analysis based on actual quantities of various elements and prevailing rates. These correlations can be taken as the basis for determining the cost of the scheme having alternatives based on the number of units. This will be helpful in knowing the cost of the scheme which is the foremost requirement for taking up a project for development. Further, these correlations can be modified for different conditions such as type of turbine, type of generator, and soil conditions. ■

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Energy and exergy efficiency comparison of community-size and domestic-size paraboloidal solar cooker performance

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1. Introduction

The fast-depleting traditional sources of energy, growing energy requirement and environmental pollution have forced scientists to explore alternative sources of energy. The suitability of solar energy for decentralized applications makes it an attractive option to supplement or substitute the energy supply from other sources. Solar cooking is the most direct and promising application of solar energy. Solar energy is a promising option capable of being one of the leading energy sources for cooking [Biermann et al., 1999; Wentzel and Pouris, 2007]. Box-type solar cookers have limitations of low capacity, low efficiency, more time required for cooking, less variety available in cooking products and outdoor cooking. Solar cooker designs of reflector or concentrator type overcome some of these limitations. Negi and Purohit [2005] observed that the boiling point of water with the concentrator cooker is reached faster than with the conventional box-type cooker using a booster mirror. Patel and Philip [2000] conducted stagnation temperature, water-heating and cooking tests to evaluate the performance of three concentrating-type domestic solar cookers. Habeebullah et al. [1995] presented work related to a parabolic concentrating type cooker using bare receiver and an insulated pot with a glazed insolation window in an oven-like design. They showed that the oven-type receiver is highly efficient when compared with the bare type. The speed of cooking is practically independent of the heat rate, once the contents of the vessel have been sensibly heated up to the cooking temperature [Lof, 1963], therefore, the testing procedure for the present work is based on the sensible heating of a known quantity of water up to the boiling point.

The traditional way of evaluating the performance of solar cookers is based on their energy efficiency defined as the ratio of output energy to the input energy supplied. Available energy/exergy based on the second law of thermodynamics provides an analytic framework based on quality of energy. The exergy or rational efficiency based on the concept of exergy is a true measure of performance of a thermal system [Bejan, 1988; Kaushik et al., 2000].The energy and exergy efficiencies of a low-cost parabolic type solar cooker by water-heating test in a cooking pot have been determined by Ozturk [2004]. In the present paper the instantaneous and daily energy and exergy efficiencies of a community-size solar cooker (CSC) and a domestic-size solar cooker (DSC) are calculated on the basis of the experimental results [Kaushik and Bansal, 2002].

2. Description of the systems

2.1. Community-size solar cooker

The community-size solar cooker (Figure 1) mainly consists of four parts: mild steel stand, primary reflector disk, secondary reflector and a tracking device. The primary reflector disk is parabolic in shape and has a reflective area of 7.3 m^2 and aperture diameter 3800 mm lengthwise and 2750 mm widthwise, and its depth is 300 mm. The primary reflectors are of 3 mm thick acrylic sheets having a reflectivity of 73 % which are fixed on a mild steel parabolic frame. The secondary reflector is also made parabolic in shape and in it aluminium sheets having a

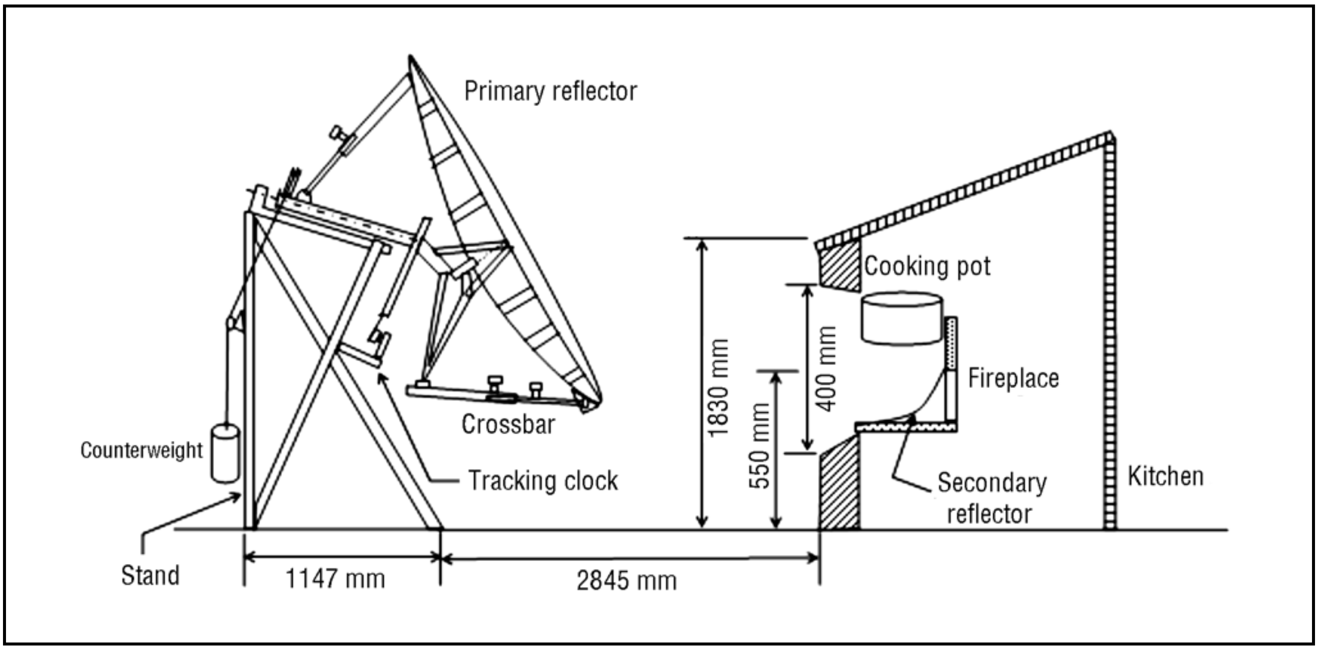

Figure 1. Community-size solar cooker for indoor cooking

reflectivity of 65 % are mounted. The reflective area of the secondary reflector is 0.36 m^2. To cope with the movement of the sun, a semi-automatic tracking mechanism based on clock action is introduced. This tracking mechanism rotates the primary reflector disk at the rate of 15º per hour to keep the solar radiation constantly falling on the secondary reflector which is placed inside the kitchen. There is also a provision of seasonal adjustment by two levers/crossbars which hold the primary reflector disk at the top and at the bottom. These levers provide the primary reflector disk ± 23º adjustment which has to be done manually twice a month. The wall which is facing the primary reflector disk is kept at a distance of 2.845 m or less than the focal distance.

2.2. Domestic-size solar cooker

The shape of the cooker (Figure 2) is paraboloidal (dish) type having 1.37 m aperture diameter. This solar cooker consists of a mild steel structure and aluminium sheets as reflector only. The reflective area of the solar cooker is 1.47 m^2. The focal length of the cooker is 280 mm while the focal area of the cooker is 0.134 m^2. The reflectivity of the mirror facets is 0.75. The solar tracking in this cooker is done manually: the cook has to reposition it each 20-30 minutes.

2.3. Testing procedure and measurements

The experiments were conducted at the Indian Institute of Technology (IIT), Delhi. Initially the testing of the CSC was done with an ordinary 2 mm thick cylindrical aluminium black-bottom pot of capacity 50 litres (l), and then the testing was also done with a pressure cooker vessel with and without sinking it in a cooking stove. The testing of the DSC was done with an ordinary cooking pot of 5 l capacity, with and without insulation. The temperature of water at three different depths, the instantaneous solar radiation and the ambient temperature were noted down using appropriate instruments just before starting the experiment, and thereafter the readings were taken every half-hour up to when the water got boiled or reached its maximum temperature.

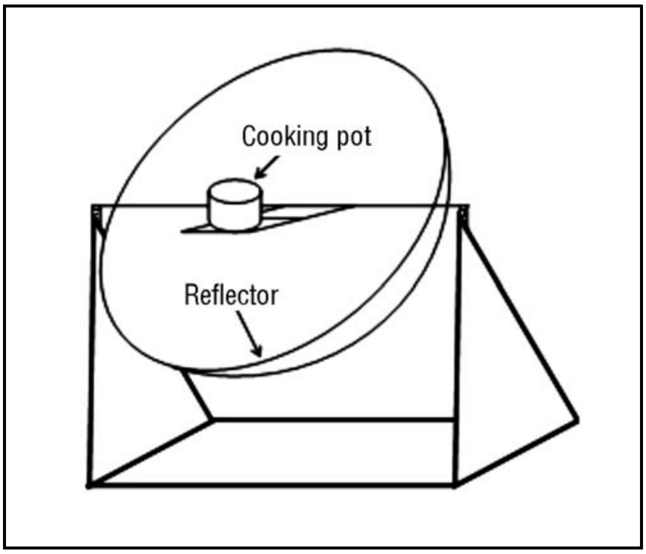

Figure 2. Domestic-size solar cooker for outdoor cooking

3. Evaluation for energy and exergy efficiency

The maximum useful work from solar radiation sets the upper limit of performance for solar energy conversion devices. Petela [1964] examined for the first time the exergy of solar radiation, and concluded that thermal radiation from the sun is relatively rich in exergy. Bejan [1987] presented a unified theory to explain the exergy of solar radiation. The input exergy $Ex_{in,solar}$ or exergy of solar radiation per unit collection area [Bejan, 1987] reaching the ground is

$$Ex_{in,solar} = I\left[1 - \frac{T_a}{T_s}\right] \text{W/m}^2 \quad (1)$$

where I is the mean solar radiation intensity between consecutive readings and T_a is the ambient temperature. The

Table 1. Performance of CSC and DSC with ordinary cooking pot

Time of day (IST[1])	Ambient temperature (K)	Solar radiation (W/m^2)	Mean temperature of water (K)	Input (W)		Cooker output (W)		Efficiency (%)	
				Energy	Exergy	Energy	Exergy	Energy	Exergy
Performance of CSC with ordinary cooking pot and mass of water in pot 20 kg									
10:30	299	600	297						
11:00	301	680	319	4672	4421.71	1026.66	26.24	21.97	0.59
11:30	304	680	333	4964	4695.85	653.33	47.00	13.16	1.0
12:00	306	700	344.66	5037	4762.66	544.13	54.28	10.80	1.14
12:30	306	750	353.66	5292.5	5003.30	420	51.89	7.93	1.04
13:00	307	750	357.66	5475	5175.34	186.67	25.8	3.41	0.5
13:30	308	730	360.1	5402	5105.37	113.87	16.30	2.10	0.32
Performance of DSC with ordinary cooking pot and mass of water in pot 5 kg									
11:00	301	440	299.3						
11:30	304	460	324	661.5	625.77	288.17	8.31	43.56	1.33
12:00	304.5	470	341.6	683.55	646.41	205.33	17.57	30.04	2.72
12:30	304.5	450	352.6	676.2	639.43	128.33	15.74	18.98	2.46
13:00	304	460	357.6	668.85	632.51	58.33	8.35	8.72	1.32

Note

1. IST = Indian Standard Time

temperature of the sun T_s is taken equal to 5600 K.

The energy efficiency η_I based on the first law is defined as the ratio of cooker output energy (increase of energy of water due to temperature rise) to the energy input (energy of solar radiation). Thus, the instantaneous energy efficiency is given by

$$\eta_I = mc_p\,(T_{fw} - T_{iw}) \,/\, IA\Delta t \qquad (2)$$

where m is the mass of water in the pot, T_{iw} and T_{fw} are the initial and final temperatures of water in the time interval Δt and A is the area of the reflector. The specific heat of water c_p is taken equal to 4200 J/kgK.

The second law efficiency η_{II} or exergy efficiency is defined as the ratio of cooker output exergy (increase of exergy of water due to temperature rise) to the exergy input (exergy of solar radiation). Thus the instantaneous exergy efficiency is given by

$$\eta_{II} = mc_p\left[(T_{fw} - T_{iw}) - T_\alpha \ln\frac{T_{fw}}{T_{iw}}\right] \Big/ I\left[1 - \frac{T_a}{T_s}\right] A\,\Delta t \qquad (3)$$

The average energy/exergy efficiency is calculated as the ratio of the sum of all the values of cooker output energy/exergy calculated by taking the consecutive readings to the sum of all the values of input solar energy/exergy calculated by taking the consecutive readings.

4. Results and discussion

Initially, testing of the CSC was done with an ordinary cooking pot and it was observed that some improvement in the cooking vessel should be made because the efficiency was rather low at that stage. Therefore, a pressure cooker of maximum available capacity (22 l) was used instead of the ordinary pot. There was some notable reduction in the heating time. Furthermore, it was observed that the heating time would be further reduced and the efficiency would be higher if we sank the pressure cooker approximately 200 mm down in the cooking *chulha*/stove so that it could absorb a large part of the solar radiation directly coming from the primary reflector at its front side and the rest of the radiation could reach its bottom through the reflection from the secondary reflector. Therefore, testing was also done with a sunken pressure cooker and a significant gain in terms of reduced heating time and improved thermal efficiency was noted. The testing of the DSC was done with an ordinary cooking pot with and without insulation.

Table 1 shows the experimental results of the CSC and DSC for typical days. For the CSC, the total cooker output energy is 5.3 MJ while the total input solar energy is 55.52 MJ. Thus, the average energy efficiency is 9.55 %. The total cooker output exergy is 398.7 kJ while the total input solar exergy is 52.50 MJ. Thus, average exergy efficiency is .759 %. It had taken 180 minutes to increase the temperature of the water up to 360.1 K with 55.52 MJ of input solar energy. The peak instantaneous energy efficiency achieved is 21.97 % and instantaneous energy efficiency decreases continuously with time due to less heat energy gain as the temperature of the water increases. The instantaneous exergy efficiency for this case first increases, reaches a peak value and then decreases with time, which shows that for maximum instantaneous

Table 2. Test results summary of CSC and DSC

No.	Type of cooker	Cooking pot type	Mass of water in pot (kg)	Test duration (IST)	Temperature variation of water in pot (K)	Ambient temperature variation (K)	Solar radiation intensity range (W/m^2)	Total input solar energy, exergy (kJ/kg of water)	Instantaneous efficiency range (%)		Average efficiency: energy, exergy (%)
									Energy	Exergy	
1	CSC	Ordinary	40	08:00 to 12:00	307 to 366	306 to 317	252 to 695	1445.2, 1364.0	12.94 to 26.05	0.177 to 1.72	17, 1.18
2	CSC	Ordinary	20	10:30 to 13:30	297 to 360.1	299 to 308	600 to 750	2775.8, 2624.7	2.10 to 21.97	0.32 to 1.14	9.55, 0.76
3	CSC	Pressure cooker	16	14:15 to 16:00	307 to 369.5	315 to 315.5	603 to 730	1977.5, 1866.2	6.95 to 16.32	0.16 to 1.60	13.27, 0.91
4	CSC	Pressure cooker (sunk in stove)	21	11:30 to 13:30	285 to 371.5	289 to 293	520 to 560	1357.8, 1287.4	17.10 to 32.55	0.92 to 4.47	26.75, 3.14
5	DSC	Ordinary	5	11:00 to 13:00	299.3 to 357.6	301 to 304.5	440 to 470	968.4, 915.8	8.72 to 43.56	1.32 to 2.72	25.28, 1.96
6	DSC	Ordinary	5	10:30 to 12:30	297 to 369	300 to 306	540 to 620	1264.8, 1196.1	4.00 to 48.73	0.72 to 4.03	23.91, 2.19
7	DSC	Insulated	5	10:30 to 12:30	296 to 368	296 to 304	480 to 540	1084.8, 1026.7	8.90 to 53.45	1.60 to 4.45	27.87, 2.89

exergy efficiency instantaneous initial temperature must be optimum. The peak instantaneous exergy efficiency is 1.139 %. It is also clear from the results that instantaneous energy efficiency at a high temperature of water becomes quite small in comparison to its peak. However, the instantaneous exergy efficiency does not decrease proportionately. For the DSC the average energy and exergy efficiency are 25.28 % and 1.964 % respectively.

Table 2 shows the summary of experimental results of the CSC and the DSC. The results 1 and 2 of Table 2 show that to boil water, the loading of the pot with water or food to be cooked should be done to its maximum capacity. The results 2 and 3 show that a pressure cooker pot requires less energy input though the amount of water taken is less in the pressure cooker pot case. The result 4 shows that efficiencies achieved are high with the pressure cooker pot in sunken position since in earlier cases reflection losses are more because the total input solar radiation is reflected twice (first by the primary reflector and then by the secondary reflector). By sinking the pressure cooker into the cooking place, the pot directly faces maximum solar radiation reflected by the primary reflector while the rest of the solar radiation reaches the bottom of the pressure cooker through further reflection by the secondary reflector. In the sunken position heat loss from the pot also decreases as the temperature around the pot is also higher in comparison to ambient temperature. It is clear from the results 5 and 6 that instantaneous energy/exergy efficiency is dependent on the solar radiation intensity and the initial temperature of water in the pot. Initially the instantaneous energy/exergy efficiency for the result 6 is higher, as the solar radiation intensity is more, while latter on the instantaneous energy/exergy efficiency for result 6 is lower, as the instantaneous initial temperature of water in the pot is more. As the rate of heat loss through the pot increases in direct proportion to the temperature difference between the water in the pot and the ambient air, provision should be made for insulating the pot from ambient air. It is clear from the results 6 and 7 that energy/exergy efficiency is more with the insulated cooking pot due to less heat losses.

On the basis of average energy efficiency from the results 4 and 7 in Table 2, it can be said that the performance of the DSC is comparable with that of the CSC. However, the average exergy efficiency of the CSC with pressure cooker pot in sunken position is higher than the average exergy efficiency of the DSC. Thus there is some potential for improvement in the DSC. This point is not clear from the energy analysis viewpoint only and exergy analysis gives a clearer picture regarding the improvement potential. The exergy efficiency of the CSC having a concentration ratio approximately equal to 20 suns is also less than the theoretical possible value due to more optical losses in the community-size cooker.

5. Conclusions

The CSC provides high performance, which is indicated by high energy efficiency, exergy efficiency and low characteristic boiling time in comparison with the DSC and other cookers reported in the literature. The low efficiency of these cookers is attributed to the optical and thermal losses from the reflector and pot. The exergy efficiency of any solar cooker or solar thermal device is very low because input solar radiation is rich in exergy and being utilized in the form of heat at low temperature. The exergy efficiency can be increased only marginally by increasing the reflectivity of reflectors, proper designing of cooking place and by using a suitable cooking pot. The time required to heat the water up to boiling temperature indicates that such cookers are suitable to cook a meal faster and the quality of the meal cooked will be on a par with the quality of the meal cooked by traditional means. ■

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