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Article

A Comprehensive Empirical Analysis on Performance Assessment of Different Solar Cookers

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Abstract: The environmental impact and associated health issues have been seen as a significant global challenge. Efforts have been made to make solar cookers efficient to reduce the health risk and environmental impact of traditional cooking energy supplies used in rural areas. The solar cookers effectiveness for cooking purposes must be assessed in a specific area before installation. In essence, this paper assesses the experimental efficiency of German Scheffler, small mirror pieces, and aluminum foil based solar cookers. The solar cookers performances are evaluated at international standards by analyzing the figure of merits such as standard cooking power, sensible heating time, and exergy efficiency by using 1.7652 kg water and 1-liter oil as a heating material. The regression analysis is also performed to observe experimental data compliance with regression line. The time required to attain a water temperature of 95˚C by German Scheffler and small mirror pieces is 25 min and 1 hour with their exergy efficiency of 48.51% and 19.16% respectively, while the aluminum foil solar cooker achieves maximum water temperature of 74˚C within 2 hours and 5 minutes with 13.47% exergy efficiency. Similarly, the highest oil temperature of 275˚C is observed for the German Scheffler solar cooker. From experimental and regression results, it is revealed that German Scheffler possesses more cooking power relative to other solar cookers and their performances are highly dependent on following factors such as solar radiations, ambient temperature, environment (dust particles concentration and wind speed), radiation reflective material, aperture area, and heat losses respectively.

Keywords: Cooking power; Solar energy; Solar radiations; Sun tracking

1. Introduction

The world revolution has an adverse effect on environment due to use of conventional fuels in terms of greenhouse gas emissions. The utilization of solar energy in forms of electricity generation, heating water, storing energy in a material for room heating, energy efficient lightening and cooking food thus helps in less dependent on non-renewable resources. The food cooking area plays a substantial role in total fuel consumption espe-

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cially in developing countries, that accounts about one-third of total primary energy utilization, while 10 % represents household energy use with respect to worlds total primary energy usage [23]. Different cooking energy sources such as agricultural waste, dung, fuelwood, coal, kerosene, liquid petroleum gas (LPG) and biomass have been used in households of developing countries, especially in rural areas. According to the World Health Organization (WHO), biomass is used as a primary fuel for cooking by more than 2.5 billion people, or 52 % of the population of developed countries. These fuels have harmful impacts on the environment and household health, contributing to approximately 1.5 million premature deaths each year as a result of indoor air pollution. Every year, about 1.3 million people, mainly women and children, die prematurely as a result of indoor air pollution caused by biomass, contributing to a death percentage of 85% while remaining is due to coal usage [21].

The fuel wood, agricultural waste and animal dung are major contributors in the emission of hydrocarbons, carbon monoxide and particulate matters that greatly affects the women's health and premature deaths of children because of their customary cooking responsibility [6]. Young children are especially vulnerable to respiratory disease, which account for the majority of premature deaths caused by direct exposure to such emissions. These emissions contribute about 36% of lower respiratory infections and 22% of chronic respiratory diseases [25].

Cooking practices that are inefficient and unsustainable can also have serious environmental consequences, such as land degradation and air pollution (local and regional). The wood scarcity obliges people more dependent on animal dung and agricultural waste that leads to soil degradation due to decrement of soil nutrients and thus increases the soil erosion tendency [7]. The particulate matters emitted by formerly discussed sources also becomes a factor of outdoor air pollution if the indoor cooking areas are properly ventilated. Such emitted particles in the atmosphere have effect on the environment and people's health in terms of global warming and cardiovascular and respiratory diseases respectively [16].

To mitigate above problems, research has been initiated in the field of solar cooking by different researchers to introduce efficient and easy maneuverable solar cookers. Solar cookers utilize solar energy to convert it into a useful heat energy, that can be used for different applications i.e., pasteurizing milk, drying foods, water sterilization, and cooking [3]. For this reason, different literatures on parabolic solar cooker efficiency, particularly the time required to achieve maximum oil temperature in comparison to the solar cooker (parabolic type) used in this paper, are reviewed in the results and discussion section. There are also different types of solar cookers available such as box, concentrator, and indirect.

1.1. Box type solar cooker

The box type solar cooker comprises of an upper glass lid and three surrounding insulated walls, accompanied with or without reflective material. The interior of the box is of black color to introduce the greenhouse effect due to solar radiations penetrated through upper glass lid to be trapped inside, heating up the black pot containing food.

1.2. Concentrator type solar cooker

The main working principle of such type pf solar cookers is to focus the direct radiation with the help of reflecting mirrors either spherical, Fresnel lens or parabolic type on the single point, where food pot is situated.

1.3. Indirect type solar cooker

These types of solar cookers are mainly used for indoor cooking, where either the large flat collector type plates or vacuum tubes are used to generate heat or steam, that is transferred to the cooking pot area by means of pipes (Anilkumar, Maniyeri and Anish, 2020; [14]).

There are also some merits and de-merits for the formerly discussed solar cookers. For instance, the box and collector type solar cookers have some common aspects such as both solar cookers utilizes direct and diffuse solar radiations and are safe from cooking

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perspective while, have a difference in maximum temperature attainability. The concentrated types of solar cookers are efficient and can achieve high cooking temperatures whereas, they are more reliant on direct beam radiations and have a safety issues related to burning eyes relative to box and collector type solar cookers [11].

In order to make cooking more effective, solar cookers are incorporated with phase change materials (PCMs), that enhances the cooking time period. The PCMs convert their forms from solid to liquid and liquid to solid either releasing or absorbing heat. Heat is absorbed by solid PCMs results in changing their phase from solid to liquid and heat is released by such PCMs when the temperature drops after regaining their shape. These PCMs can be insulated and their heat can be used for later cooking time. The melting point of these PCMs must be greater than 200 °C, that would result in changing their phase and later, the released heat from PCMs can be used for cooking especially for frying, baking and roasting, that requires temperature within 150 – 190 °C [5].

PCMs are further classified as organic, inorganic and eutectic phase change materials depending upon their thermo physical, chemical and kinetic properties respectively. Organic PCMs are further categorized as paraffin and non-paraffin PCMs, where both of them possess phase change interchangeability characteristics, while non-paraffin PCMs have high thermal conductivity relative to paraffin PCMs respectively. Inorganic PCMs are classified into salt hydrates and metallic PCMs. Both PCMs possess high thermal stability and fusion of heat is considerably regular irrespective of their phase change from solid to liquid. Eutectic PCMs are based on composition of two substances that melts and solidifies in form of crystals congruently during crystallization process. The melting point of eutectic PCMs are lower than the composition melting point of the individual substances [24].

Among all, parabolic solar cookers have been gaining more importance and privileges because of their high cooking power ability. Such cookers can have concentration ratio up to 50 and attain maximum temperature of 300 ˚C [20]. In parabolic solar cookers, the sun rays are being reflected by parabola surface coated with reflective material to concentrate light rays at one focal point where food pot is situated for cooking purpose [17].

1.4. Comparison of different parabolic style solar cookers proposed by different researchers in relation to the parabolic solar cooker used in this paper

In this paper, the efficiency of three different types of solar cookers are evaluated based on their maximum water and oil temperature attainability. The performance of the German Scheffler solar cooker, a parabolic type, due to their shape synchronicity, has been evaluated in comparison with other parabolic solar cookers used by different researchers, as discussed below. Such solar cookers with their research gaps in comparison to the techniques applied in current research paper are summarized in Table 1.

Ouannene & Chaouachi had proposed a parabolic solar cooker with depth and diameter of 26 cm and 180 cm correspondingly. The cooking pot area of circular grid type was placed in parallel to parabolic dish, supported by means of two stems. The 2-liter water heating material was used to record a temperature after 5 min interval by following American Society of Agricultural Engineers (ASAE) standards. The cooling test was also performed to see water heat retain ability after approaching temperature of 95 ˚C. The oil heating test was also carried out and maximum temperature recorded was 130 ˚C. The 2-liter water was changed consecutively after reaching 95 ˚C boiling temperature within time period of 9:45 am to 6:00 pm. It takes about one hour to boil water during first test and such heating time difference decreases during solar noon due to increased solar flux. Some foods were also cooked and best time suggested was between 1:30 pm to 2:30 pm. Due to its larger dimensions and weight, there is a limitation of effective manual tracking [18].

A dual reflector parabolic solar cooker had been proposed by another researcher, named Farooqui. The main attribute is of its light weight, low cost and can cook oil and water-based foods. Each reflector is made up of a fiber glass having 90 cm diameter and

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focal length of 105 cm. Experimentation was carried out to measure stagnation and materials (water and vegetable oil) temperature on different days. The maximum oil and internal pot temperature measured was 294 ˚C and 330 ˚C respectively. Energy and exergy analysis were also done, and it was found that an average cooking power of 485 W with exergy output power and efficiency of 70W and 8 – 10 % was attained. The curve fitting method was also employed, where experimental data was fitted with second order polynomial equation [8].

The parabolic solar cooker with the heat storage element was proposed by [12]. The system comprises of two axis tracking mechanism, parabolic reflector, absorber, circulation pump, and heat storage tank. The absorber was placed at the focal position of parabolic reflector and was composed of two iron cylinders i.e. inner and outer cylinder. The wool was located between such cylinders to minimize heat losses, where the temperature sensor was also situated at the back of the cylinder. The fabrication of heat storage tank was also based on two black iron cylinders and between them, the insulator i.e. wool was placed. The circulation pump was used to transfer heat from the material (water or synthetic oil), retained in the absorber to the heat storage tank. The maximum water and oil temperature achieved was 97 ˚C and 153 ˚C within 2.5 hours and 5 hours respectively. The maximum energy and exergy efficiency recorded was 29% and 2.6% correspondingly. Regression analysis was also carried out and found experimental data conformity with the first order polynomial equation of regression line [12].

Moussaoui et al proposed a parabolic trough style solar thermal cooker in which the cooking heat was provided by a circulated heat transfer fluid, i.e. oil. A vacuum tube mounted at the focal point of a parabolic trough, consisting of an absorber mirror, contains two small and one wide copper tube for heat transfer fluid, i.e. oil. The hot oil was circulated among two of the smaller tubes to heat the pot, while larger tube was able to return non-heated oil. The cooking test was performed and the maximum edible oil temperature reached up to 198 ˚C within 1 hour, while maximum heat transfer fluid temperature in smaller and larger tube at the same instant recorded was 277.5 ˚C and 153 ˚C respectively [15]

This paper analyzes the efficiencies of three separate solar cookers (German Scheffler, small mirror and aluminum foil) in terms of cooking strength, sensible heating time and exergy efficiency. These metrics are measured at international standards by using water as a heating material, while oil being used to detect food sources. Regression analysis is performed to assess experimental data conformity and to create a statistical relationship between standard cooking power and the water and atmospheric temperature differential of each solar cooker. The Scheffler's cooker reaches the optimum oil and water temperature compared to other solar cookers and each solar cooker has the capability of cooking variety of foods. Such experimental and regression techniques assist in determining the solar cookers effectiveness for a particular region before their installation. By performing the experiment and regression technique, the different solar concentrator reflecting materials, their mechanical structure and the climate condition under which the solar cookers have been operated with their effect on materials thermal conductivity are assessed. There is a constraint in adjusting the azimuth angle of manually tracked solar cookers (small mirror and aluminum foil) relative to single axis tracker, accompanied by German Scheffler solar cooker to utilize maximum incident solar radiation. Experimental results indicate that solar cookers performances are highly affected by solar radiations, ambient temperature, dust concentration, wind flow, radiation reflective material, radiative and conduction heat losses respectively.

The feasibility of solar cookers effectiveness is evaluated in the climate condition of the Islamabad region of Pakistan. The experiment on water heat content for the respective solar cookers (German Scheffler, small mirror and aluminum) have been conducted on 9, 19, and 23 October 2017 and oil tests have been carried out respectively on 10, 17 and 26 October 2017. Such month is observed to be hazier, as more particulate matters emitted from smoke and dust particles are suspended in the air, absorbing more sunlight instead

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of direct solar irradiance reaching the surface, while the rest of the sunlight is received in a scattered manner [4]. The highest particulate matter (PM_{10}) average mass concentration of about 152.4 μgm^{-3} with the humidity level of 51.5% and mean temperature of 37.6 $^{\circ}$C are observed in the month of October of the Islamabad region that exceeds maximum limit of 150 μgm^{-3}, declared by the WHO [13].

Table 1. Finding Literature review research gap in comparison to the research methodology used in this paper.

Solar cooker type	Literature reviewed	Place	Research gap	Research technique applied in this paper
Parabolic solar cooker	[18]	Tunisia, North Africa	The oil heating time was not estimated. The authors did not highlight the factors affecting the experimental data and neither performs the regression analysis.	The solar cookers performances are tested exclusively under hazel condition to see their effectiveness by keeping in view that the user will never find the ideal situation for cooking, while the researchers of the literature reviewed did not account such condition.
Dual reflector parabolic solar cooker	[8]	Islamabad, Pakistan	The influential factors such as environmental conditions with their impact on experimental data had been not discussed after using curve fitting method.	
Parabolic solar cooker	[12]	Meknes, Morocco	The environmental factors with their impact on experimental values were not discussed after the results obtained through regression technique.	The curve fitting tool was employed by one of the researchers using the excel software, instead of MATLAB used in this paper, where the experimental data found to be good fitted with the third order polynomial equation. Also, the curve response of regression line compliance with experimental data in relation to different environmental factors has not been addressed by the researchers.
Trough type Parabolic solar thermal cooker	[15]	Oujda, Morocco	Regression analysis is not performed to validate experimental results. Furthermore, environmental factors influencing the obtained findings have not been considered.	

2. Methodology

The performances of different types of solar cookers are analyzed in Islamabad location having latitude and longitude of 33.73° and 73.08° respectively as shown in fig. 1.

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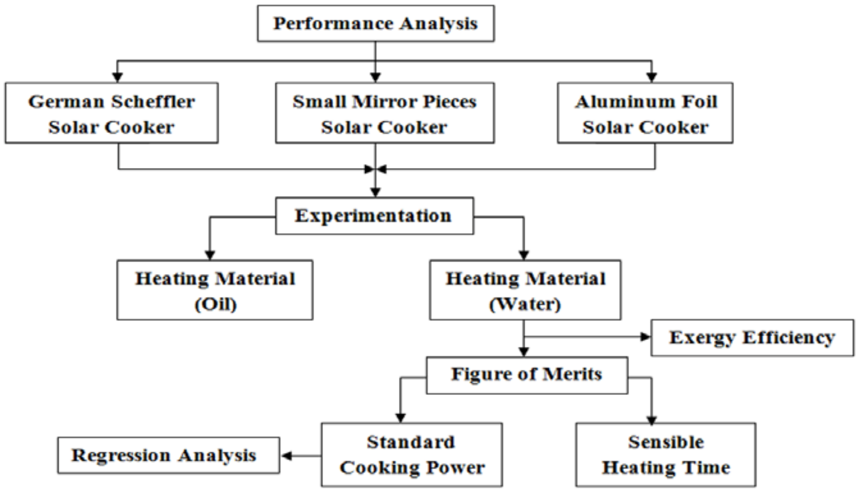

Figure 1. Flow chart describing performance analysis for different types of solar cookers.

2.1. Solar cooker parameters

The parameters such as aperture area, focal length and surface area for different types of solar cookers reflectors are measured as shown in table 2 by using following equations [19], [26].

$$f = \frac{D_{ap}^{\ 2}}{16h} \tag{1}$$

$$A_{ap} = \frac{\pi D_{ap}}{4} \tag{2}$$

$$A_s = \frac{8\,\pi}{3} f^2 \left[\left[\left(1 + \frac{Dap}{4f} \right)^2 \right]^{\frac{3}{2}} - 1 \right] \tag{3}$$

2.2. Standards

The solar cookers used in this research are tested at standards outlined in Paul A. Funk's article. To evaluate the efficiency of various solar cookers, the following test conditions are used in terms of controlled and uncontrolled parameters. Solar altitude and azimuth, wind speed, air temperature and insolation are all uncontrolled variables. This prevents results from varying due to heat transfer coefficients that are approximately equal to convective heat transfer coefficients. An ambient temperature of (25 – 35)˚C is suitable because cooking power is greatly influenced at regions with extreme temperatures, so a range of 15˚C is acceptable that leads to moderate data inconsistency [10].

The horizontal total incident radiation falling perpendicular to the plane is also measured and should have values above 450 W/m² and below 1100 W/m² respectively. To avoid experimental results uncertainty, the variation in insolation values above than 100 W/m² during 10 min interval are not considered practically feasible. Testing should be initiated from 10:00 am to 5:00 pm solar time. This is due to the fact that the solar zenith angle remains constant at noon and the difference in solar incident radiations perceived by the cooking aperture area is minimal [10].

Other than environmental factors, the controlled parameters i.e. cooking vessels, temperature sensing, thermal loading, solar tracking, and data collection are the substantial factors that can influence the test results. The type of cooking pot used must be an inexpensive aluminum having a black exterior body with a thermal loading of 5 – 7 kg water per meter square of solar cooker aperture area. It should be reported in a paper with

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water weight of different value. The reason for water being used is because of its density and specific heat closely related to that of food [10].

Thermocouple is used for measuring the water temperature and its placement should be in middle of the pot. Excessive bending and improper placement of thermocouple wire will lead error in results due to thermal stratification and sensor intrusion within the pot. To perceive maximum solar incident radiation on the cooker's aperture area, the azimuth angle is monitored using manual adjustment or an automated tracking system. The adjustment frequency of 15 min is typically employed for all cooker types. The change in water temperature is measured at 10 min intervals or by using data loggers for precise measurement in seconds [10].

Table 2. Parameters calculated for different types of solar cookers

Solar Cookers	Diameter 'Dap' (m)	Depth 'h' (m)	Focal length 'f' (m)	Aperture area 'Aap' m2	Surface area 'As' m2
German Scheffler	1.38	0.165	0.72	1.085	9.71
Small mirror pieces	3.98	0.203	4.877	3.129	148.46
Aluminum foil	3.35	0.144	4. 871	2.629	121

2.3. Figures of Merit

The two specific thermal figures of merit related to solar cookers are discussed in this paper such as calculating standard cooking power and sensible heating time. The regression analysis is also carried out to find statistical relationship between cooking power and materials temperature difference, where their response is determined by a regression coefficient value. Such coefficient of determination value should be above than 75 % [22].

The standard cooking power is calculated as

$$P = \frac{MC\Delta T}{\Delta t} \tag{4}$$

Where

'ΔT' is the temperature difference of water at beginning and end of the experiment for specific time interval.

The normalized cooking power is measured by,

$$P_n = P\left(\frac{700\ W/m^2}{I_{measured}}\right) \tag{5}$$

To determine how long a cooker will cook the food, the standard sensible heating time equation (6) is used that tells time required to reach a food temperature of 50˚C as shown below

$$t_0 = t\left(\frac{I\Delta T_0}{I_0 \Delta T}\right) \tag{6}$$

The approximate value used for 'ΔT_0' is 50˚C, representing the temperature region prior phase change. The exergy efficiency is also calculated for each solar cooker that describes how much solar radiations are utilized from the sun and is given by [8].

$$\psi = \frac{\left(\mathrm{M.C.}\left[(\mathrm{T_{wf}} - \mathrm{T_{wi}}) - \mathrm{T_a}\ln\left(\frac{\mathrm{T_{wf}}}{\mathrm{T_{wi}}}\right)\right.\right)}{\mathrm{I}.\left[1 + 0.333\left(\frac{\mathrm{T_a}}{\mathrm{T_s}}\right)^4 - 1.333\left(\frac{\mathrm{T_a}}{\mathrm{T_s}}\right)\right]\mathrm{A_{ap}}.\Delta t} \tag{7}$$

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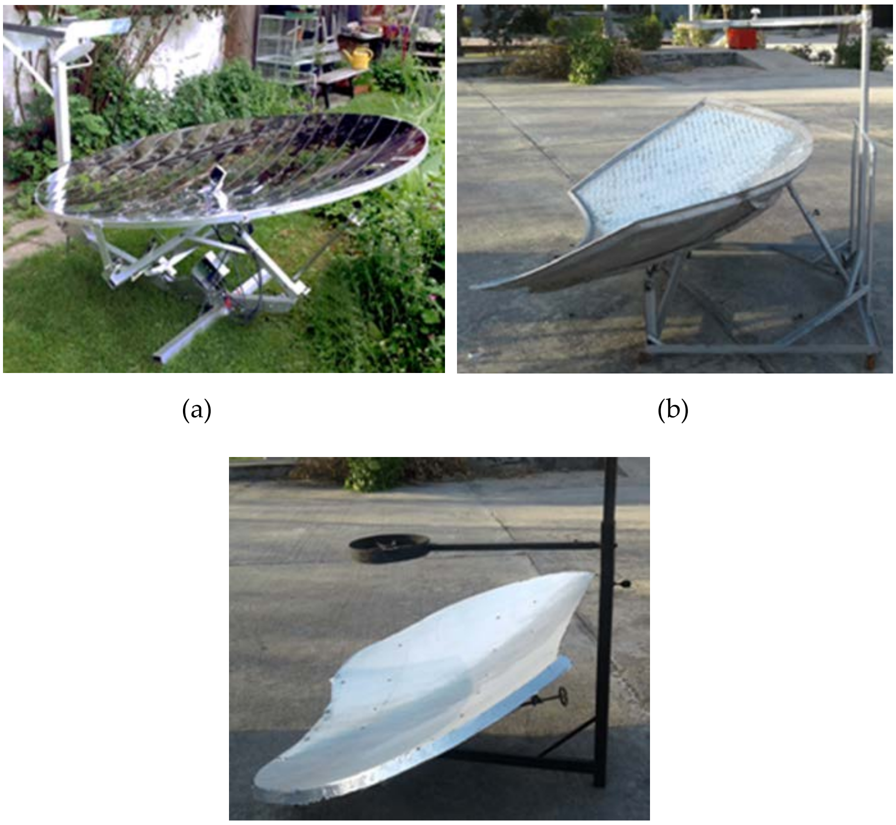
3. Experimentation

In this research paper, the performances of three different types of solar cookers have been analyzed i.e. German Scheffler, small mirror pieces and aluminum foil based solar cooker. The ambient and water temperatures are recorded at time interval of 5 minutes [22]. Before testing, the former standards discussed have been adhered by measuring the horizontal total incident radiation and wind speed by illuminometer and anemometer respectively.

The materials used to analyze solar cookers performances are water and vegetable oil. The materials (water and oil) temperatures are measured by using k-type thermocouple inserted through hole situated on pot lid. The total quantity of water and oil being used in each experiment are 1.7652 kg and 1 liter correspondingly. The pot type used is of stainless steel having black body equipped with mirror lid with total weight of 1.2048 kg. The weight of pot containing water except lid cover is of about 2.970 kg.

The solar azimuth angle is also tracked for the solar cookers to utilize maximum solar incident radiations. The Scheffler solar cooker as shown in fig. 2a is equipped with single axis tracker, while mirror and aluminum foil based solar cookers shown in fig. 2b and fig. 2c are tracked manually through horizontal pan bearer rod and aperture area displacement respectively. The solar altitude angle is adjusted according to Islamabad latitude for each solar cooker aperture area.



(a) (b)

(c)

Figure 2. Solar cookers (a) German Scheffler (b) Small mirror pieces and (c) Aluminum foil

4. Results & Discussion

The total time required to achieve maximum oil temperature in each parabolic solar cooker (existing research (German Scheffler) and reviewed literature) is selected as a figure of merit to assess their cooking feasibility as shown in fig. 3. The German Scheffler solar cooker used in this paper has been compared with the other researchers' parabolic

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solar cookers due to their shape synchronicity. It is observed that the maximum oil temperature of 275˚C is achieved by the German Scheffler in a duration of 1 hour and 5 minutes relative to other three parabolic solar cookers used by different researchers ([18], [12], [14]) with oil temperatures of 130˚C, 153˚C, and 198˚C respectively. The time acquired by two later researchers to reach such temperatures are 5 hours and 1 hour correspondingly. Farooqi, one of the researchers, had achieved highest oil temperature of 294˚C in a least duration of 38 minutes among all solar cookers.

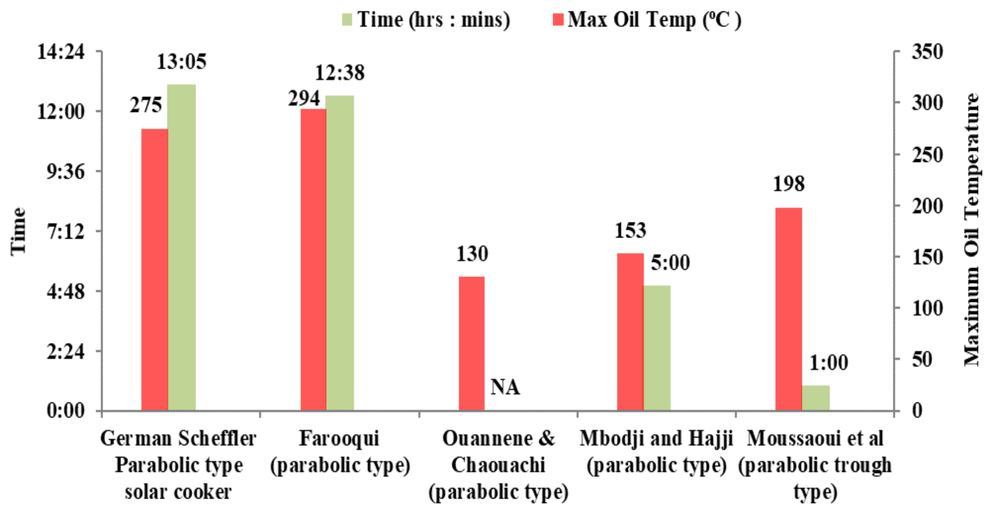

Figure 3. Maximum oil temperature achieved by various researchers in relative to current parabolic solar cooker used in this paper

The observing time interval for measuring oil and water temperatures, as well as solar insulations, is 5 minutes for all experiments. The German Scheffler, small mirror pieces and aluminum foil based solar cookers are tested on the 9th, 19th, and 23rd of October, 2017. The temperatures (water and ambient) and solar radiations measured for each solar cooker relative to solar time are shown in fig. 4 (a, b & c).

In case of Scheffler type solar cooker, the difference in water temperature measured at 850 W/m^2 and 810 W/m^2 is greater than the temperatures obtained at later solar insolation values. Although solar radiation decreases abruptly at some instants but does not have any stern effect on water temperature and as a result, a gradual increase in temperature is observed. This is because of effectively focusing the solar radiations in a concentrated way instead of diffracted one by means of a single axis tracking. The total time acquired by water to reach its boiling point is 28 minutes, while a temperature of 95˚C is attained in 25 minutes.

In small mirror pieces solar cooker, the water temperature starts to rise as solar radiation exceeds 750 W/m^2. The steady increase in temperature difference of water is observed at constant radiation of 750 W/m^2 within the time interval of 12.52 hours to 13.12 hours, while such temperature difference tends to decrease at lower insolation values of 730 W/m^2 and 690 W/m^2 subsequently. It takes about 1 hour to reach a water temperature of 95˚C. Due to manual tracking, the light focus is not as successful as it is in former solar cooker, which has a significant impact on the water temperature at constant and reduced solar radiations.

The maximum water temperature reached by the third type of solar cooker (aluminum foil) is about 74°C in 2 hours and 5 minutes. There are several reasons of not achieving water temperature up to 95˚C such as environmental conditions, heat losses, tracking limitations and insufficient heat conduction. The day at which such experiment was conducted is considerably hazy from environmental perspective. The presence of airborne dust particles in the atmosphere causes partial absorption and scattering of solar incident radiation, resulting in a reduction in solar intensity [2].

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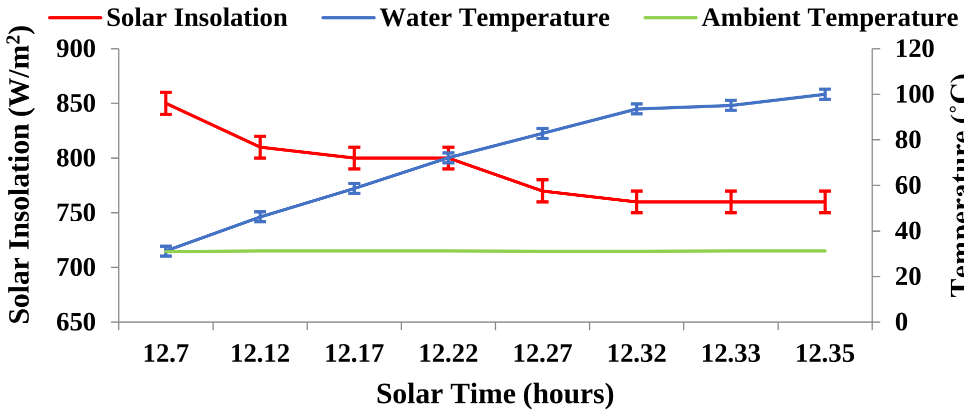
There is a limited aperture area rotation and unable to change azimuth angle up to 180˚ as in case of other solar cookers, thus incapable of full solar radiation utilization. The metal thickness of the horizontal pot carrier rod, where conductive heat losses under the pot surface predominate, is another factor that contributes to a slight rise in water temperature.

The vegetable oil temperatures achieved are also recorded for respective solar cookers on specific dates as shown in table 3. Such temperatures are measured as maximum after specific time intervals and afterwards their temperature tends to decrease as shown in fig. 5 (a, b & c).

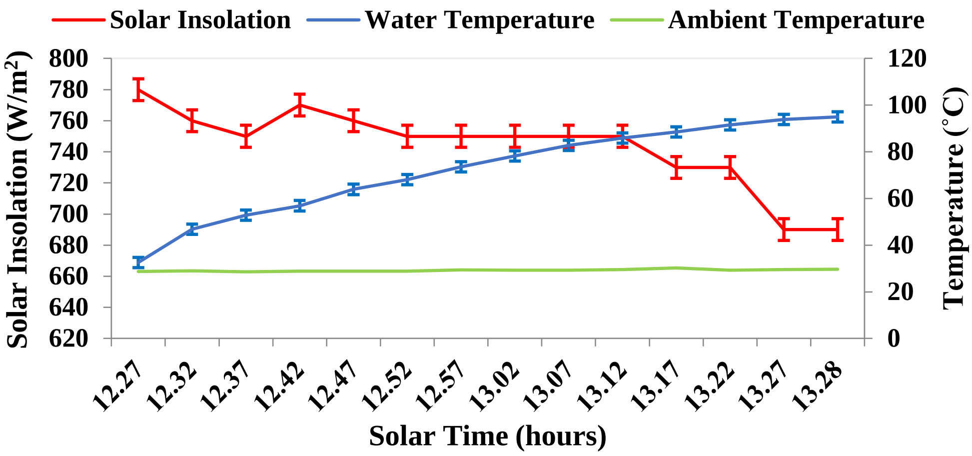
The oil temperature tends to increase more rapidly when there is a less difference in insolation value of about 1 mW/cm^2 in third type of solar cooker. The gradual increase or decrease in oil temperature is observed as solar radiations decreases at some consecutive time intervals shown in fig. 5c. To minimize conductive heat losses, a pot carrier rod has been changed as previously used in measuring water temperature. The more oil temperature can be achieved if ambient temperature and tracking facility is same as acquired by other solar cookers.

Table 3. Maximum vegetable oil temperature measured for respective solar cookers

Solar cooker type	Date (dd/mm/yyyy)	Start solar time (hours)	End solar time (hours)	Initial oil temperature (˚C)	Final oil temperature (˚C)
German Scheffler	10/10/2017	13.36	14.41	36.0	275
Small mirror pieces	17/10/2017	12.40	13.40	30.0	201
Aluminum foil	26/10/2017	12.32	14.32	33.4	119



(a)



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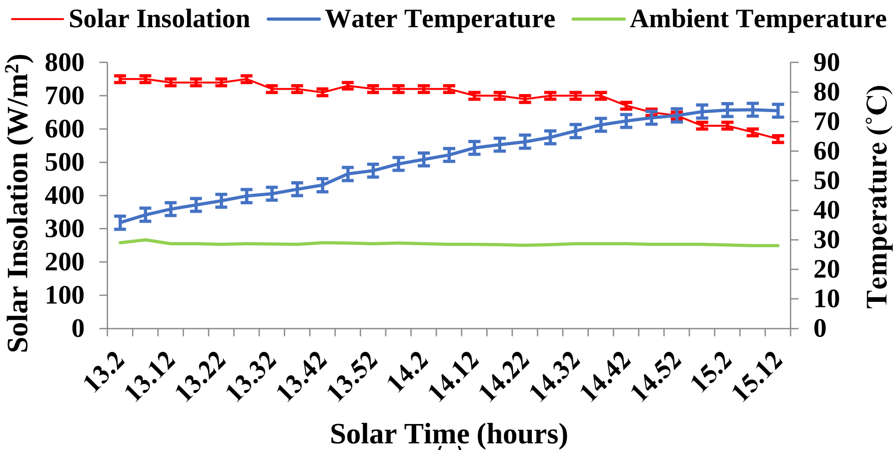

(c)

Figure 4. Solar radiation and Temperature (water and ambient) measured for (a) German Scheffler (b) Small mirror pieces and (c) Aluminum foil solar cooker with their uncertainties

The German Scheffler and small mirror pieces solar cookers are experiencing almost same ambient temperature at different solar radiations as shown in fig. 5 (a & b), thus results in achieving more oil temperature difference in former relative to later solar cooker type. Such temperature difference can be further increased in German Scheffler solar cooker if experiment is conducted at same radiation levels as perceived by small mirror pieces solar cooker.

Uncertainty analysis is also carried out for the measured values of temperature (water & oil) and solar insolation. The equipment's used for measuring the temperature and solar insolation are k-type thermocouple and Illuminometer device with their measuring accuracy of ± 2.2 ℃ and $\pm 10 \text{ W}/m^2$ respectively. The calibration type of uncertainty is applied for such measured quantities at specific solar time as shown in fig. 4 & 5, where the uncertainty in the measurements is directly influenced by the measuring device [1]. The uncertainties in such measured parameters are shown in the table 4.

The statistical relationship between normalized power 'P_n' (adjusted cooking power) and temperature difference 'T_d' (water and ambient) have been obtained by using curve

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fitting tool in Matlab as shown in fig. 6 (a, b & c). The data measured from three experiments are subjected to be based on third order polynomial equations with their regression coefficients having bounding accuracy of 95 % as shown in table 5. The response between 'P_n' and 'T_d' is determined by coefficient of determination 'R^2' values, showing the percentage of data acquiescence to the regression line. After generating regression power line equation for each solar cooker, the cooking power and sensible heating time for each solar cooker at 50˚C temperature difference along with exergy efficiency is calculated as shown in the table 5. The exergy efficiency of German Scheffler solar cooker is more relative to other solar cookers due to difference in perceiving solar radiations by each solar cooker aperture area.

The cooking power regression line has a curved response and is due to the following reasons such as reflector condition, dust particles concentration and wind speed. In case of German Scheffler solar cooker, the response tends to be curvy at higher water and ambient temperature difference that indicates the presence of wind affecting the water temperature.

Table 4 Uncertainties in the measured parameters (temperature and insolation) for respective solar cookers

Solar cooker type	**Heating material**	**Temperature uncertainties**		**Insolation uncertainties**	
		Positive	**Negative**	**Positive**	**Negative**
German Scheffler	Water	33.4, 48.4, 60.9, 74.3, 85, 95.8, 97.31, 102.2	29, 44, 56.5, 69.9, 80.6, 91.4, 92.91, 97.8	860, 820, 810, 810, 780, 770, 770, 770	840, 800, 790, 790, 760, 750, 750, 750
	Oil	38.2, 85.6, 131.1, 170.5, 197.2, 219.2, 236.2, 251.2, 262.2, 269.2, 274.2, 277.2, 277.2, 275.2	33.8, 81.2, 126.7 166.1, 192.8, 214.8, 231.8, 246.8, 257.8, 264.8, 269.8, 272.8, 272.8, 270.8	820, 770, 780, 790, 810, 800, 830, 820, 820, 800, 800, 820 790, 770	800, 750, 760, 770, 790, 780, 810, 800, 800, 780, 780, 800, 770, 750
Small mirror pieces	Water	34.8, 49, 55, 59.1, 66.1, 70.3, 75.8, 80.4, 84.9, 88.1, 90.7, 93.8, 96.1, 97.2	30.4, 44.6, 50.6, 54.7, 61.7, 65.9, 71.4, 76, 80.5, 83.7, 86.3, 89.4, 91.7, 92.8	790, 770, 760, 780, 770, 760, 760, 760, 760, 760, 740, 740, 700, 700	770, 750, 740, 760, 750, 740, 740, 740, 740, 740, 720, 720, 680, 680
	Oil	32.2, 77.8, 113.7, 141.9, 159.7, 173.9, 185.7, 191.9, 199.7, 201.8, 203.2, 203.2	27.8, 73.4, 109.3, 137.5, 155.3, 169.5, 181.3, 187.5, 195.3, 197.4, 198.8, 198.8	950, 950, 950, 950, 940, 940, 950, 950, 950, 950, 950, 950	930, 930, 930, 930, 920, 920, 930, 930, 930, 930, 930, 930
Aluminum foil	Water	38, 40.7, 42.6, 44, 45.4, 47, 47.8, 49.3, 50.7, 54.5, 55.6, 57.9, 59.4, 60.9, 63.3, 64.4, 65.4, 66.9, 69, 71.1, 72.4, 73.5, 74.3, 75.6, 76.1, 76.2, 75.9	33.6, 36.3, 38.2, 39.6, 41, 42.6, 43.4, 44.9, 46.3, 50.1, 51.2, 53.5, 55, 56.5, 58.9, 60, 61, 62.5, 64.6, 66.7, 68, 69.1, 69.9, 71.2, 71.7, 71.8, 71.5	760, 760, 750, 750, 750, 760, 730, 730, 720, 740, 730, 730, 730, 730, 710, 710, 700, 710, 710, 710, 680, 660, 650, 620, 620, 600, 580	740, 740, 730, 730, 730, 740, 710, 710, 700, 720, 710, 710, 710, 710, 690, 690, 680, 690, 690, 690, 660, 640, 630, 600, 600, 580, 560
	Oil	35.6, 54.9, 67.6, 78.7, 90.1, 93.4, 98.2, 107.5, 111.5,	31.2, 50.5, 63.2, 74.3, 85.7, 89,	760, 760, 770, 760, 770, 770, 750, 710, 730,	740, 740, 750, 740, 750, 750, 730, 690, 710, 720, 730, 700,

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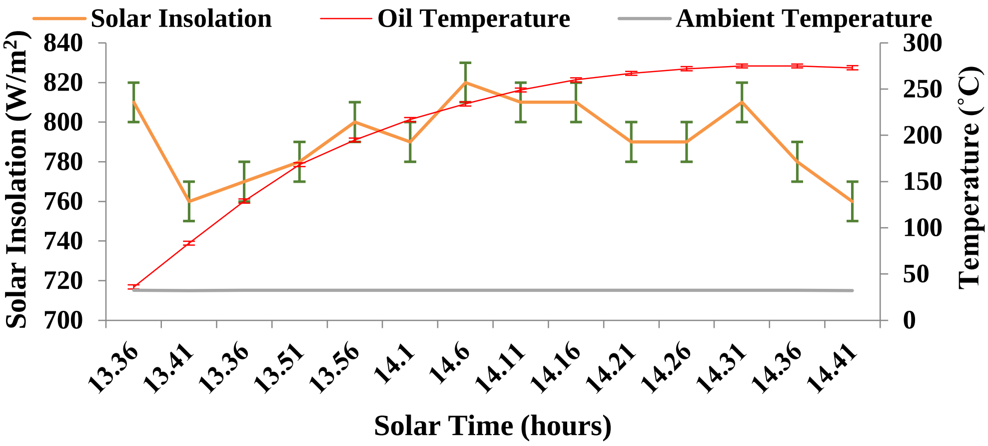
	113.6, 114.4, 114.5, 116.1, 118.8, 118.9, 117.3, 116.1, 117.3, 121.2, 119.6, 118.1, 113.5, 113.1, 110.6	93.8, 103.1, 107.1, 109.2, 110, 110.1, 111.7, 114.4, 114.5, 112.9, 111.7, 112.9, 116.8, 115.2, 113.7, 109.1, 108.7, 106.2	740, 750, 720, 750, 750, 710, 660, 700, 710, 720, 720, 710, 700, 700, 650	730, 730, 690, 640, 680, 690, 700, 700, 690, 680, 680, 630

By observing nonlinear cooking power response in case of aluminum foil and small mirror pieces based solar cookers, the above-mentioned factors have significant effect on cooking power in former type solar cooker relative to later one. The choice of a reflecting material and its physical condition plays a substantial role in solar radiation reflection, where some scratches are observed in aluminum foil solar cooker that leads to poor light focusing under pot area. The negative cooking power value indicates the inability of water to reach a temperature difference of 50˚C.

Table 5 Polynomial based estimated regression equation for solar cookers with R^2 value

Solar cooker	Cooking power (W)	Sensible heating time (min: sec)	Exergy efficiency (%)	Regression coefficient of determination (R2)	Estimated cooking power regression equation
German Scheffler	260.23	17 min: 56 sec	48.51	0.6898	$P = a1(\Delta T)^3 + a2(\Delta T)^2 + a3(\Delta T) + a4$ Where a1 = 0.0008226 (-0.06059, 0.06223) a2 = -0.02518 (-4.84, 4.789) a3 = -2.089 (-99.61, 95.43) a4 = 324.8 (-171.5, 821.1)
Small mirror pieces	99.85	31 min: 14 sec	19.16	0.9297	$P = b1(\Delta T)^3 + b2(\Delta T)^2 + b3(\Delta T) + b4$ Where b1 = -0.00496 (-0.007768, -0.002152) b2 = 0.5773 (0.2842, 0.8705) b3 = -22.51 (-31.3, -13.73) b4 = 402.1 (327, 477.2)
Aluminum foil	-21.96	Unable to achieve temperature difference of 50˚C	13.47	0.3417	$P = c1(\Delta T)^3 + c2(\Delta T)^2 + c3(\Delta T) + c4$ Where c1 = -0.0046 (-0.009882, 0.0006823) c2 = 0.3333 (-0.09237, 0.7589) c3 = -7.462 (-17.86, 2.933) c4 = 92.89 (18.13, 167.7)



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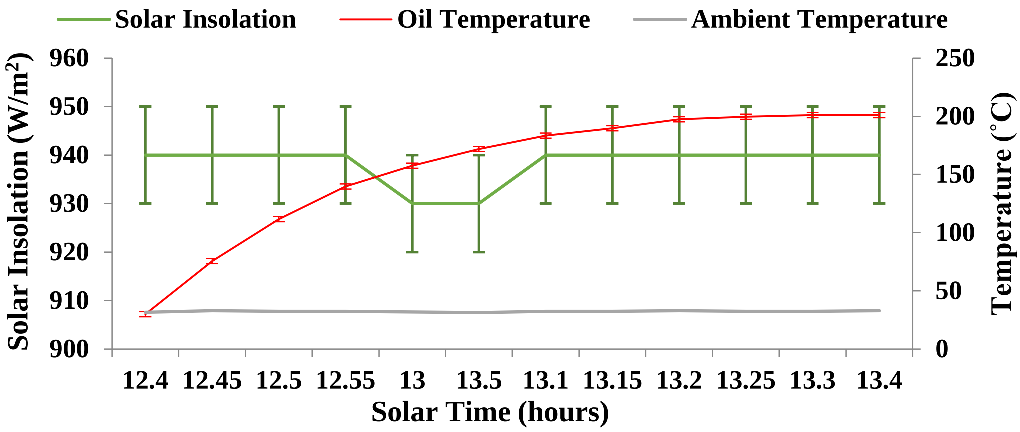
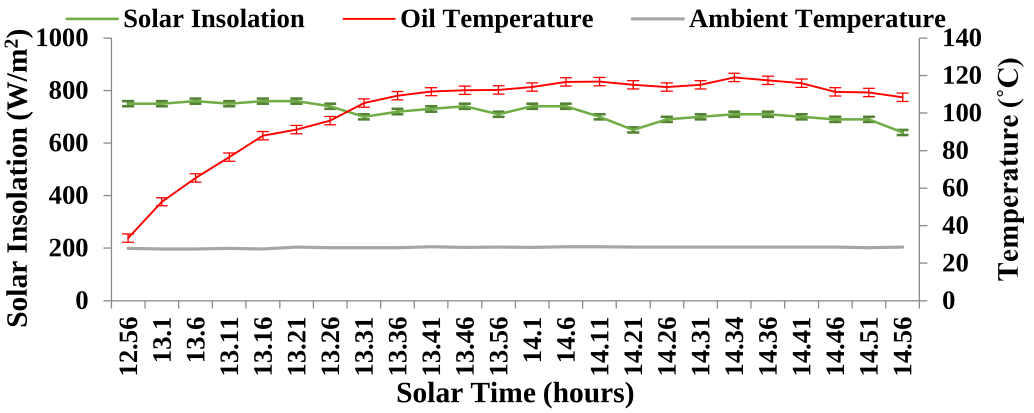
(a)

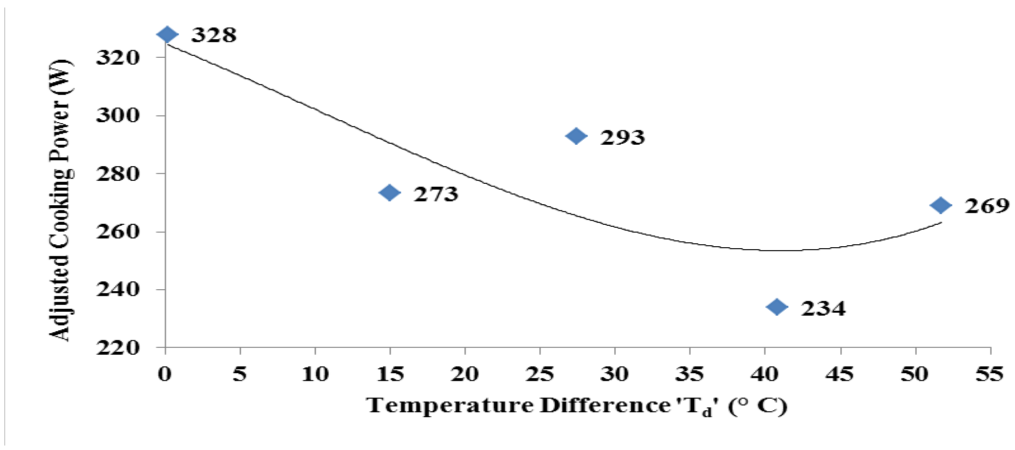


(b)



(c)

Figure 5. Solar insolation and temperature (oil and ambient) measured with respect to solar time for (a) German Scheffler (b) Small mirror pieces and (c) Aluminum foil solar cooker with their uncertainties



(a)

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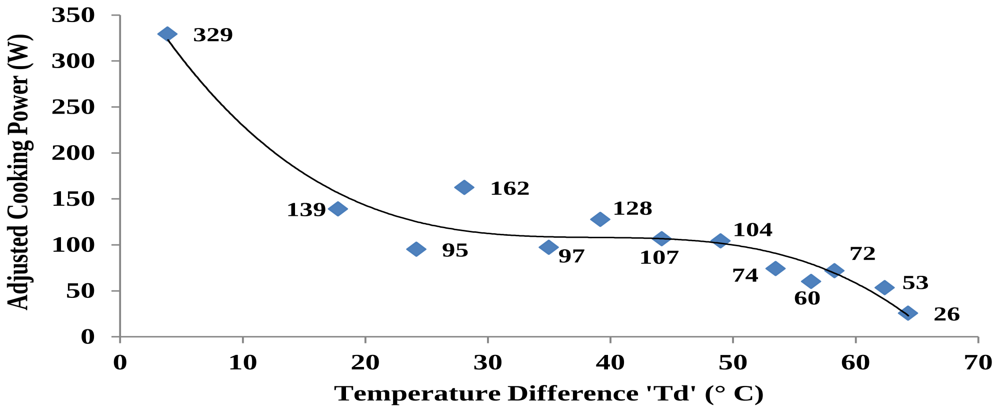
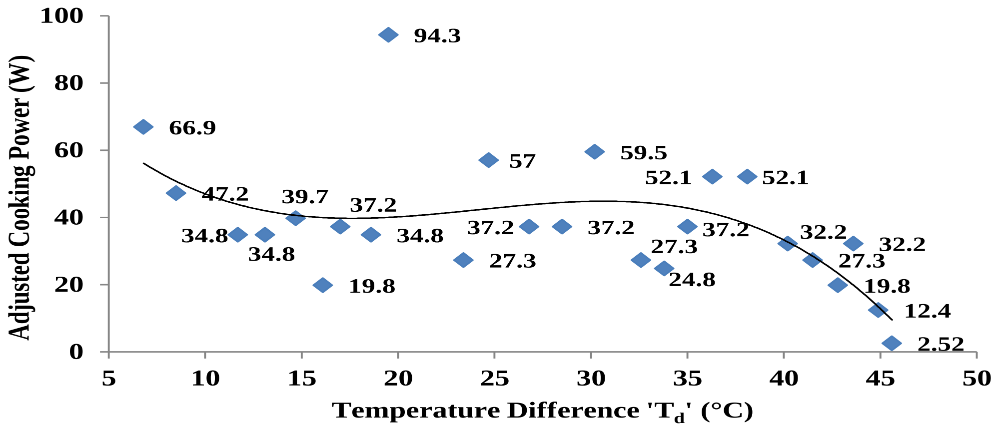


(b)



(c)

Figure 6. Response of a cooking power regression line with measured data for (a) German Scheffler (b) Small mirror pieces and (c) Aluminum solar cooker case

The non-linearity in regression line is also because of radiative heat losses that are more preponderant at extreme temperatures for both heating contents. This is because of excessive difference in heating material and ambient temperature after each interval. Such temperature difference can be minimized with proper insulation of cooking pot [9].

The incorporation of optimization algorithms can enhance assessment studies [27], [28]. Also the event-driven tools are beneficial in terms of the computational effectiveness and real-time compression [29], [30]. The feasibility of incorporating these tools in the suggested assessment method can be investigated in future.

5. Conclusions

All types of solar cookers have been tested by following international standards and their performances have been evaluated by measuring figures of merit i.e. standard cooking power, sensible heating time, and exergy efficiency. The experiments are conducted for 1.7652 kg water and 1-liter oil respectively. The maximum oil temperature achieved by German Scheffler, small mirror pieces, and aluminum foil solar cookers are 275˚C, 201˚C and 119˚C respectively, thus able to cook variety of foods such as meat, fish, fried eggs, chicken and vegetables. However, less water boiling time is acquired by German Scheffler relative to other solar cookers. In comparison to other solar cookers, the water and oil temperatures of aluminum foil-based solar cookers are greatly affected by ambient temperature and changes in solar radiation values. The heating contents temperatures of the two types of solar cookers i.e. single mirror and aluminum foil solar cookers, are immensely influenced by tracking limitations, while the environmental and reflective material condition plays a significant role in achieving the optimal oil and water temperature in all solar cookers. In all types of solar cookers, radiative heat losses at high temperatures are predominant and can be reduced by insulating the cooking pot area. The thickness of the pot carrier rod in an aluminum foil solar cooker can result in less heat transfer to the material, which can be overcome by replacing it. The German Scheffler parabolic solar cooker feasibility is also analyzed in comparison with other parabolic solar cookers found in literature reviewed in terms of time required to achieve maximum oil temperature. As compared to one of the researcher's solar coolers, Farooqi, the time taken to reach maximum oil temperature in the German Scheffler solar cooker is more, whereas high temperature is reached in a shorter time span than other researchers' solar cookers. The high temperature in a short duration can also be attained by performing the experiment in a clear sky condition, as perceived by Farooqi solar cooker in the same Islamabad region. The exergy efficiency will be different for each solar cooker if such experiments are performed in a summer season with clear sky that will allow solar cookers aperture area to utilize more direct beam radiations. Regression analysis is carried out to determine response of adjusted cooking power with respect to ambient and water temperature difference that assists in determining percentage compliance of experimental data with cooking power regression line. The regression coefficient of determination values for German Scheffler, small mirror pieces and aluminum foil solar cookers are approximately 69%, 93%, and 34% respectively that indicates experimental data compliance with regression line. The regression coefficient value of 34% indicates the least accountability of variability in data (power with respect to temperature) and this is because of swear environmental condition, reflective material, and radiative heat losses experienced by aluminum foil solar cooker. The two solar cookers i.e. German Scheffler and small mirror pieces can also be utilized in agricultural area to assist farmers especially in drying the variety of products such as vegetables, fruits, spices and condiments. The solar cookers can be retrofitted with the circulating tubes containing such heated oil content and a circulating fan, where forced convective heat transfer method can be used for drying former mentioned products.

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