INNOVATIVE ENERGY TECHNOLOGY SYSTEMS AND ENVIRONMENTAL CONCERNS: A SUSTAINABLE APPROACH
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Design of Automated Test Rig for the Performance Evaluation of a Parabolic Concentrating Dish Type Solar Cooker

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Abstract

Most parts of India are blessed with an ample amount of sunshine, with around 300 sunny days per year and the peak value of solar radiations reaching as high as 800 w/m^2 to 1000 w/m^2. This indicates the potential use of solar radiations for direct thermal applications besides the availability of solar radiations resources; there are large energy consumptions in cooking of food, due to large population and the cooking practices. The solar cookers provide available link between the energy need of the population vis-as-vis abundantly and uniformly available resources. The concentrating dish type solar cookers are become popular because of their faster and reliable cooking, property of generating high concentration solar radiations. For the large scale implementation, the efforts are also being made for the characterization and standardization of the parabolic concentrating dish type solar cookers for this purpose. The test procedures have also been developed, for its thermal performance evaluation. These test procedures are based upon heating and cooling tests which require a continuous measurement of certain requisite parameters viz temperature of water inside the cooking pot (T_w), ambient temperature (T_a) , beam solar radiation (I_b), wind velocity (V) etc.In the present work a test rig has been developed incorporating the test procedure developed by the R& D group of Ministry of New and Renewable Energy, Govt. of India, for the thermal performance evaluation of dish type solar cooker. The test rig basically comprises of the instrumentation with computer based data logger and sensors of each of the above requisite parameters. These sensors include thermocouple, RTD, Pyreheliometer, and Anemometer etc.A number of test have been performed on a sample of dish type solar cooker. A few of these tests data which complies with the wind velocity range below 0.5 m/s as per the test procedures have been reported and analysed. Further the heating and cooling curves have been plotted for these tests. The trends of heating and cooling curves have been found the close proximity of those reported by the research groups. Furthermore calculations for the two thermal performance parameters i.e over all heat loss factor ($F'U_L$) and optical efficiency factor ($F'\eta_0$) have been made for each test data it has been observed that the values of ($F'U_L$) and ($F'\eta_0$) do not have

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lot of variation from one test to another. Also these values are in close proximity to the values of ($F'U_L$) and ($F'\eta_0$), for a good quality of concentrating dish type solar cooker. This indicates the reproducibility of the test results.Therefore the test setup installed in yhe present work can produce a large scale computer based data, if a number of test on each of the sample or a proto type concentrating dish type solar cookers, are performed. This large scale data would enable the analysis and design improvnents, besides the characterization and standardization of the concentrating dish type solar cooker and therefore would help in catalysing a large scale promotion of solar cookers in the society.

1. Introduction

Dish solar cooker is a concentrating type parabolic dish solar cooker with aperturediameter of1.4 meter and focal length 0.28 meter. The reflecting material used for fabrication ofthis cooker is anodized aluminium sheet which has a reflectivity of over 75%.The tracking of the cooker ismanual and thus has to be adjustedin15 to 20 minutes during cooking time. Ithas a delivering power of about 0.6 KWwhich can boil 2 to 3 liters of water inhalf an hour. The temperature achievedat the bottom of the vessel could bearound 350 to 400^0C which is sufficientfor roasting,frying and boiling. Thecooker having athermal efficiency ofaround 40% can meet the needs of 10to 15 people and can be used from onehour after sunrise to one hour beforesunset on clear days.

1.1 Principle of Operation

The parabolic solar cooker uses sun energy as the heat source for cooking different kinds of food. Three basic phenomena are employed in the design and operation of the cooker. These are:

- When solar radiation (sunlight) strikes a dark surface, it changes to infra red radiation.
- When light falls on a shiny surface, it is reflected and so can be directed to a desired point.
- In optics it is known that a concave
- mirror will reflect a parallel beam of light to a focal point

1.2 Parabolic Concentrating Dish type Solar Cooker and its Construction

A parabolic concentrating dish type solar cooker has the following parts

- Paraboloid dish
- Cooking pot
- Supporting frame and stand of parabolic dish
- Tracking mechanism

2. Theory of Performance Evaluation of a Parabolic Concentrating Dish Type Solar Cooker

Thermal performance of a Solar Cooker is the ratio of heat energy given to water to the solar radiation energy intercepted on parabolic dish.The performance of the parabolic concentrating solar cooker depends mainly on two parameters:

- Optical efficiency factor ($F'\eta_0$)
- Heat loss factor ($F'U_L$)

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The optical efficiency factor defines the theoretical upper limit of the overall [5] efficiency of concentrating solar cooker. It relates to the perfection of reflector surface area, its reflectance, absorptance of the outer surface of the cooking pot etc. Heat loss factor defines heat losses from a parabolic concentrating solar cooker primarily depend upon the pot water temperature, wind speed, surface area of the cooking pot and orientation of the reflector.

3. Design of an Automated Test Rig for the Performance Evaluation of a Parabolic Concentrating Dish Type Solar Cooker

The parabolic solar cooker is a direct concentrating cooker with a dish type reflector (or concentrator) directing most of the intercepted radiations to a point of focus called the focal point. The cooking vessel (or pot) is positioned at this focal[7] point, thus creating a heating situation very similar to the traditional open fire cooking. The concentrator is a shallow dish shaped frame mounted firmly on a rotating base which allows the concentrator to be positioned at the desired angle for proper tracking of the incident solar energy. Sheets of wire mesh are riveted on the concentrator frame to support the reflecting materials (reflectors). These reflectors are fixed in several stripes onto the parabolic metal frame to create a continuous reflecting surface which are supported to focus the sun radiation. Across the concentrator are four hollowed rods fixed at[8] each corner. These rods support the gyroscopic pot stand on which the pot is to be placed. The bottom of the pot is painted black for high heat absorption.

3.1 Working Principle of Parabolic Concentrator Solar Cooker

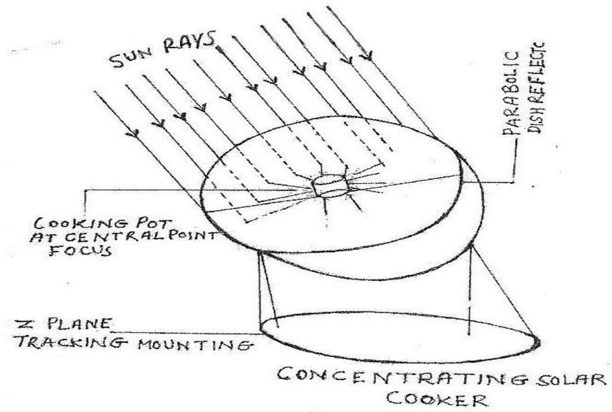

Fig. 1: Paraboloid Concentrator Solar Cooker.

The optical efficiency factor defines the theoretical upper limit of the overall efficiency of concentrating solar cooker. It relates to the perfection of reflector surface area,[13] its reflectance, absorptance of the outer surface of the cooking pot etc. Heat loss factor defines heat losses from a parabolic concentrating solar cooker primarily depend upon the pot water temperature, wind speed, surface area of the cooking pot and orientation of the reflector.

Different test procedures for thermal performance evaluation of a concentrating solar cooker

- Test Procedures Method Proposed by Mullick et al. (1991)
- Draft Test Procedure Proposed by MNRE

- Test Procedure for Thermal Performance Evaluation of a Paraboloid Concentrator Solar Cooker: Method Proposed by Funk (2000)

Test Procedures Method Proposed by Mullick et al. (1991)

This method initially consisted of two parts

- No load test or stagnation test
- Load test and its analysis

Curve drawn between (T_w-T_a) and time during heating is called heating curve and the curve drawn between (T_w-T_a) and time during cooling is called cooling curve. Heating and cooling curve has been drawn in figure.

The cooling curve:

Analyzing over a very small time interval during the sensible cooling of water, the time taken dτfor a fall of dT_W (-ve) in water temperature is

Analysis

Curve drawn between (T_w-T_a) and time during heating is called heating curve and the curve drawn between (T_w-T_a) and time during[11] cooling is called cooling curve. Heating and cooling curve has been drawn in figure.

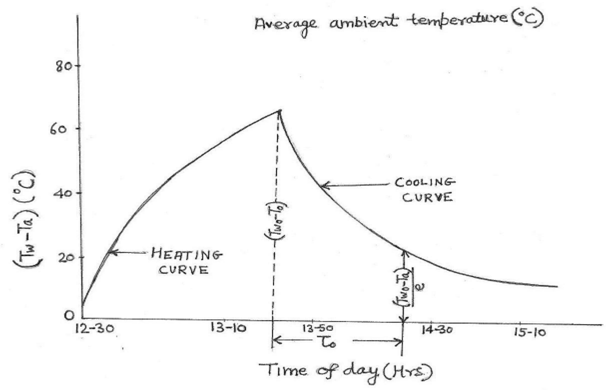

Fig. 2: Heating Curve.

$$d\tau = -\frac{(MC)'_w}{Q_L} dT_w = -\frac{(MC)'_w}{A_t F' U_L (T_w - T_a)} dT_w$$

$$\tau = -\frac{(MC)'_w}{A_t F' U_L} In\left[\frac{T_w - T_a}{T_{wo} - T_a}\right]$$

$$(T_w - T_a) = (T_{w_0} - T_a)e^{-\tau/\tau_0}$$

$$\tau_0 = \frac{(MC)'_w}{A_t F' U_L}$$

The heating curve

During the heating of water, the time taken, dτ , for a water temperature rise dT_W is

If the water temperature rises from T_{w1} to T_{w2}

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$$\tau = \tau_0 In \left[\frac{F'\eta_0 - \frac{F'U_L}{C}\left(\frac{T_{w2} - T_a}{I_b}\right)}{F'\eta_0 - \frac{F'U_L}{C}\left(\frac{T_{w1} - T_a}{I_b}\right)} \right]$$

$$F'\eta_0 = \frac{F'U_L}{C} \left[\frac{\left(\frac{T_{w2} - T_a}{I_b}\right) - \left(\frac{T_{w1} - T_a}{I_b}\right) e^{-\tau/\tau_0}}{1 - e^{-\tau/\tau_0}} \right]$$

The time for heating of water from ambient temperature 100 ^{o}C, τ_{boil}, can be obtained by the following equation

4. Methodology Adopted & Test Setup Installed

The test procedure followed for the thermal performance evaluation of parabolic concentrating solar cooker in the present work is based upon the methods proposed by

- Mullick et.al
- Draft test procedure

$$\tau_{boil} = \tau_0 In \left[\frac{1}{1 - \frac{F'U_L}{F'\eta_o} \frac{1}{C} \left(\frac{100 - T_a}{I_b} \right)} \right]$$

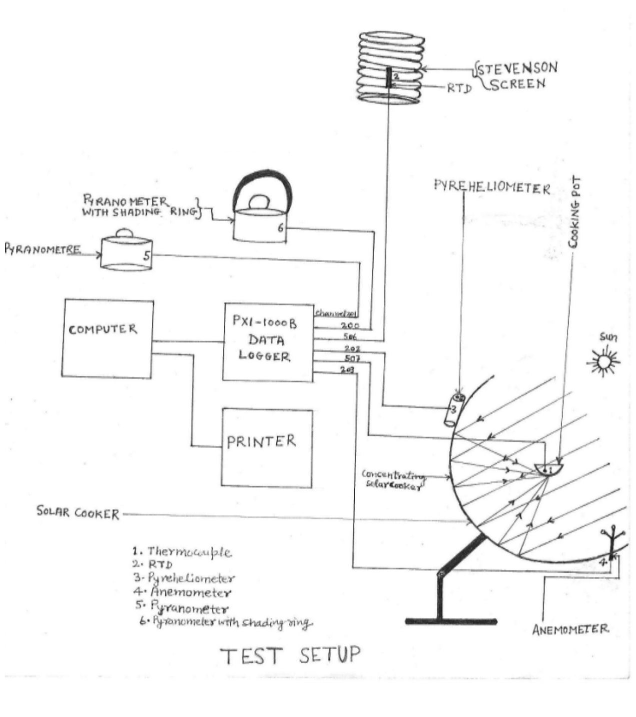

Fig. 3: Test Setup.

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Fig. 4: cooking pot with parabolic dish, for heating test.

4.1 Test Procedure

Parabolic reflector of solar cooker is cleaned properly and then it is focused towards the sun. A thermocouple[15] (for measurement and monitoring of water temperature in the cooking pot at regular intervals) is installed through a hole (made by removing the safety valve) in the lid of pressure cooker and sealing it properly with M-seal. It is installed in such a way that it remains immersed in the water without touching the walls of the bottom of the pot and the other end is connected to[24] data logger at a predefined channel (channel number 507). One RTD sensor is fitted into Stevenson Screen to monitor ambient temperature.It was connected to a predefined channel (channel number 506). A Pyranometer is mounted on the horizontal plane to measure global solar radiation and is connected to data logger at channel number 201. A pyreheliometer (for measuring intensity of direct solar radiation in the normal direction to the aperture area of the paraboloid), is mounted on the outer frame of the paraboloid dish in such a manner that no[16] shadow cast on the exposed area of the dish and it is in the normal direction to the plane of aperture. Tracking of the dish is carried out manually at every 10 minutes to ensure that the dish remains normal to sun with the[25] motion of the sun. It was connected to channel number 202.A Pyranometer with shading ring is mounted on the horizontal plane to measure diffuse radiation and is connected to data logger at channel number 200. An anemometer is installed on the rim of the parabolic dish to monitor continuously the wind[17] velocity and is connected to the data logger at channel number 203.Take predefined amount of water in cooking pot. Cooking pot is put at focal point of the parabolic concentrating dish which lies at the tray meant for keeping the cooking pot. Now cooking pot in the tray is adjusted in such a way that the bright spot of the sunrays is positioned on the bottom of the cooking pot.

4.2 Methodology

Heating Test: Measurements of ambient temperature (Ta), water temperature in the cooking pot (T_W), intensity of the direct solar radiation on the aperture plane of the parabolic[19] concentrating solar cooker (I_b), diffuse radiation (I_d) and global solar radiation (I_G) are recorded at an interval of 5 minutes each, till the water in cooking pot gets its stagnation temperature.

Cooling Test: After reaching the stagnation temperature, the parabolic reflector is shaded by a black umbrella to ensure blockage of solar radiation and the[20] continuous recording of T_a (ambient air temperature) and T_w (water temperature) is done every two minute[27] interval for the first half an hour and later at 5 minutes interval till the difference (T_w-T_a) reaches

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below $(1/e)^{th}$ of the value of(T_w-T_a) at the start of cooling test. After this, the recording of data is not required.

Heating test is conducted to determine optical efficiency factor ($F'\eta_0$) from heating curve while cooling test is conducted to determine heat loss factor ($F'U_L$) from cooling[21] curve as shown in figure. To find $F'U_L$, the equation is used which is as follows. Where

A_{pot}=Total surface area of the cooking pot, m²

$(MC)'_w$=Total heat capacity, which is equal to the sum of the heat capacity of cooking pot (MpotCpot) and the water (Mw Cw), J/K

C_{pot}=Specific heat of the material of cooking pot, J/Kg K

C_w=Specific heat of water J/Kg K

M_{pot}=Mass of empty cooking pot with lid, Kg

Mw=Mass of water kept in cooking pot during the test, Kg.

τ_0=The time constant for cooling

To find $F'\eta_0$, the equation is used which is as follows

$$F'\eta o = \frac{\frac{(F'U_L)A_{pot}}{A_{aperture}}\left[\left(\frac{T_{wf}-T_a}{I_b}\right)-\left(\frac{T_{wi}-T_a}{I_b}\right)e^{-\tau/\tau o}\right]}{1-e^{-\tau/\tau o}}$$

Where

T_{wi}=temperature of water of cooking pot at the beginning of the Interval, ^oC

T_{wf}=Temperature of water in the cooking pot at the end of interval, ^oC

τ=Duration of the interval (e.g. 10 minute or 600 seconds), s.

I_b=intensity of beam radiation incident on the aperture of the Concentrator, averaged during the interval, W/m².

Ta=Ambient air temperature averaged during the interval, ^oC

A_{pot}=Total surface area of the cooking pot, m².

$A_{aperture}$=Aperture area of the paraboloid concentrator cooker, m².

$$\tau = -\frac{(MC)'_w}{A_t F'U_L} In\left[\frac{T_w-T_a}{T_{wo}-T_a}\right]$$

$$F'\eta o = \frac{\frac{(F'U_L)A_{pot}}{A_{aperture}}\left[\left(\frac{T_{wf}-T_a}{I_b}\right)-\left(\frac{T_{wi}-T_a}{I_b}\right)e^{-\tau/\tau o}\right]}{1-e^{-\tau/\tau o}}$$

4.3 Requisite Parameters and Sensors

The various parameters required for the thermal performance evaluation are:

Ambienttemperature,temperature of water kept inside cooking pot, total global solar radiation, diffused radiation,direct solar beam radiation, wind velocity. Various sensors required for the measurement of these parameters are:

- RTD,thermocouple,anemometer,
- pyreheliometer,pyranometer,pyranometer with shading ring.

Basic thermocouple connection & current through two dissimilar metal

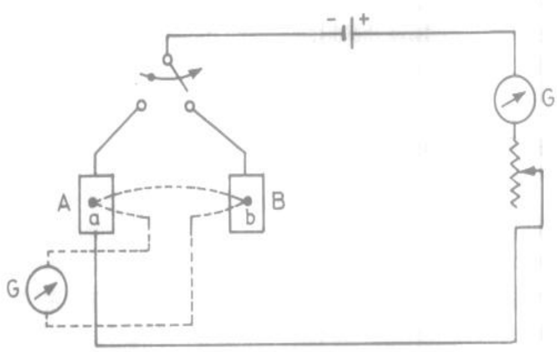

Fig. 5: Circuit diagram of Pyreheliometer.

The basic function of the data logger is to automatically make[23] record of the measurements of instruments. Data logger measures the data effortlessly as quickly, as often and as accurately as desired.

5. Results and Discussion

Data Monitoring

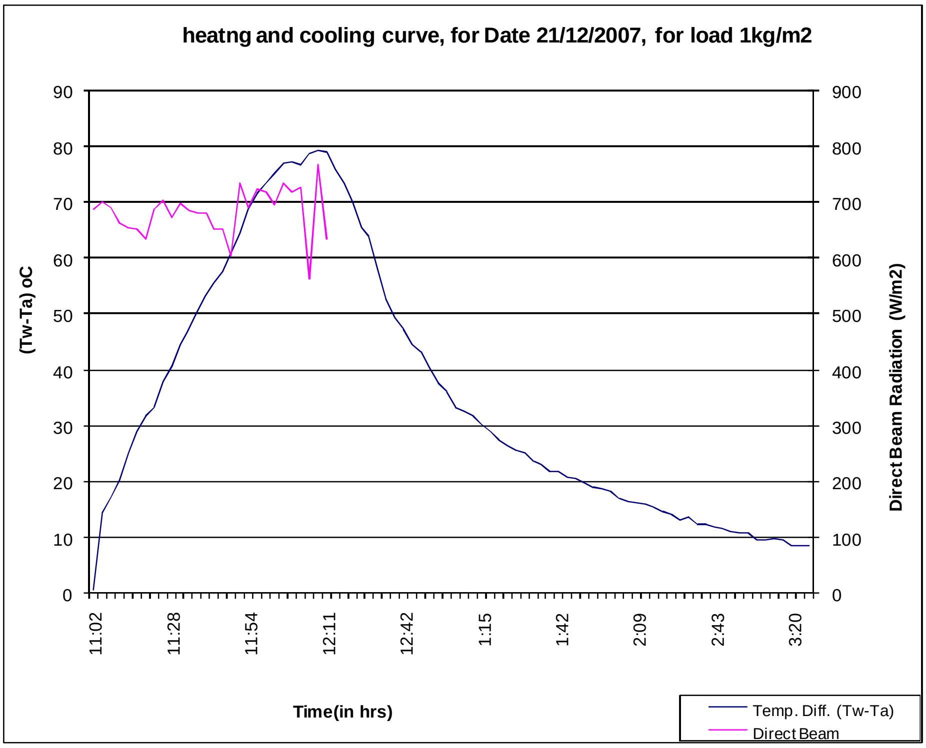

Fig. 6: Heating and cooling Curve for load 1 kg/m^2

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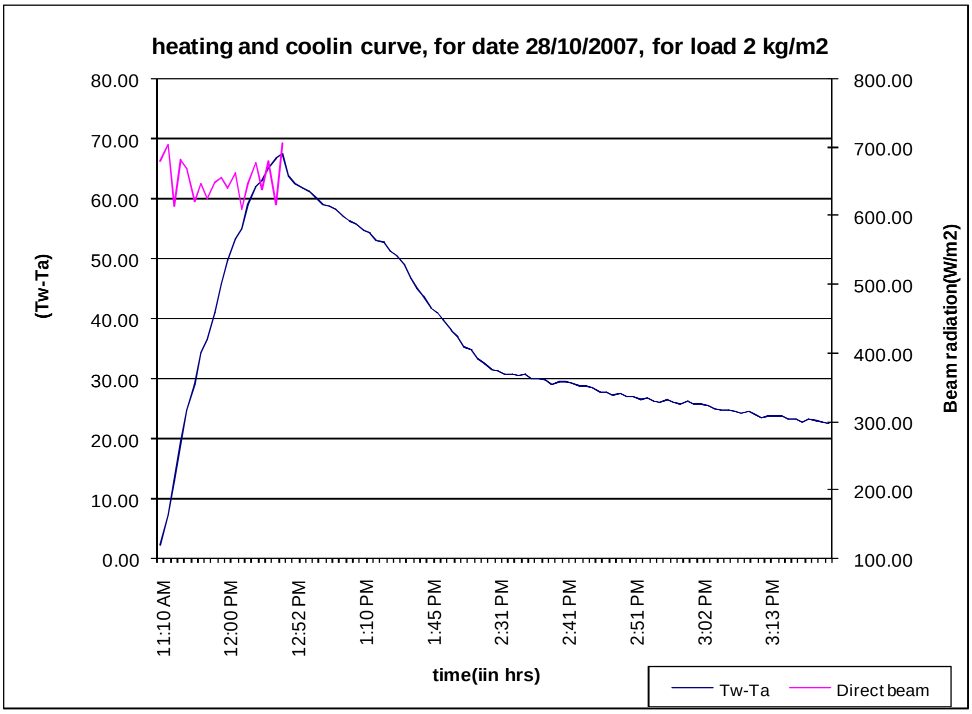

Fig. 7: Heating and cooling Curvefor load $2kg/m^2$

Calculation of $F'U_L$ and $F'\eta_0$ for test data set 5.4:
From cooling test data

$e=2.7182$, $T_W=101\,^0C$, $T_a=22.1\,^0C$, $M_W=1$ Kg/m^2

$$\frac{(Tw - Ta)initial}{e} = 29.03$$

where
$(T_W)_{max}=(T_W)$ at stagnation=101 ^oC
T_a=Ambient temperature at the time of $(T_W)_{max}$

$$F'U_L = \frac{(MC)_w}{A_{pot}\,\tau_o}$$

Time Constant τ_0 = 12:11 PM - 01:18 PM
= 1h & 7m
= 1 * 60+7 m
=67 minute = 4020 seconds

$T_{Wf}=101\,^0C$, $T_a=22.10\,^0C$, $I_b=699$ w/m^2 $T_{Wi}=22.9$, $T_a=21.4$, $I_b=701$ w/m^2
τ=83 minute
$=(5.63*10^3)/0.1714*4020=8.16$

$$F'\eta o = \frac{\frac{(F'U_L)A_{pot}}{A_{aperture}}\left[\left(\frac{T_{wf}-T_a}{I_b}\right)-\left(\frac{T_{wi}-T_a}{I_b}\right)e^{-\tau/\tau o}\right]}{1-e^{-\tau/\tau o}}$$

$$F'\eta o = \frac{\frac{(8.16)*0.1714}{1.53}\left[\left(\frac{101-22.10}{699}\right)-\left(\frac{22.9-21.4}{701}\right)*e^{-83/67}\right]}{1-e^{-83/67}}$$

=0.251

6. Conclusion

The test data sets of heating and cooling, enables the heating and cooling curves, calculation of time constant and the two thermal performance parameter, overall heat loss factor (F' U_L) and optical efficiency factor (F'η_o), as desired by the test procedures. The value of these parameters viz. (F'U_L) & (F'η_o), as calculated for the four tests are found in close proximity of the respective values for a good quality parabolic concentrating dish type solar cooker. It may be concluded that the setup installed in the present work, gives a fair evaluation of the thermal performance of the solar cooking device, being tested. The test data produced by the test setup can reliably be used for the thermal performance characterization and the developmental testing of the parabolic concentrating dish type solar cooker.

6. 1 Scope for Future Work

The test setup may be used to study the effect of wind speed on the thermal performance of the solar cooker.

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