An exergy based unified test protocol for solar cookers of different geometries

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Abstract: It is good for the consumer to have solar cookers of various varieties in terms of geometrical designs, performance and price but it is a ch allenge to develop a u niform test standard for evaluating the thermal performance of the cookers irrespective of their geometrical construction. Due to the lack of uniform test protocol, consumer cannot compare the quantitative performance of the cookers of different configuration and become confused. For this end, we plotted graphs between exergy output and temperature difference, for solar cookers of different designs and it resembled a parabolic curve for each design. The peak exergy (vertex of the parabola), can be accepted as a measure of devices' fuel ratings. The ratio of the peak exergy gained to the exergy lost at that instant of time can be considered as the quality factor of the solar cooker. Besides, the exergy lost is found to vary linearly with temperature difference irrespective of the topology of the device and the slope of the straight line obtained through curve fitting represents the heat loss coefficient of the cooker. The proposed parameters can lead to development of unified test protocol for solar cookers of diversified designs.

Keywords: *Solar Cookers, Test Protocol, Exergy Analysis*

Nomenclature

A	*gross area of glazing surface*	m^2
c	*specific heat capacity of water*	*J/kg K*
E_o	*output energy*	*J*
E_{Xi}	*input exergy*	*kJ*
E_{Xo}	*output exergy*	*kJ*
F_1	*first figure of merit*	m^2 *K/W*
F_2	*second figure of merit*	
G	*instantaneous solar insolation*	W/m^2
m	*mass of water*	*kg*
T_{am}	*instantaneous ambient temperature*	*K*
T_f	*final water temperature*	*K*
T_i	*initial water temperature*	*K*
T_s	*surface temperature of sun*	*K*
Δt	*time interval*	*s*

1. Introduction

Solar cookers are a very useful and popular thermal device which is available throughout the world. It is one of the few renewable energy thermal gazettes which are portable, user friendly, easily operable, meant to fulfil the very basic need and economically competitive. Its affordable price makes it v ery attractive commercially, especially among the rural populace in the developing countries. In order to meet the demands of broad spectrum of the society and penetrate the market, different novel varieties of solar cookers have become available in accordance with peoples' need and purchasing capacity. Solar box type cookers (SBC) are available for domestic as well as community based applications. Similarly, SK-14, SK-10 and Scheffler paraboloid type concentrating cooker are also present in the market for fast cooking for domestic/community and industrial applications. In addition parabolic trough type concentrating cookers are being reported in recent studies for both domestic as well community type applications. D epending on the topology of the cooker construction, different test procedures and thermal indicators have been established, which act as benchmark thermal performance evaluators for various geometrical varieties of the cooker. On one hand it is good for the customer to have solar cookers of diversified designs in terms of geometry, performance and price but on t he other hand it is a challenge to develop a uniform test standard for evaluating the thermal performance of the cookers irrespective of their geometrical construction. In the absence of such unified test/standard protocol, it is very confusing for the customer to compare the performance of these devices. In addition, to promote renewable energy technologies (RETs), many governments throughout the world, are adopting environment friendly policies. This includes the provision of providing direct/indirect subsidies and other benefits to the user on the usage of the RETs. Many a times, manufacturers are not able to receive the subsidy benefits because the parameters set for eligibility criterion matches one design of solar cooker and not the others. Through the present manuscript, we propose an exergy based unified test protocol for solar cookers of different geometries. In this protocol, the test methodology for conducting full load test for solar cookers remains the same but the analyzing procedure has been altered so as to fulfill the above necessities. In order to develop a realistic and unified test protocol, we utilize the reported data from different well known published manuscripts and analyze it comprehensively to cater to the above mentioned needs.

2. Methodology

In order to test the performance of the solar box type cooker, two figures of merit (FOM) viz. F_1 and F_2 are generally calculated, as given by Mullick [1]. The first FOM, F_1 is defined as the ratio of optical efficiency to the heat loss factor by bottom absorbing plate and is a measure of the differential temperature gained by the absorbing plate at a particular level of solar insolation. The second FOM, F_2 is more or less independent of climatic conditions and gives an indication of heat transfer from absorbing plate to the water in the containers placed on the plate. Bureau of Indian standards have also accepted these parameters as performance indicators for SBC [2]. However, as per international test protocol for solar box cookers, the performance should be estimated in terms of its standardized cooking power as given by Funk [3], which is calculated through extrapolation of the curve/data. The value of the cooking power determined through this procedure comes out to be high and does not represent the actual cooking potential of the cooker. Internationally, the procedure for measuring the efficacy of cooking of solar cookers based on parabolic trough and Scheffler concentrating type topology is not very well known, nevertheless Scheffler concentrators are generally employed for very large scale cooking/industrial operations. As per Ministry of New and Renewable Energy (India), thermal performance of SK-14/SK-10 type cookers should be determined by its heat loss factor, optical efficiency and cooking power [4]. In all above mentioned thermal performance evaluation processes, energy based approach is employed. But, the benchmark parameters derived from the energy based method does not provide complete information and are inadequate performance indicators because their values can be misleadingly high or low depending on the temperature difference between source and sink, even though input energy condition may remain same. Exergy is a measure of the potential of the system to extract heat from the surroundings, as the system moves closer to the equilibrium with its environment [5]. After the system and the surroundings reach equilibrium, the exergy becomes zero. In the present manuscript, we would take the case of each of the different solar cookers of the above mentioned geometries and apply the exergy based approach so as to reach a holistic/uniform approach for deciding the common thermal indicators irrespective of the cooker design topology. The exergy of solar radiation, as the exergy input E_{Xi} to the solar cooker, can be calculated using the available solar energy flux ($GA\Delta t$) and is expressible through Eq. (1) which has the widest acceptability [5, 6].

$$E_{Xi} = G\left[1 + \frac{1}{3}\left(\frac{T_{am}}{T_s}\right)^4 - \frac{4T_{am}}{3T_s}\right]A\Delta t \qquad (1)$$

where T_{am} is instantaneous ambient temperature, T_s is surface temperature of sun, G is instantaneous solar insolation, A is aperture area of cooker, and Δt is time interval. The sun's black body temperature of 5762 K results in a solar spectrum concentrated primarily in the 0.3−3.0 μm wavelength band [5, 7, 8]. Although the surface temperature of the sun (T_s) varies due to the spectral distribution of sunlight on the earth's surface, the value of 5800 K has been considered for the T_s. The energy gained by water in the vessel, kept inside the cooker, due to rise in temperature can be considered as the output energy (E_o) of the system and is mathematically given as

$$E_o = mc(T_f - T_i) \quad (2)$$

In the expression above, the output energy depends only on the difference in initial and final values of temperatures $(T_f - T_i)$ but in actual practice, ambient temperature as well as the initial and final temperature values also play the role in deciding the efficiency of the system, and this kind of qualitative effect can not be accommodated in the energy based approach. The exergy gained by water in the vessel kept inside the cooker due to rise in temperature can be considered as the output exergy (E_{X0}) [5, 6, 7, 9] of the system and is expressible through

$$E_{Xo} = E_o - mcT_{am} \ln \frac{T_f}{T_i} \quad (3)$$

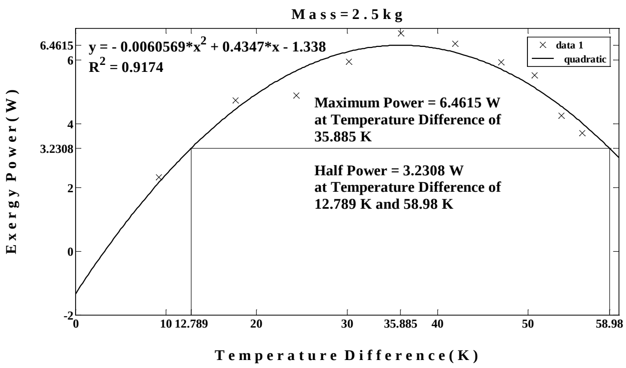
The beauty of the exergy analysis/approach is self evident in the expression above as it considers the effect of ambient temperature as well as the absolute values of initial and final temperature in addition to $(T_f - T_i)$. The second term on the right hand side of this expression signifies the exergy losses elucidating the true potential of the system in converting the input energy. Thus, exergy analysis is a more complete synthesis tool because it accounts for the temperatures associated with energy transfers to and from the cooker, as well as the quantities of energy transferred, and consequently provides a measure of how nearly the cooker approaches ideal efficiency. Here, we propose to plot a graph between output exergy power and temperature difference and fit the data points with second order polynomial; temperature difference is the difference in the instantaneous water temperature and ambient temperature. From the fitted curve, it is easier to obtain the peak value of exergy, which is very near to the actual value of the peak exergy. The temperature difference gap corresponding to the half exergy points of the curve can be determined. The exergy lost during the test period can also be plotted against temperature difference so as to estimate the overall heat loss coefficient of the cooker. In order to determine the above mentioned parameters, we are taking the data from various manuscripts for each of the different solar cookers geometries.

3. Results and Discussion

Four different geometries of solar cookers are considered for depicting their thermal performance on the basis of exergy based parameters. These geometries are domestic box type cooker, domestic SK-14 type cooker, Scheffler community type cooker, parabolic trough type cooker. The proposed four exergy based parameters, which can be considered as the benchmark indicators of the performance of the cookers are as follows, (i) Peak Exergy, (ii) Quality factor, (iii) Exergy temperature difference gap product, (iv) Heat loss coefficient. Peak exergy is the highest/maximum exergy output power obtained through curve fitting by plotting the graph between exergy output power and temperature difference. This can be realistically considered as a measure of its fuel ratings. The ratio of the peak exergy gained to the exergy lost at that instant of time can be considered as the quality factor of the solar cooker. A higher quality factor is always desirable. The product of the temperature difference gap corresponding to the half power points and the peak exergy power can also considered to be another benchmark indicator in this kind of analysis. Higher temperature difference gap means the lesser heat losses from the cooker. This kind of scheme is generally considered in electronics for expressing the performance of a BJT amplifier, as gain bandwidth product and also a quality factor in case of a notch/band pass filter. The heat loss coefficient of the device can be calculated by dividing the value of the slope of the line, obtained through linear curve fitting of exergy lost variations with temperature difference, by the value of glazing/focal area. In this approach, we are not dependent much on extrapolation and all the parameters were realistically calculated from the graphs/data. Calculations of the above mentioned topologies of the solar cooker are described in the subsequent sub-sections.

3.1. Domestic solar box type cooker

The variation in the exergy output as a function of temperature difference for domestic SBC of aperture area 0.25 m^2 is presented in Fig. 1, which depicts the case when the amount of water inside the cooking vessels/pots is 2.5 Kg. The maximum exergy power obtained through curve fitting is 6.46 W and the temperature difference gap corresponding to the half power points is 46.2 K. The peak exergy and temperature difference gap product for this case is found to be 298.5 WK. The experimental data, for performing calculation and obtaining the thermal parameters, is taken from Kumar [11].



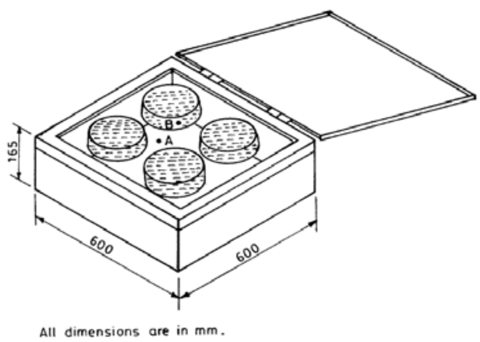


Fig. 1. Variation of Exergy output power with Temperature Difference for Domestic SBC with its schematics.

The curve between the exergy lost v/s temperature difference is plotted in Fig. 2. Heat loss coefficient is obtained by dividing the slope of the curve (which depicts the exergy lost per change in temperature, i.e., W/K), by the gross aperture area. The heat loss coefficient and quality factor, for 2.5 kg mass of water, are found to be 5.24 W/K m^2 and 0.123, respectively. The specific heat loss coefficient for this cooker is found to be 2.096 W/K m^2 kg.

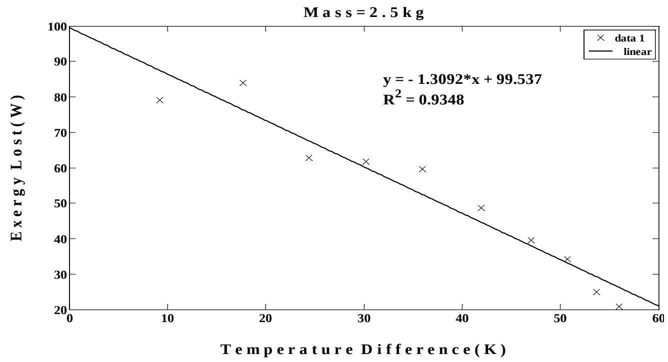


Fig. 2. Variation of Exergy power lost with Temperature Difference for Domestic SBC.

3.2. SK-14 type cooker

The variation in the exergy output as a function of temperature difference for domestic SK - 14 type of gross aperture area 1.47 m^2 and a focal area of 0.134m^2 is presented in Fig. 3, which depicts the case when the amount of water inside the cooking vessels/pots is 5 Kg. The reflective area of the cooker is 1.47 m^2 with its focal length equal to 0.28 m. The maximum exergy power obtained through curve fitting is 18.21 W and the temperature difference gap corresponding to the half power points is 40.374 K . T he peak exergy and temperature difference gap product for the two cases is found to be 735.3 WK. The experimental data, for performing calculation and obtaining the thermal parameters, is taken from Kaushik [7]. The curve between the exergy lost v/s temperature difference is plotted in Fig. 4. The heat loss coefficient and quality factor, for 5 kg mass of water, are found to be 40.35 W/K m^2 and 0.106, respectively. The specific heat loss coefficient for this cooker is found to be 8.07 W/K m^2 kg.

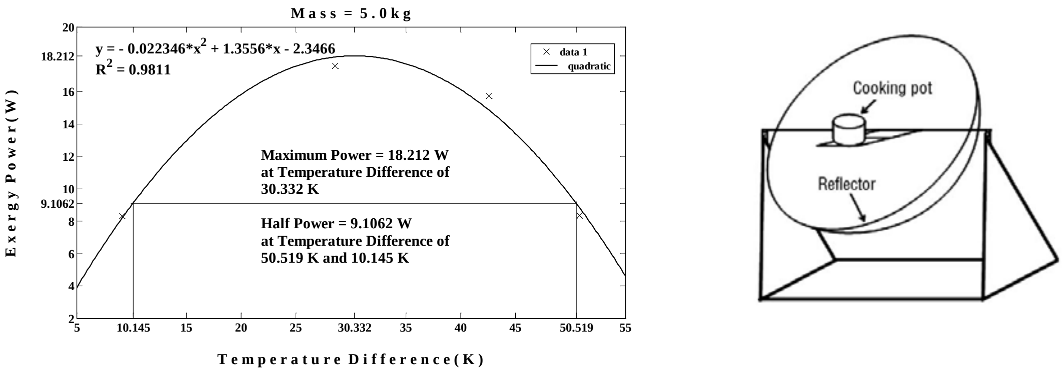


Fig. 3. Variation of Exergy output power with Temperature Difference for SK-14 type cooker with its schematics.

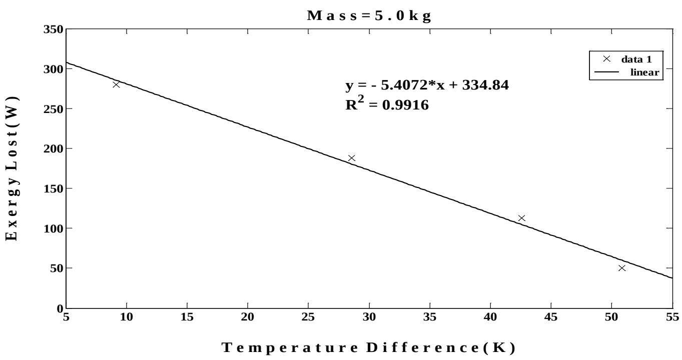


Fig. 4. Variation of Exergy power lost with Temperature Difference for SK-14 type cooker.

3.3. Scheffler Community type cooker

The variation in the exergy output as a function of temperature difference for Scheffler community type of gross aperture area 8.21 m^2 and a secondary focal area of 0.36 m^2 is presented in Fig. 5, which depicts the case when the amount of water inside the cooking vessels/pots is 20 Kg. The primary reflector area of the concentrator is 7.3 $m^2$with aperture diameters of 3.8 m lengthwise and 2.75 m widthwise and has depth of 0.3 m. The reflective area of secondary reflector is 0.36 m^2. The maximum exergy power obtained through curve fitting is 55.75 W and the temperature difference gap corresponding to the half power points is 39.62 K. The peak exergy and temperature difference gap product for the two cases is found to be 2208.815 WK. The experimental data, for performing calculation and obtaining the thermal parameters, is taken from Kaushik [7]. The curve between the exergy lost v/s temperature difference is plotted in Fig. 6. The heat loss coefficient and quality factor, for 20 kg mass of water, are found to be 54.125 W/K m^2 and 0.099, respectively. The specific heat loss coefficient for this cooker is found to be 2.706 W/K m^2 kg.

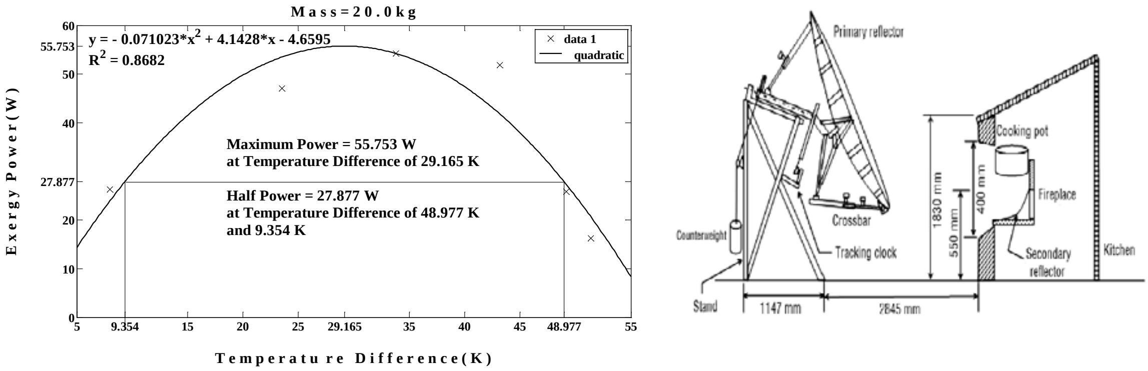


Fig. 5. Variation of Exergy output power with Temperature Difference for Scheffler type cooker with its schematics.

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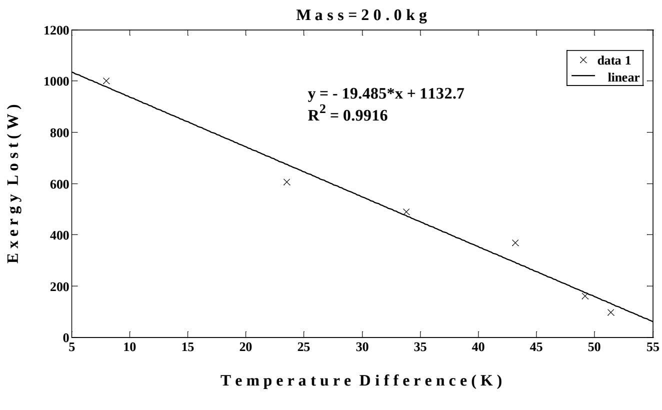

Fig. 6. Variation of Exergy power lost with Temperature Difference for Scheffler type cooker.

3.4. Parabolic trough type concentrating cookers

The variation in the exergy output as a function of temperature difference for parabolic trough type concentrating cooker of aperture area 0.9 m^2 and focal area of 0.088m^2 is presented in Fig. 7, which depicts the case when the amount of water inside the cooking vessels/pots is 6.3 Kg. The maximum exergy power obtained through curve fitting is 6.92 W and the temperature difference gap corresponding to the half power points is 23.15K. The peak exergy and temperature difference gap product for the two cases is found to be 160.198 WK. The experimental data, for performing calculation and obtaining the thermal parameters, is taken from Ozturk [8]. The curve between the exergy lost v/s temperature difference is plotted in Fig. 8. The heat loss coefficient and quality factor, for 6.3 kg mass of water, are found to be 47.73 W/K m^2 and 0.087, respectively. The specific heat loss coefficient for this cooker is found to be 7.58 W/K m^2 kg.

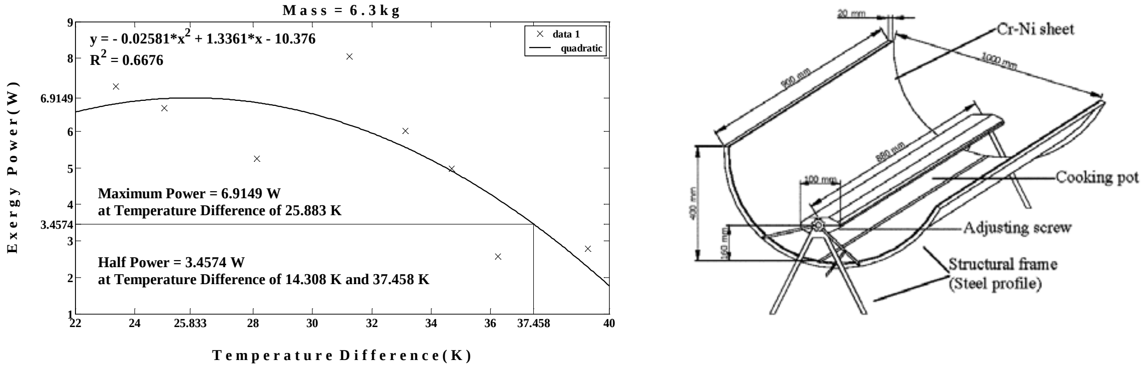

Fig. 7. Variation of Exergy output power with Temperature Difference for parabolic trough cooker with its schematics.

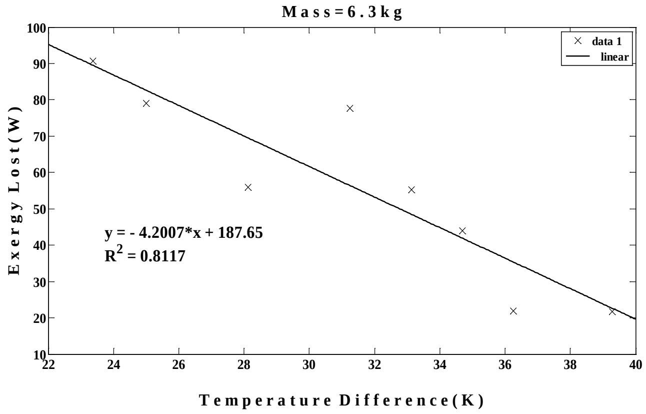

Fig. 8. Variation of Exergy power lost with Temperature Difference for parabolic trough cooker.

The cooker which attains higher exergy at higher temperature difference is the better one. It has been also noticed that the variation in the exergy lost with temperature difference is more linear when temperature of water varies in the range of 60°C to 95°C (see Fig. 2, 4, 6, 8). This range of temperature is also generally used in calculation/determination of F_2 *(second figure of merit)*, which is an important and well known performance indicator for SBC [1, 12]. The amount of heat energy at higher temperature is more valuable than the same amount of heat energy at lower temperature and in energy analysis it is not possible to take into account such qualitative difference. The exergy analysis is a more complete synthesis tool because it account for the temperatures associated with energy transfers to and from the cooker, as well as the quantities of energy transferred, and consequently provides a measure of how nearly the cooker approaches ideal efficiency.

4. Conclusion

An exergy based analysis is applied to solar cookers of different designs. Variations in exergy output and exergy lost with respect to temperature difference are studied and four thermal performance indicators, viz. peak exergy, quality factor, exergy temperature difference gap product and heat loss coefficient, are proposed. The approach presented through this manuscript is comprehensive, realistic and flexible for it can easily accommodate the effect of variations in solar insolation (peak to valley) which can be greater than 300 W/m^2. The exergy output power, if required, can be converted into standardized exergy power on par with standardized cooking power. To establish a test standard for different types of solar cookers, one may require more comprehensive testing and data analysis. However, the proposed parameters may stimulate the discussion and strengthen the case for exergy based test standards.

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