solar water heater, solar reflector etc.) (Chakrabarti and Chakrabarti 2002). However, the argument need to be relooked and should think about long term benefit from these systems due to their long term durability and stability. For example, one time capital investment of solar reflector used in this experiment was $3513 and if the subsidy amount of $1249 will be considered, which Govt. of India provide to the rural India for promotion of solar equipment, the total amount will come down to $2264. The capital investment can be recovered roughly in 8.7 years (considering 260 days sunshine in a year) if $1 per day (assumption), a household spends in wood for meal preparation. This period will even be much lesser for community utilization with an additional benefit of cutting carbon foot print.

System limitations

Every exiting system comes with certain disadvantages, so few limitations was noted for this system too. Flat plate mirrors are the main component of this system, which concentrate solar radiation for heating water and due to outdoor installation, the mirrors become dusty, resulting in decrease in energy flux. Hence, time to time cleaning is required in order to get optimum performance. Adjustment of focus is another limitation of this system in case of failure of automatic tracking system. The whole system may collapse in cloudy days, which is the limitation of the all type of solar related energy harvesting systems. Moreover, this system cannot cook fried items.

CONCLUSION

A solar reflector in association with receiver cum steam generator was investigated for its applicability for preparation of food under different climatic conditions. A header steam pressure of 1.5 kg/cm^2 was found to be sufficient for cooking basic meals (rice, dal and kheer) and as compared to the traditional method of cooking, this system was proven to be excellent due to less time consumption (7 min vs. 27 min in traditional cooking system for rice preparation) and fuel saving. The results outlined from this experiment suggesting potentiality of this system to be used as real time cost effective solution for meal preparation in the rural sector of the country.

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