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DESIGN AND ANALYSIS OF PARABOLIC SOLAR CONCENTRATOR WITH DIFFERENT RIM ANGLES

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Abstract:

Energy is one of the issues that are causing the most controversy as fossil fuels are the greatest pollutants and the greatest contributors to the greenhouse effect. The increasing importance of environmental concern, fuel savings and unavailability of power has led to the renewal of interest in renewable energies. It therefore stands to reason that developing countries whose energy consumption rate is increasing at a very fast rate should be investigating new energy systems based on renewable energies that do not pollute and which are inexhaustible such as the Solar system. This paper concerned with design of parabolic concentrator for its ability to capture maximum direct solar radiation and compare in terms of higher concentration ratio using a ray tracing software. And further to validate this research, a small size ss-304 parabola for the domestic application is studied. Experimental study of parabolic trough collector is carried with its manual sun tracking system. This is conducted in order to improve the performance of solar concentrator in the solar field, with different geometries based on change in rim angle.

Key Words: Solar Energy, Solar Radiation, SS304-Parabolic Reflector & Ray Tracing

Introduction:

A solar collector is a device used for collecting solar radiation and transfers the energy to a fluid passing in contact with it. Utilization of solar energy requires solar collectors. These are general of two types:

- Non-Concentrating Type
- Concentrating Type

The solar energy collector with its associated absorber is the essential component of any system for the conversion of solar radiation energy into more usable form e.g. heat or electricity. In the non-concentrating type the collector area is same as the absorber area. On the other hand in concentrating collectors the area intercepting the solar radiations is greater, sometimes very greater than the absorber area.

There are many different types of concentrating solar collectors in use today. Concentrators can be reflecting or refracting, cylindrical, spherical, parabolic, and they can be continuous or segmented. Receivers can be convex, flat, cylindrical, covered or uncovered. Because of the complexity and very wide scope of concentrators and concentrator designs, it is difficult to find developed general analyses of each specific type of concentrator. Therefore each solar concentrator design must be studied on a per case basis [1].

The Solar thermal energy can be used for:

- Cooking / Heating
- Drying / Timber Seasoning
- Distillation
- Electricity / Power Generation
- Cooling and Refrigeration
- Process Heating

The idea behind a concentrating solar collector is to minimize the heat losses associated with solar collection. In many instances it is desirable to deliver energy at higher temperatures than those possible with flat plate solar collectors. In this case, a parabolic "mirror" concentrates incident solar irradiation onto a much smaller receiver area, greatly decreasing heat loss and maximizing the available energy from the sun.

Parabolic trough power plants use parabolic trough collectors to concentrate the direct solar radiation onto a tubular receiver. Large collector fields supply the thermal energy, which is used to drive a steam turbine, which, on its part, drives the electric generator.

Parabolic trough power plants constitute the biggest share of the installed concentrating solar power technology. Distinguishing between parabolic trough power plants, Fresnel power plants, solar tower power plants and dish/Stirling systems, the parabolic trough power plants provide over 90% of the capacity of concentrating solar power plant technology that is in operation.

One important factor in the analysis of solar concentrators is the concentration ratio. The concentration ratio is defined as the ratio of the area of the aperture of the concentrator to the area of the receiver that is reflected upon by the concentrator. This is in essence the heart of a solar concentrator. Solar tracking is also necessary for efficient use of concentrating collectors. Without tracking the collector becomes almost useless except for a very short time period once a day. Large scale concentrators today use automated tracking systems that can track the sun on a biaxial path. Due to cost restrictions and complexity, and the small scale of this project, manual turning of the concentrator was chosen as the preferred method of solar tracking.

The future of concentrating solar collectors will rely greatly on improved engineering, design, and materials. It is very important to maintain the quality of the optical systems of solar concentrators for long periods of time.

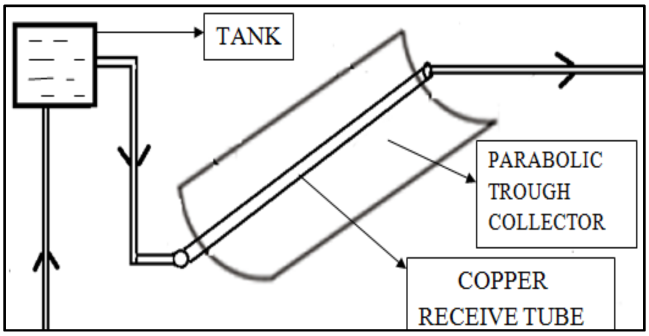


Figure 1: Line diagram of parabolic trough collector

Parameters for the Geometrical Description of a Parabolic Trough:

In order to describe a parabolic trough geometrically, the parabola has to be determined, the section of the parabola that is covered by the mirrors, and the length of the trough.

The following four parameters are commonly used to characterize the form and size of a parabolic trough: trough length, focal length, aperture width, i.e. the distance between one rim and the other, and rim angle, i.e. the angle between the optical axis and the line between the focal point and the mirror rim

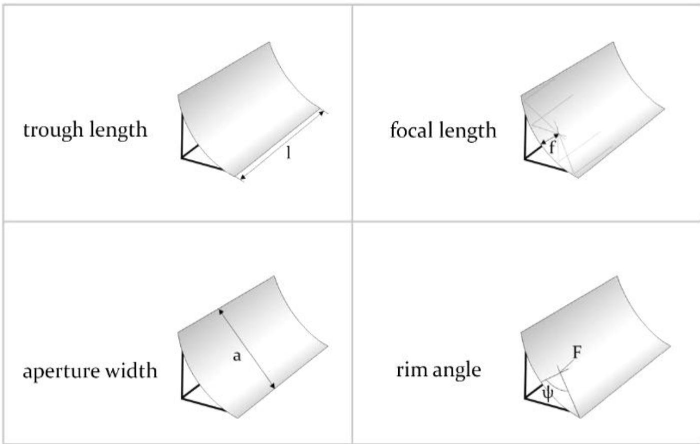


Figure 2: Parameters for the geometrical description of a parabolic trough [2]

- The length of the trough is an unproblematic measure and does not need any explanation.
- The focal length, i.e. the distance between the focal point and the vertex of a parabola, is a parameter that determines the parabola completely (in the mentioned mathematics expression of a parabola, the focal length f is the only parameter).

$$y = \frac{x^2}{4f} \qquad (1)$$

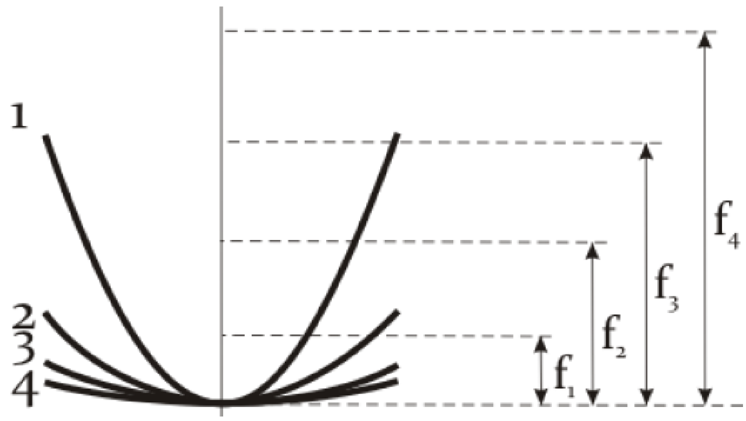


Figure 3: Focal length as shape parameter [2]

- The aperture width, i.e. the distance between one rim and the other.
- The rim angle, i.e. the angle between the optical axis and the line between the focal point and the mirror rim, has the interesting characteristics that it alone determines the shape of the cross-section of a parabolic trough. That means that the cross-sections of parabolic troughs with the same rim angle are geometrically similar. The cross-sections of one parabolic trough with a given rim angle can be made congruent to the cross-section of another parabolic trough with the same rim angle by a uniform scaling (enlarging or shrinking). If only the shape of a collector cross-section is of interest, but not the absolute size, then it is sufficient to indicate the rim angle.

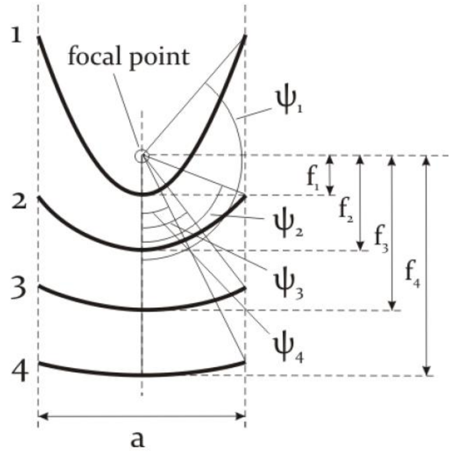


Figure 4: Relation between the focal length and the rim angle for a constant trough aperture width [2]

Theory behind Design of Parabolic Collector:

Mirror Area and Aperture Area:

Besides the mentioned linear measures, also surface area measures are important. There is, first, the aperture area, which is an important constructive measure. At a given DNI and a given Sun position it determines the radiation capture. The aperture area A_{ap} is calculated as the product of the aperture width a and the collector length l

$$A_{ap}= a*l \qquad (2)$$

The surface area of a parabolic trough may be important to determine the material need for the trough. The area is calculated as follows

$$A = \left(\frac{a}{2}\sqrt{1+\frac{a^2}{16f^2}} + 2f.\ln\left(\frac{a}{4f} + \sqrt{1+\frac{a^2}{16f^2}}\right)\right) * l \qquad (3)$$

Rim Angle:

The rim angle is a very important constructive trait of collectors. For instance, it has an effect on the concentration ratio and on the total irradiance per meter absorber tube [W/m]. Qualitatively, we can understand in the following way that there must be some ideal rim angle range and that is should neither be too small nor too large:

We consider, first, perfect mirrors, disregarding possible slope errors.

If the rim angle is very small, then the mirror is very narrow and it is obvious that a broader mirror (with a larger rim angle) would enhance the power projected onto the absorber tube.

If the rim angle is very big, then the way of the reflected radiation from the outer parts of the mirror is very long and the beam spread is very big, reducing, hence, the concentration ratio. A mirror with a smaller rim angle and the same aperture width would permit a higher concentration ratio.

Additionally, if we consider real mirrors with a certain degree of geometrical inexactness, then it is important to maintain a low distance to the absorber also because the effects of these geometrical mirror errors. The larger the distance to the absorber, the more weight carries the radiation aberration due to mirror slope errors. Once more, at a given aperture width, very small rim angles as well as very large rim angles imply large distances between the mirror and the focal line (in the case of very large rim angles for the outer parts of the mirror) and should be avoided.

Receiver:

Receivers for parabolic trough power plants have the task to convert the radiation that is projected onto them into heat and to transport the heat to the pipes, which leads it further to the power block. Important are high radiation absorption and low heat losses. A constructive challenge is the heat expansion of the receiver due to the changing temperatures between operation and non-operating state.

The absorber tube must have a sufficient diameter to permit a high intercept factor. The intercept factor is the ratio of the total reflected radiation to the reflected radiation that hits the absorber surface. On the other hand, the absorber diameter should not be too big in order to maintain the thermal losses low. An absorber tube with a big diameter has a large surface area per meter and loses therefore more heat than an absorber tube with a smaller diameter.

In order to estimate the appropriate absorber tube diameter, we will take an absorber, the diameter of which is just sufficient to receive all the radiation reflected by a geometrically perfect parabolic mirror, i.e. by a parabolic mirror that does not have slope errors and that does not widen the beam radiation due to microscopic errors. The necessary absorber diameter to reach an intercept factor of 1 depends, then, on the distance of the absorber tube from the mirror and on the solar beam angle. The solar beam angle is the opening angle of the direct solar radiation. It amounts to 32' (it is not zero because of the extension of the Sun disc). Because of this beam angle the Sun image at an ideal parabolic trough is not a one-dimensional mathematical line but has a two-dimensional extension. The rays that are reflected from the mirror are reflected with a corresponding angular variance of 32'.

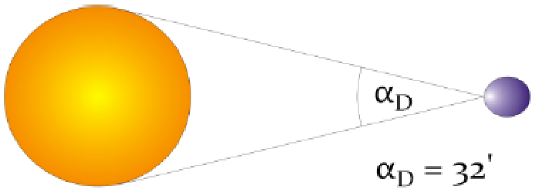


Figure 5: Sun beam angle [2]

The distance between the mirror and the absorber is different for the different points of the mirror. The largest distance is between the mirror rim and the absorber. So we take the rim of the parabolic mirror to determine the absorber diameter.

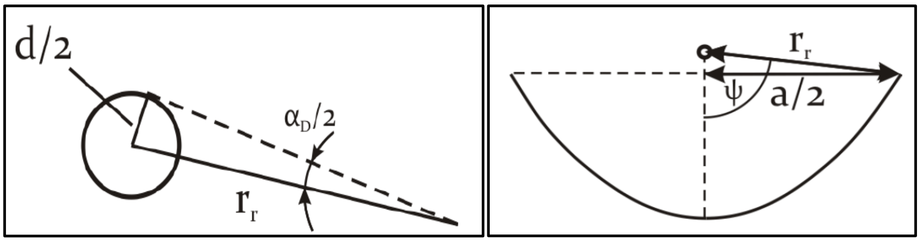


Figure 6: Geometrical parameters at the collector and the receiver [2]

The foregoing figures illustrate the relation between the absorber tube diameter, the half solar beam angle and the distance between the absorber tube and the mirror rim

$$\frac{d}{2} = r_r * \sin\frac{\alpha_D}{2} \qquad (4)$$

Where d is the absorber diameter, αis the Sun beam angle and $r_r$the distance between the absorber tube and the mirror rim.

Alternatively, the diameter can be expressed with the aperture width and the rim angle. Taking into consideration that

$$r_r = \frac{\alpha}{2\sin\Psi} \qquad (5)$$

$$d = a.\sin\frac{\alpha_D}{\Psi} \qquad (6)$$

This is valid for perfect mirrors without surface imperfections. Additionally, the calculation supposes that the direct radiation hits the collector with the incidence angle zero, because only in this case the distance from the mirror rim to the absorber tube is a/2 for the reflected light. Generally, the incidence angle is not zero and the distance for the reflected light is larger. That means that the absorber tube has to be dimensioned a bit larger in order to maintain high intercept factors also in situations when the incidence angle is large. In order to take into account the effect of the varying incidence angle. However, it is an optimization task to find the ideal absorber diameter that allows to reach a high average intercept factor without being too large and to cause too high thermal losses.

Limits with Flat Receivers:

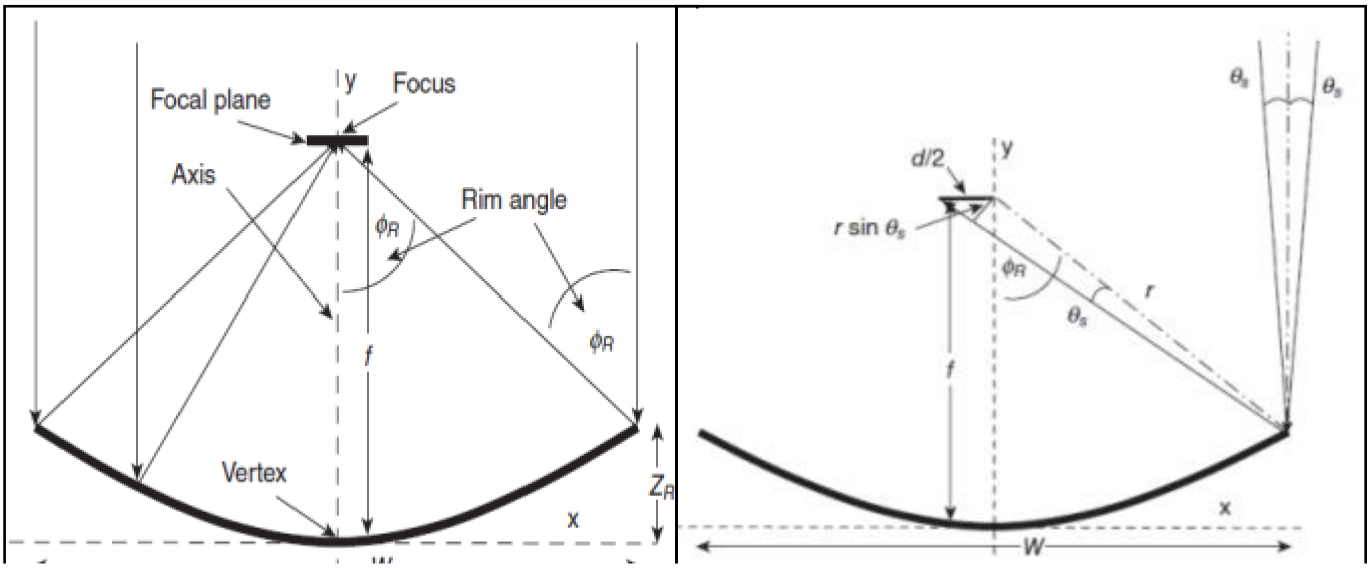


Figure 7: Limit for Flat receiver [3]

Each point on a parabolic mirror will reflect a cone of rays that matches the angular distribution of the solar source (half-angle size θ_s). Consider the size of the spot formed by the cone of rays reflected from the points on the mirror, when incident on a flat target placed in the focal plane. The rays from the rim will form the widest such spot. The distance x of the reflection point from the axis is

$$x = 2r \sin \Phi_R \qquad (7)$$

And the width of the focal spot on the focal plane due to reflection from this point will be

$$d = \frac{2r \sin \theta_S}{\cos \Phi_R} \qquad (8)$$

If the receiver is large enough to accept reflected spots from the entire mirror surface, then the diameter of the receiver will be defined by the reflected spot size from points at the edge of the mirror with x = W and $\Phi = \Phi_R$. The geometric concentration ratio for a parabolic trough with flat receiver will then be

$$C_g = \frac{A_c}{A_R} = \frac{LW}{Ld} = \frac{W}{d} \qquad (9)$$

Substituting W and d, we get

$$C_g = \frac{\sin 2\Phi_R}{2 \sin \theta_S} \qquad (10)$$

To find the optimal rim angle for a parabolic trough, take the derivative with respect to Φ_R

$$\frac{dC_g}{d\Phi_R} = \frac{d}{d\Phi_R}\left(\frac{\sin 2\Phi_R}{\sin \theta_s}\right) = \frac{2\cos 2\Phi_R}{2 \sin \theta_s} = 0 \; at \, \Phi_R = 0{,}45°, 90°.. \qquad (11)$$

The maximum concentration ratio corresponds to Φ_R = 45°, and gives a maximum concentration ratio for a trough, with flat receiver and solar acceptance angle θs = 4.65 mrad, of

$$C_{g,trough,flat,max} = \frac{1}{2 \sin \theta_s} \approx 108 \qquad (12)$$

Limits for cylindrical receivers

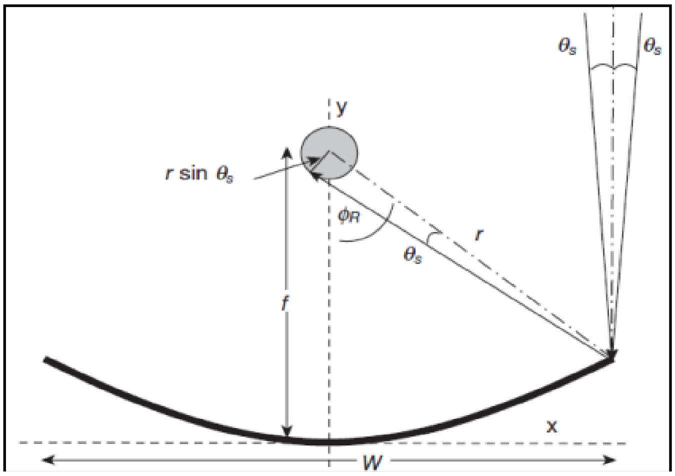


Figure 8: Limit for cylindrical receiver [3]

Another possibility to consider is using a receiver with a circular cross section as shown. In this case, the diameter of the target needs to be

$$d = 2r \sin \theta_s \qquad (13)$$

For a trough with cylindrical receiver,

$$C_g = \frac{A_c}{A_R} = \frac{LW}{L2\pi r \sin \theta_s} = \frac{\sin \Phi}{\pi \sin \theta_s} \qquad (14)$$

Solving for maximum geometric concentration ratio as before, the optimal trough rim angle is Φ = 90°, and that at this angle, gives

$$C_{g,trough,cyl,max} = \frac{1}{\pi \sin \theta_s} \approx 68.5 \qquad (15)$$

Simulation of Parabolic Collector Using Software:

The simulation in the present paper was done by an optical simulation tool, Tracepro. It's an opto-mechanical software used for design, analysis, and optimization of optical and illumination systems. Features that can be applied are Material properties, Surface properties, Surface source, Light Sources. Temperature distribution, Irradiance/Illuminance Maps showing irradiance or illuminance can be obtained from this software.

We established the geometry models in the 3-dimensional drawing software Solid works and then imported the geometrical model to the optical tool. Models that are drawn has aperture area and receiver diameter constant for all cases only the rim angle is changed. So for changing rim angle we have chosen the theoretical maximum values (i.e. 45°,60°,68.5°,90°) for simulation. Beyond 90° is not considered as it will possess significant shading effect.

The surfaces facing the incident lights of the surface were set as the reflective surface. In order to make sure that the concentrator (1000mmW*1000mmL) is completely covered under the light irradiation, we established a surface light source (1000mmW*1000mmL) in the vertical direction 5000mm from the concentrator, and defined the light source as illumination form uniformly distributed on the light source surface with equal importance to the solar range from 200nm to 2000nm range.

Table 1: Surface property for simulation

Property	**Parameter**	**Value**
Absorber	Absorptivity Diameter(d) Length (L)	1 ½ inch (Inner dia-1.27 cm Thickness-0.09cm) 1 m
Reflector	Specular reflection Absorption Aperture width (W) Aperture area (A_{ap})	0.95 0.05 1m 1m^2
Light source	Radiation Number of rays Solar range of absorption	1000W/m^2 1,20,000 200-400nm (UV-7%) 400-700nm (Visible-39%) 700-3500nm (Far IR-52%)

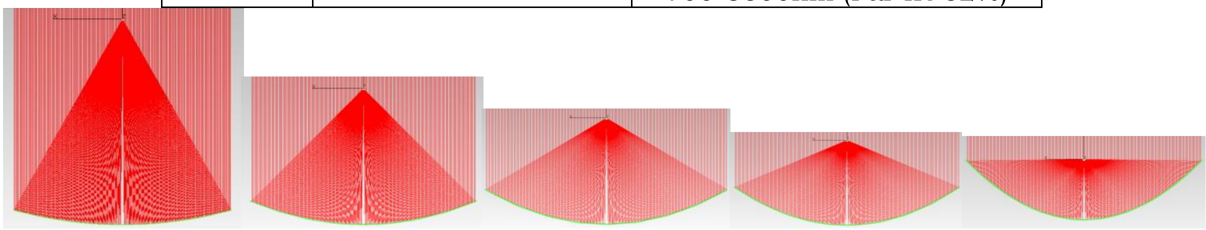
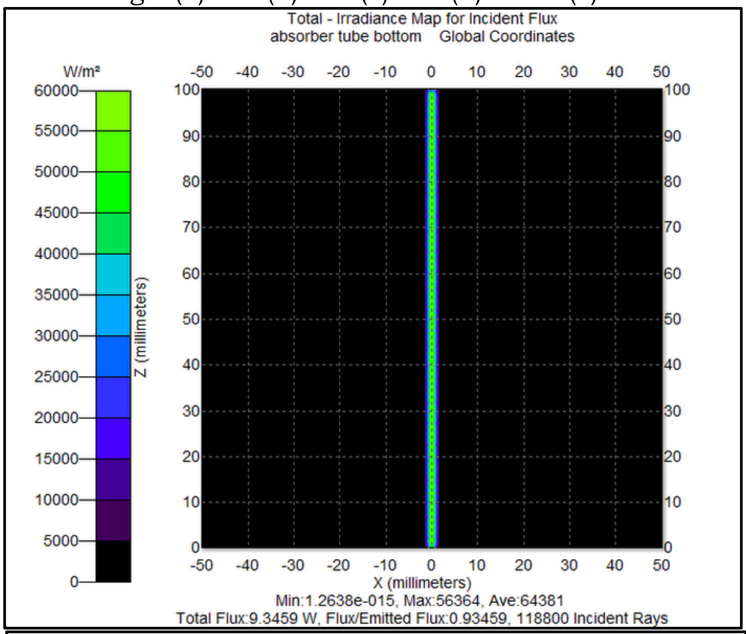
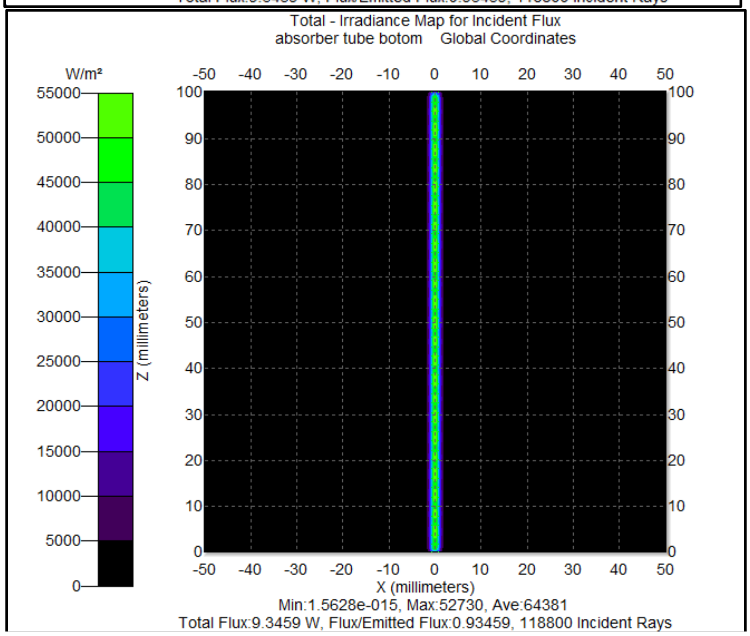


Figure 9: Ray traced for constant aperture area and receiver diameter with different rim angle (a) 30° (b) 45° (c) 60° (d) 68.5° (e) 90°





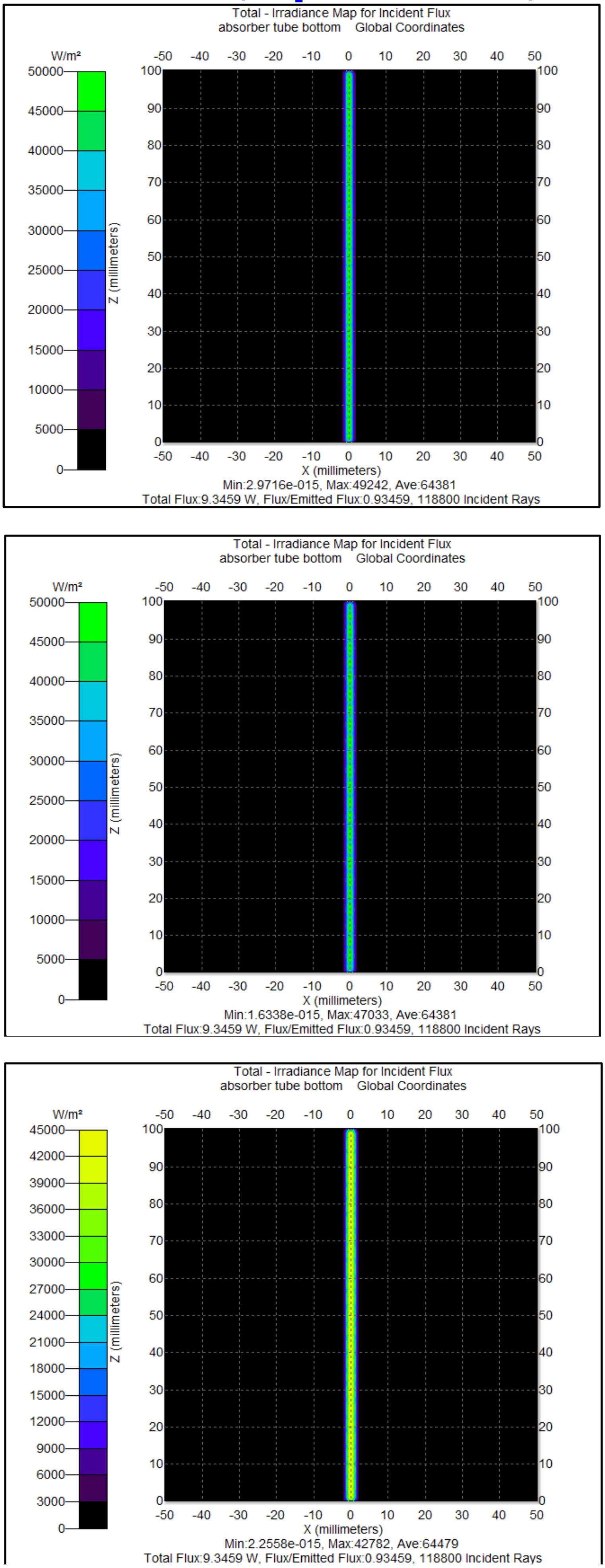


Figure 10: Irradiance plot for different rim angles considered.

Table 2: Simulation results in each rim angle

Rim angle	Focal length (f) m	Maximum radiation on tube W/m²	Geometrical Concentration Ratio (C_g)	Observation
30°	0.933	56364	32.59	Entire bottom side of tube area not covered
45°	0.6	52730	32.59	Better CR_{max}
60°	0.431	49242	32.59	Lesser CR_{max}
68.5°	0.367	47033	32.59	Least CR_{max}, but uniformly spread
90°	0.25	42782	32.59	Bottom heat very less

Experimental Validation:

Design Small Scale:

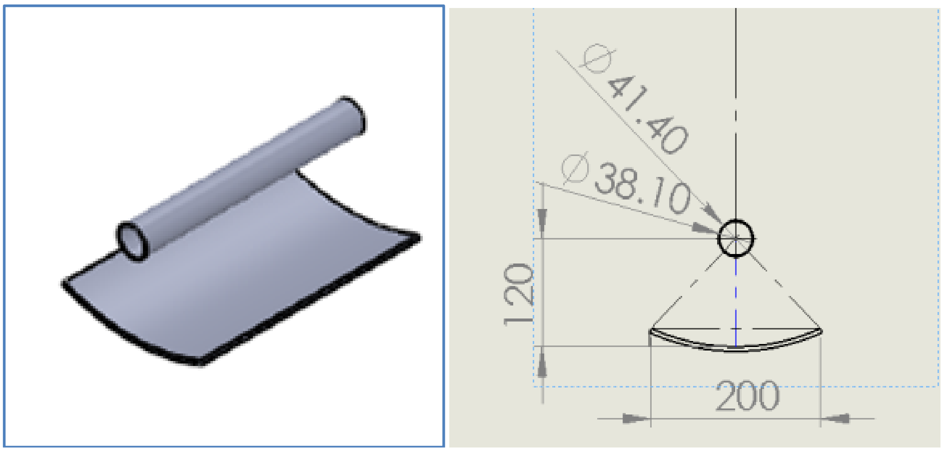


Figure 11: 3-D model and 2-D diagram of designed parabolic reflector

Table 3: Design parameters of the mini-scale model

Parameter	Value
Inner Diameter	38.10 mm
Outer Diameter	41.40 mm
Focal Length	120 mm
Length	300 mm
Aperture Width	200 mm
Aperture Area	60000 mm²
Rim Angle	45^0
Geometric Concentration Ratio	3.83

Working Principle:

The Solar radiations coming parallel to the focal line of the parabola (reflector) collects at the surface of reflector and concentrate it to the focal point. If the reflector is in the form of trough with parabolic cross section, the solar radiation focuses along a line. In concentrating collectors the term concentration ratio (C) is a very important parameter. It is defined as the ratio of the collector area at which radiation collects to the area (absorber) at which these radiations are concentrated. Concentration ratio is defined as the ratio of the collector area to the absorber area. So with the decrease in the absorber area the concentration ratio increases and hence more quickly the high temperatures are reached. So higher concentration ratio means higher temperature can be achieved of the working fluid.

Manual Tracking system

Theoretically, the parabolic troughs in the solar field of a CSP plant can have any horizontal orientation. Sun tracking is always possible. However, there is a preferred orientation, which is the north-south alignment with the respective east-west tracking. Here we use manual tracking.

Table 4: Material used for the concentrator

Part	Material	Parameter	Value
Absorber	copper	Absorptivity	0.4-0.65
Reflector	Stainless steel 304	Spectral reflectivity Absorptivity	0.6 0.4

Instruments Used:

- Pyranometer: To measure solar insolation (w/m²)
- Digital thermocouple: To measure temperature (°C)
- Measuring jar: To measure the mass flow meter (kg/s)

Results:

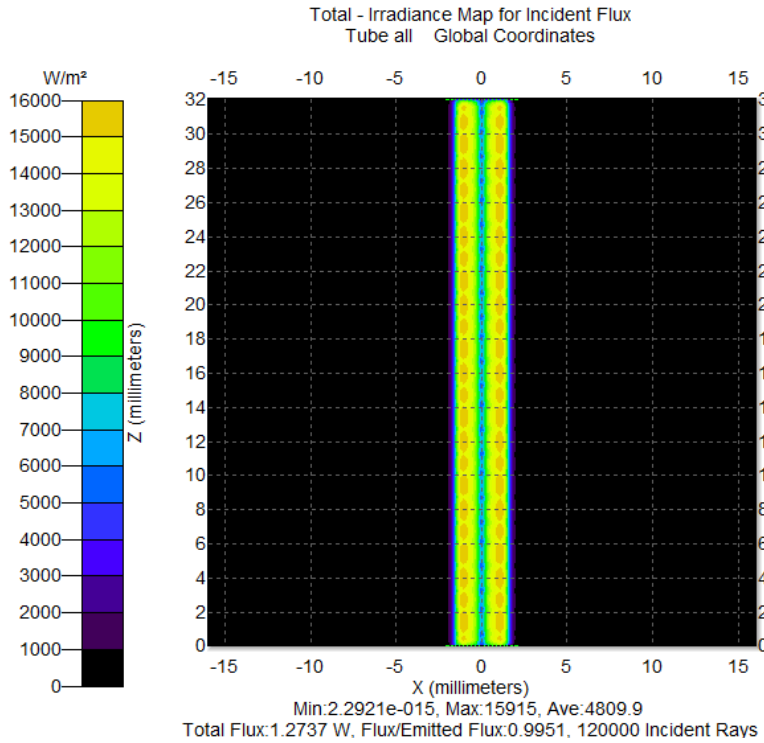


Figure 12: Irradiation plot for the mini setup

Table 5: comparison of simulation and real time system

Parameter	Simulation (at Optimize Rim Angle)	Experiment
Irradiation	1000 W/m²	700 W/m²
Concentration Ratio	4.81	3.83
Heat Incident	60 J	42
Heat Absorbed	57 J	11
Efficiency	0.95 (with Perfect Absorber)	0.26

Conclusion:

In this work, solar parabolic trough collector is studied and different rim angles are modeled and the effective concentration is studied based on the irradiation plots obtained from the ray tracing software. Based on this study it is concluded that parabolic concentrator field can be set in such a way a that initially uniform heating concentrators with rim angle near to 90° has to be used for initial heating and in the later part of the circuit higher concentration type with rim angle 45° is connected so as to facilitate for steam generation applications as overall geometric concentration is same for all the concentrators.

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