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Analysis of Temperature and Solar Flux Distribution on the Flat Plate Receiver of Small Central Receiver System

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Abstract

In central receiver system, a large group of field is used to concentrated solar radiation from the sun on a tower-mounted heat exchanger (receiver) called heliostat field. Each heliostat continuously track the sunray by two axes sun tracking mechanism that reflect the incident sun radiation to a flat receiver located at top of the tower.The height of tower receiveris generally about 1/6th the length of the farthest heliostat in the field. A flat plate receiver was experimentally evaluate by solar central receiver system in order to study the change of receiver surface temperature and flux density distribution on the receiver plate.The solar flux distribution at focal region of concentrator system can be estimated, if the temperature on focal region is measured. The receiver surface temperature can be change with change in intensity of beam radiation, concentration ratio, ambient temperature and wind speed.Thermocouple methodconsidered to estimate flux distribution on receiver surface. The analysis of variation in temperature on the vertical receiver plate is done by varying the number of heliostats from 1 to 9. The maximum temperature obtained from 9 heliostats is around 231°C near the solar noon. The heliostats can be focus on the vertical and inclined receiver surface, its seen that minimum spread of reflected radiation with minimum end loss from the periphery of the receiver is obtained by 15° tilt angle.For the small central receiver system of 9 heliostats the peak flux value is found for vertical receiver (zero degree tilt angle) is around 5352W/m^2 and in case of 15° tilt angle peak flux is 5792 W/m^2.The modeling and experimental testing result showed that the both the concentrated solar power result lie in the range of 2025 W.

Keywords:*Heliostats, Flat plate receiver, Thermocouple method, Temperature and Flux distribution*

1. Introduction

The central receiver system (CRS) often also called as solar tower system. Solar radiation from the sun is collected by two axes sun tracking mechanism is known as heliostat field, which reflect concentrated solar radiation on to the receiver located at top of tower. The tower receiver absorb concentrated solar radiation and converted this solar energy into heat at high temperature level. Further, heat energy converting it into electricity by using thermal power cycle (Omar Beharn et al, 2013).The systematic operation central receiver system is strongly dependent on concentrated solar beamquality produced jointly by all individual heliostat. So, tracking control is essential to keep good aiming of heliostats. In order to measure radiative flux and temperature distribution on the receiver surface. Heliostat control need adjusting the angles of the sun tracking mechanism according to calculations heliostat normal vector bisects the angle between solar vector and relative target position vector (K.-K. Chong et al, 2012).The tower receiver absorbed concentrated solar radiation from heliostat field and transferring solar energy to heat transfer fluid. Flux distribution on the focal plane of the receiver is main term which is related to energy generation from the solar central receiver system. A point focusing central receiver system forms a flux distribution in two dimension (X, Y) at the focal plane of the receiver.

For accurate measurement of flux distribution, the direct and indirect technique used to measured flux on the receiver surface. In direct heat flux measurement system, MDF (MedidaDirecta de Flujo) system has been designed, mounted and used successfully on the top of the tower at the Plataforma Solar de Almeria (PSA) to measure the concentrated solar power by heliostat field onto the flat receiver surface(J. Ballestrin, 2014). A flux sensor which directly gives concentrated solar flux values. The camera target method is an indirect method used to capture light reflected from surface of the receiver. The diffuse reflected light is recorded by the charge couple device (CCD) sensor. A flat plate calorimeter is an indirect technique based on energy balance method to obtained incident flux concentration on the receiver surface. In ordered to avoid thermal losses from receiver surface. A volumetric receiver has been developed and tested at DLR Cologne (Keith Lovegrove et al,2012). The above method gives accurate flux distribution on receiver surface, but these method are specialized and costly.

An indirect and simple method is called thermocouple method used to estimate solar flux density distribution on the receiver surface by measuring temperature at large number of point (V. Rakesh Sharma et al,2005). The area element method is used to measure the temperature of receiver plate, which is mounted at focal plane of the Scheffler dish. In this method, each thermocouple represent the average temperature ofrespective finite area element and this method was successfully implemented on Scheffler dish concentrator, called ARUN at Latur (C.A. Kinjavadekar et al, 2010).

In this research work we presented an experimental analysis of temperature and flux measurement on tilted receiver plate. The thermocouple method is implement on central receiver system proposed by V. Rakesh Sharma et al, 2005,used to measured temperature receiver plate. The optimum tilt angle of the receiver is use to described minimize solar image on the top of the tower, complete utilization of concentrated solar energy from heliostat field and minimize convective losses from the receiver surface. The estimation temperature and flux distribution at horizontal position X and the vertical position Y at focal plane of the heliostat field by measuring temperature at a large number of point on the receiver surface by using area element method.The focus test, Experimental test set-up, test procedure and its results are discussed in this paper.

2. Mathematical formulation for focus test method

A flat plate receiver (3mm thickness) with known emissivity and thermal conductivity is located at the focal region of the heliostats system. Solar radiation reflected from heliostats field (flat mirror) can be concentrated on front surface of receiver plate and its back surface is insulated with ceramic wool insulation.

Consider small strip of receiver plate of radius ‘r’ and width ‘dr’ as shown in fig.1 below

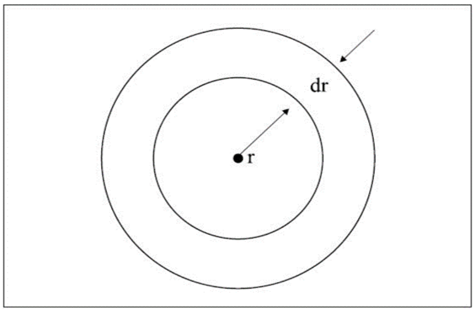


Fig.1 Strip of flat plate receiver

The energy balance equation for the flat plate receiver Can be expressed as,

$$\text{Absorbed energy}=\text{Energy loss due to (conduction} + \text{convection} + \text{reradiation)} \quad .....(1)$$

The energy loss due to conduction consist of two parts, heat conduction from one strips element to adjacent strip of plate and this heat loss due to conduction is negligible as compared to the convective and radiation heat loss term. Other part ofheat conduction through the insulation on the opposite side of the plate (V. Rakesh Sharma, 2005). The heat loss due to conduction through the insulation consist of conduction through insulation and then convection through surrounding ambient air form outside surface of the insulation. The convective resistance is very small as compared to the conduction resistance, hence it can be neglected. Thus eq. (1) can be written as;

$$\phi_c(x)=\frac{h(T_x-T_{amb})+\sigma\varepsilon(T_x{}^4-T_{sky}{}^4)+\frac{k_i}{L}(T_x-T_{amb})}{\alpha} \quad .....(2)$$

Where,

$\phi_c(x)$= Concentrated solar flux at a distance x,(W/m^2).

h=Convective heat transfer coefficient of the receiver plate, (W/m^2K)

T_x=Temperature of the point at distance x from the center of the receiver plate, (K)

T_{amb} =ambient temperature, (K)

T_{sky} = sky temperature,(K)

σ=Stefan-Boltzmann constant, (W/m^2K^4)

ε=Emissivity of the receiver plate

K_i=Thermal conductivity of insulation, (W/mK)

L=Thickness of the insulation,m

α=Absorptivity of the receiver plate

The average convective heat transfer coefficient of the receiver plate can calculated from the following correlation,

$$h=\frac{\overline{Nu}\ K_a}{L} \quad .....(3)$$

$$\Psi=[1+(\frac{0.492}{Pr})^{\frac{9}{16}}]^{\frac{16}{9}} \quad .....(4)$$

Where,

$\overline{Nu}$= Nusselt Number

K_a = Thermal conductivity of air

Ψ = Prandtl number function

Churchill and chu correlated the average Nusselt number for laminar and turbulent flow on a vertical plate of length L (A. F. Mills, V. Ganesan, 2009),

$$\overline{Nu}=0.68 + 067(Ra\ \Psi)^{\frac{1}{4}}$$
$$\text{For } Ra\leq 10^9 \quad .....(5)$$

$$\overline{Nu}=0.68 +0.67(Ra\ \Psi)^{\frac{1}{4}}\ (1+1.6\times 10^{-8}Ra\ \Psi)^{\frac{1}{12}}$$
$$\text{For } 10^9 \leq Ra < 10^{12} \quad ..... (6)$$

$$\overline{Nu}=0.56(Ra^*\cos\Theta_i)^{\frac{1}{4}}$$
$$\text{For } 10^5 \leq Ra\cos\Theta_i < 10^{11} \quad .....(7)$$

Where,

Ra= Rayleigh number

Θ_i=Inclination angle with vertical.

The above eq. (7) is valid for only 0°< Θ_i <89°. The concentrated solar flux can be accurately calculated with help of eq.(2) and flux distribution on the surface of the receiver plate.

3. Experimental test set-up

In asolar tower receiver system is apoint focus concentrator of reflective surface (mirror) called heliostats. The field consist of 9 heliostats. The field of heliostat track the sun and reflect the sunlight to receiver, which is located at top of the tower. Flat plate as a receiver is use to focus the concentrated solar radiation form heliostat field. The height of the solar tower receiver is generally about 1/6th the length of farthest heliostat in the field. In this present, work the receiver mounted 1.8 m form base of solar tower. Photographic view of solar tower receiver system as shown in fig.2 below

Fig.2. Experimental test setup

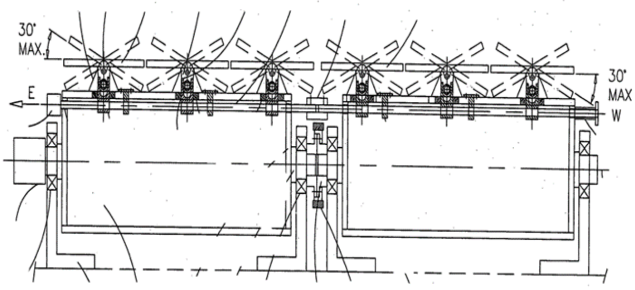
The brief description about heliostat field array and focus plate given below.

3.1 Heliostat field array

The array of heliostat field is design by Dr. Ravindra Patwardhan and this as assign for US Patent (Patwardhan R. et al, 2011). Generally, a conventional heliostat system is mounted on a pedestal and is pivotally rotatable about altitudinal and azimuthal axes. Each axis is equipped with a motorized limb that can pivotally rotate the mirror of the heliostat to adjust its position. Thus in conventional system for a single heliostat 2 motors are required and the size of the motor changes with the size of the heliostat. In the presented system, a number of heliostats are mechanically oriented and linked on a rotatable shaft. The advantage of this linked mechanism on a rotatable shaft is that all the heliostats on the can be controlled by a single DC motor and actuator arm. This helps in significantly cutting the cost of motors used in conventional system. All the heliostats are mounted on a single rotatable shaft as shown in fig.3. The shaft is given rotary motion using DC motor, this DC motor track the azimuthal motion of the sun.

Fig. 3 schematic diagram of mechanically linked heliostat

The actuator mechanism is used to tracking the



elevation motion of the sun as shown in Fig. 4.

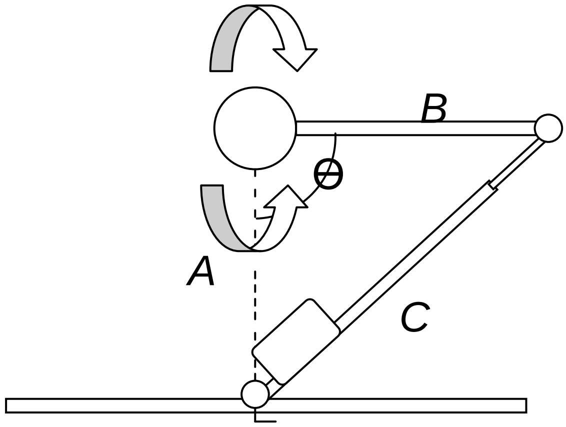


Fig.4 Actuator mechanism to control the elevation motion of the heliostat

3.2Receiver plate

The experimental test set-up consist of flat focus plate (material: mild steel, 0.9 m X 0.9 m, thickness 3 mm) and is referred to as receiver plate. The height of receiver plate 1.8 m from the base of the tower and with the distance of 6.8 m from the centered heliostat. For accurate calculation of flux distribution from temperature profile on the receiver surface, the thermocouple method is used. The grid of thermocouple arranged on the backside of the receiver plate.Each thermocouple is assumed to represent the temperature of a finite area element of area 110mm x 110mm as shown in Fig.5.It is assumed that the thermocouple represents the average temperature of the respective area element.The flux distribution on the receiver surface is calculated from all temperature point and by considering losses from exposed surface of the receiver due to convective, radiative and conductive heat loss through the insulation.

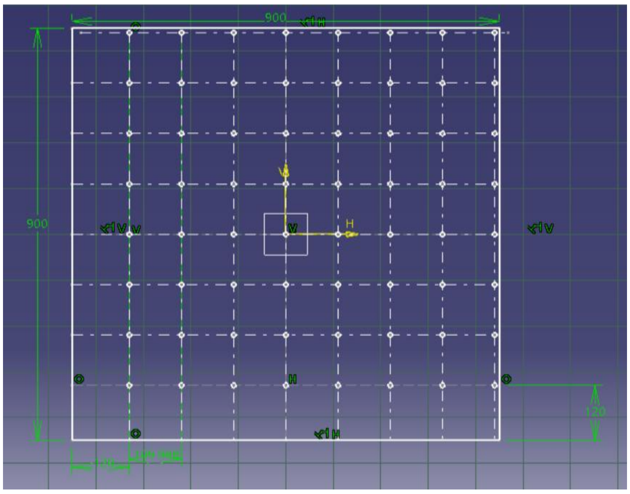


Fig.5.Thermocouple grid with 0.66 m × 0.66 m area

The arrangement of thermocouple were done on the receiver surface to absorbed maximum concentrated solar ray from the heliostats. 45K-typeof thermocouples (with uncertainty ± 0.08 °C) were placed in blind hole of 4mm in diameter and depth of 2mm, which are drilled on the backside of the receiver plate. This thermocouple are placed in the holes by using high temperature cement and it can be sustain the temperature up to 1600 °C. The front side of receiver plate is painted with three-layer coating of high temperature paint (HR 600), which can sustain up to 600°C. All 45 thermocouple readings are recorded in a grid of 7 x 7 and it covers an area of 0.66 m x 0.66 m. Each thermocouple indicates the average temperature of grid area of 0.11m x 0.11m. There will be heat loss by convection and radiation to the ambient from both side of receiver plate. To suppress the convection and radiation losses from back side of receiver surface, the back side of receiver plate is insulated with a layer of 25mm thickness of ceramic wool insulation (k_i = 0.12 W/mK) over the thermocouples.

4. Test procedure

The concentrated solar flux absorbed by black coated flat plate receiver, when the solar radiation reflected from the heliostat field. The temperature reading of the all point on the receiver plate are monitored using K type of thermocouple indicated by white dots see fig.5, which are connected to three data logger with 16 channel module. The data logger connected to personal computer and its stored the data of all 49 thermocouple temperature reading with the help of eScan software. It stores the data of all 45 thermocouples at every 10 seconds time interval and this data is stored in excel sheet format.Global radiation are measured using radiation pyranometer and diffuse radiation pyranometer with shading ring and the wind speed is measured by using three cup wind anemometer. The radiation data and wind speed is recorded on the data logger at 5 minutes interval. The solar fire device used for orienting arrays of mechanically linked heliostats for focusing the incident sunlight on the receiver.. The heliostat system is required to be focused manually only at the starting time and after that the system automatic tracks the sun during the whole testing period.

This experiment is conducted at 11 AM to 4 PM. During this period the intensity of beam radiation gradually increases and reaches its peak value at solar noon and remains nearly constant for around 10 minutes around solar noon and then gradually decreases after the solar noon.

5. Results and Discussion

The experimental is conducted on small central receiver system in April and May 2017. The temperature variation on the receiver plate is mainly due to intensity of beam radiation, concentration ratio, emissivity and absorptivity of the plate and tracking error. Based on the temperature recorded, the solar flux is calculated with help of eq.2. The following value are given by School of Energy Studies,Pune;

- emissivity of black coated receiver plate=0.92
- absorptivity of black coated receiver plate=0.92
- Thermal conductivity of insulation=0.12 (W/mK)
- Thickness of insulation=25 mm

From the temperature profile on receiver surface, it is seen that for all cases maximum temperature obtained at centerof the receiver plate and gradually decreases along the center in X and Y direction. In this present work 9 (Mirror size:2ft× 2ft) heliostats are used to achieve temperature variation on the receiver surface. Initially, single heliostat used to focus on vertical receiver plate and gradually increasing the odd number of heliostats. The average maximum temperature is achieved near the solar noon from all heliostatsas shown in fig 6. In case of 9 heliostats the maximum temperature of around 226° C was observed at 1230hrs,due to increase in beam radiation and concentration ratio.

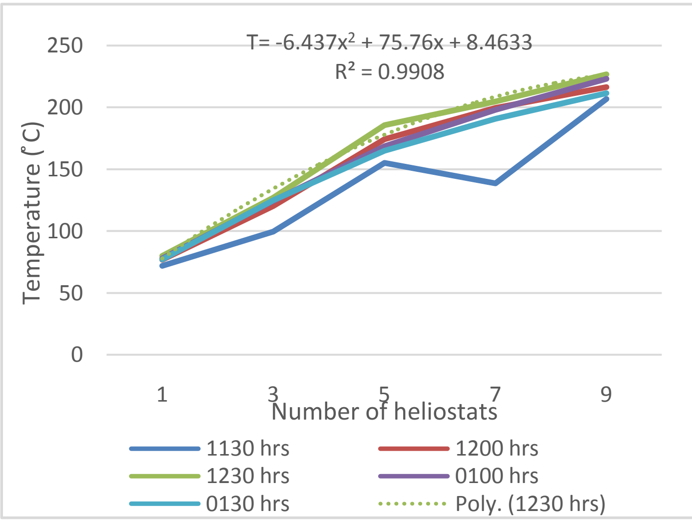


Fig.6 The variation of receiver surface temperature.

The maximum temperature on vertical flat plate receiver is achieved at solar noon. The temperature of the plate increase as the solar beam radiation is increases, maximum temperature at solar noon and then gradually decreases as beam radiation decreases,as shown in fig 7. The vertical receiver temperature also depend upon the wind speed (less than 2m/s) and ambient temperature (35̊ C). The solar beam radiation varies between 480 (W/m²) and 641 (W/m²), during the test period. The maximumtemperature has been obtained 231˚C at 1220 hrs. Because solar beam radiation is maximum at that time.

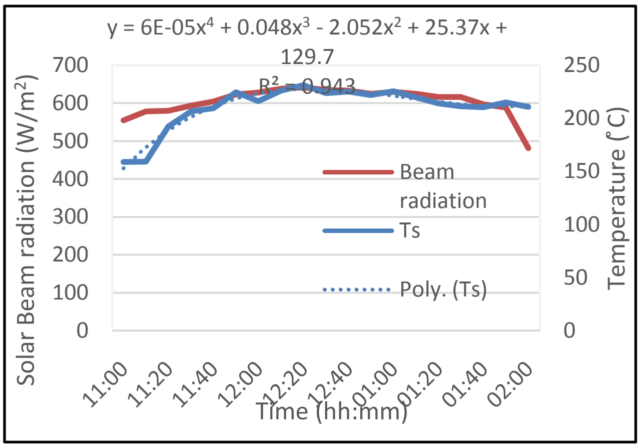


Fig.7 The effect of solar beam radiation of vertical receiver temperature.

The receiver of the central receiver system will be always operated with the certain tilt angle because the inclination of incoming solar radiation with respect to direct normal irradiation. The effect tilt angle of receiver was consider in order to analyses the exact energy distribution on the receiver surface with minimum spread of concentrated radiation. The comparison of temperature variation of receiver surface with incline and vertical surface of receiver as shown infig 8.

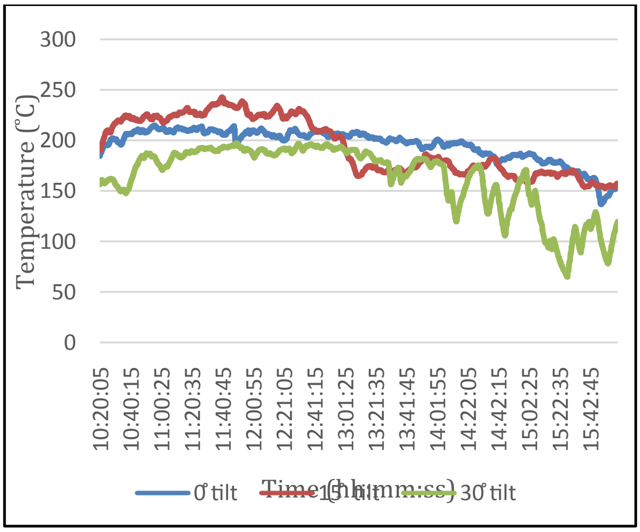


Fig.8 The temperature variation on the receiver surface by various angle

From fig 8. The temperature of the receiver surface increases due to increase in the beam radiation for all cases. The intensity of beam radiation is main factor for increase the temperature of the receiver. The temperature receiver is maximum around 240˚C at1130 hrs for the 15˚tilt angle and for 30̊ tilt angle is around197˚C. From the temperature variation of 30̊ tilt angle is due to less amount of beam radiation present at ground level and solar concentration decreases rapidly due to end losses i.e. fraction of energy at receiver surface, reflected from the primary optics, that falls beyond the receiver.

The flux distribution on the receiver plate is as shown in fig 9 and 10. The contour flux distribution of 9 heliostats with 15 tilt angle. The flux is calculated by using equation 2. The flux distribution is two dimensional that's along X axes and Y axes on the plate. From the flux distribution, it's seen that maximum flux is achieved at the centre of the plate and gradually decreases along radial direction.

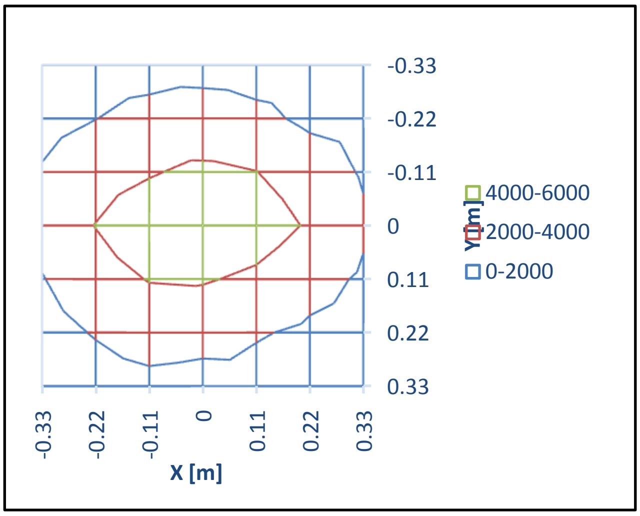


Fig.9 Concentrated radiation flux contours map on the vertical receiver plate (zero tilt angle)

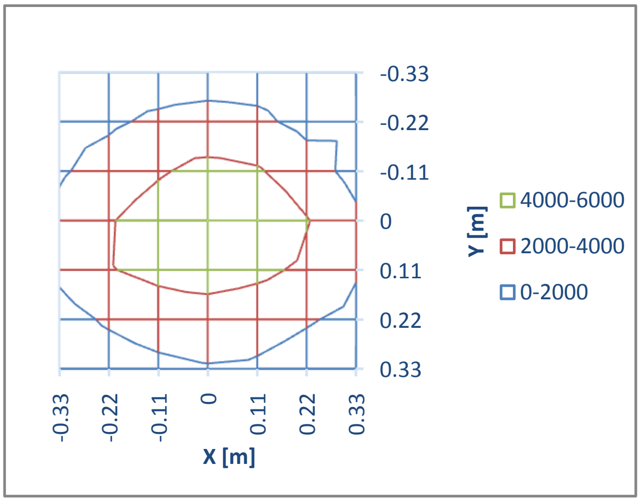


Fig.10 Flux distribution on the 15˚ tilt angle flat plate receiver plate

The concentrated flux is calculated for vertical plate receiver at the centre of the focus plate is about 5352 (W/m²) and it reduce about 788 (W/m²) at 0.33 distance from the receiver plate.In case of 15̊ tilt angle maximum flux obtained at center around 5792 (W/m²) and it reduced to 610 (W/m²)at distance of 0.33m from the centre of the receiver plate.

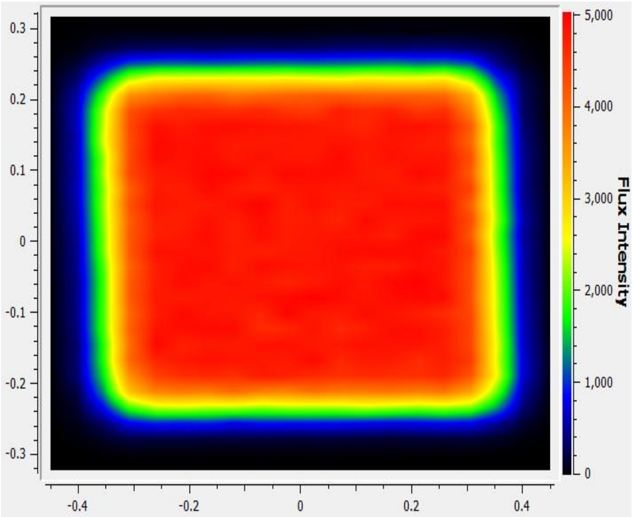


Fig.11 Flux distribution on vertical flat plate receiver using SOLTRACE software

The ray tracing model was developed using SOLTRACE software to provide a comparison with the experimental value. The model consist of array of heliostats field with 9 heliostats ray focused on 1.5 m high target. The target aperture has a 0.9× 0.9m flat receiver. The mirror properties were defined as reflectivity = 0.92, transmissivity = 1,slop error =0.95 mrad and secularity error = 0.2 mrad. The properties of target ware defined with reflectivity=0.1. The beam radiation input was obtained from the recorded value of the weather station at MIT, Pune on the specific day of testing. The number of ray interaction was set to 1000000 rays, and the maximum number of generated sun rays was 100000000 by default.
The simulation result revealed a peak flux of 5073.75 w/m^2 with an uncertainty of $\pm$ 1.6788 %. An average flux value of 2532.92 w/m^2 was obtained as shown in fig 11. Therefore by multiplying the average flux value with aperture area the total concentrated solar power incident on the flat plate receiver was calculated 2050.85 W. and the experimental value of concentrated solar power was 2002.6 W. The comparing this two value one can see that both value lie within a range of about 2025 W. The result obtained from this ray tracing model and experimental value is similar, even though slightly deviation ware observed. These deviation due to misalignment of mirror and mirror surface error. The ray tracing analysis shows similar result to the power measured by flat plate receiver.

Conclusions

The variation of temperature and flux distribution on flat plate receiver of small central receiver system, under concentrated solar radiation was determined experimentally. For accurate measurement of temperature on the surface of the flat plate by using an indirect and simple method i.e. thermocouple method. The temperature on the receiver temperature increases with increases in number heliostats, concentration radiation and intensity of beam radiation.The maximum temperature is anachieved by 9 heliostats 231°C. near the solar noon where the maximum beam radiation obtained.For the minimum spread of the concentrated solar radiation on the surface, the receiver is oriented with some angle. The high heat loss occurred at periphery of the receiver plate due to more exposed area. Wider the tilt angles are not consider since the solar concentration decreases rapidly due to end-losses i.e. fraction of energy, reflected from the primary optics, that falls beyond the receiver. The comparing concentrated power result obtained from SOLTRACE model and experimental model is slightly deviate from each other and both this value lie in the range of 2025 W. The experimental test and ray tracing model results are useful for designing the receiver for small central receiver system.

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