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Design Optimization of Circular Hyperboloid Solar Concentrator by Ray Tracing Technique

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Abstract*— Solar energy is the renewable and clean forms of energy. The importance of energy to our society is growing to make certain the quality of life and to smoothly speed up the other elements of our economy. As a result of growing demand of energy, shortage of fossil fuel and other resources, changing climate continuously, and environmental protection, the need for renewable energy sources has been growing rapidly. However, there is an urgent need to cope with intermittency and fluctuation of renewable energies. In solar energy applications, the solar air heaters (SAHs) were commonly used as heat exchanger for abundantly available solar heat. Air heating is one of the major solar thermal applications, used for space heating, laundry, crop drying, paper mill, food industries and other drying processes. This paper presents an investigation of design optimization of the optical efficiency of circular solar concentrator (through a critical parametrical analysis of different geometrical configurations). In this study, various key parameters of the circular hyperboloid solar concentrator design were systematically varied, including the aspect ratio of the circular aperture, the focal length of the concentrator, the angle of incidence of the incoming sunlight, and the shape of the reflector surface. The impact of these parameters on the overall optical efficiency of the circular hyperboloid solar concentrator was then measured, and the optimal values for each parameter were determined. The maximum optical efficiency obtained is 78% of concentrator height 1000mm and concentration ratio 22x. As acceptance angle increases, optical efficiency decreases drastically.

***Index Terms*— Solar Concentrator, Solar Air Heaters (SAHs)**

I. INTRODUCTION

The paper begins with a brief overview of the circular hyperboloid solar concentrator and its unique features. This describes the methodology used to analyze the impact of various design parameters on the optical efficiency of the circular hyperboloid solar concentrator. This presents the results of the parametrical analysis and discusses the optimal design configurations for maximizing the optical efficiency of the circular hyperboloid solar concentrator. The study provides insights into the optimal values of each parameter for maximizing the optical efficiency of the circular hyperboloid solar concentrator, which can inform the design of highly efficient and cost-effective solar concentrators.

A simple and effective ways to harness solar energy is the conversion to solar thermal energy (heat absorption) for different applications such as air conditioning [1], cooking [2, 3], water heating [4], water pumping [5], water desalination [6], drying [7]. Jaffe [8] proposed a wide variety of point-focusing concentrators for solar thermal energy use. These point focusing concentrators have many operating parameters that are optical configuration, optical elements materials, structure for support of the optical elements and receiver mount, foundation, drive, and controls. Concentrating solar power converts solar radiation to heat energy and then to electricity and concentrating photovoltaic directly converts solar radiation to electricity. Concentrating solar power is an efficient way for the production of non-domestic hot water [9] improved steam cycles [10], electricity production [11], cooking and photovoltaic electrical applications [12, 13]. Jaffe [70] stated methods for calculating and evaluating the performance of parabolic dish solar collectors and their cost/output ratio. The effects of parameters such as concentrator optical surface, specularity, pointing errors, receiver aperture size, absorptance and temperature on optimization were studied [14]. Harris [15] studied the thermal performance of a solar concentrator with changing dimensions cavity receiver's shapes (cylindrical, hetero-conical, conical, spherical and elliptical). Deviations in concentrator rim angle and cavity geometry caused large variation in power profiles inside the cavity receiver. To harness solar energy is the conversion to solar thermal energy (heat absorption) industrial process heat [16, 17]. Jaffe [18] stated methods for calculating and evaluating the performance of parabolic dish solar collectors and their cost/output ratio. After studying this literature, we decided to analyze the performance of circular hyperboloid solar concentrator under different conditions and adjusting the various parameters that influence its performance, it is possible to identify the configurations that offer the highest levels of optical efficiency and to optimize the design of the concentrator to maximize its performance. This can be achieved through a process of trial and error, with the goal of finding the configuration that offers the highest levels of optical efficiency for a given set of conditions. Geometrical changes to circular hyperboloid solar concentrator can include modifying the shape and size of the reflector, changing the material used for the reflector, and adjusting the

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positioning of the reflector relative to the sun. By making these changes and analyzing the effect on the concentrator's performance, it is possible to identify the configurations that offer the highest levels of optical efficiency and to optimize the design of the concentrator to maximize its performance. This optimization process can be achieved through a combination of computer simulations and physical testing, with the goal of identifying the configuration that offers the highest levels of optical efficiency for a given set of conditions. The height of circular hyperboloid solar concentrator can also have an impact on its optical efficiency. In general, increasing the height of the concentrator can increase the concentration ratio and improve its performance. However, there may be practical limits to the height of the concentrator, and the optimal height will depend on the specific conditions under which the concentrator is used.

II. DESIGN METHODOLOGY

The design of the Circular Hyperboloid Model geometry concentrator is based on three main geometrical parameters. The first parameter is a circular entry aperture that directs the solar radiation to enter into the concentrator. In order to capture the maximum collection of light rays, the diameter of the circular entry aperture needs to be optimized based on the acceptance angle of the geometry. The second parameter is a hyperboloid profile slide, which connects the circular entry aperture and the receiver. Based on these two parameters, the configuration of the geometry is named as Circular Hyperboloid Concentrator. The joining of the circular entry aperture and the receiver by a hyperboloid profile generates a smooth geometry.

The equation used for design of circular hyperboloid model $(x^2/a^2) + (y^2/b^2) - (z^2/c^2) = 1$

for design of circular hyperboloid model,

receiver radius $r = a = b$ and

aperture radius $R = A = B$;

Concentration Ratio $CR = Ap / Ar$,

$R = \text{Sqrt of } (CR * r)$;

Ap is aperture area of concentrator $Ap = \pi * R^2$

Ar is receiver area of concentrator $Ar = \pi * r^2$

Notations:

A=B radius of aperture area of concentrator,

a=b radius of receiver area of concentrator

All geometrical models are drafted in CREO CAD software.

A. Modelling the Geometry

Here is a detailed procedure for drawing circular hyperboloid model using CREO drafting software:

1. Launch CREO and create a new part file.
2. Create the receiver base: Select the "Sketcher" workbench and use the "Circle" for circular hyperboloid model to draw circle You can specify the dimensions of the circle using the "Dimension" tool.
3. Create the hyperboloid: Select the "Generative Shape Design" workbench and use the "Sweep" tool to create the hyperboloid. Select the base circle as the profile to sweep and draw a line or curve to use as the path. Set the sweep parameters to create the desired hyperboloid shape.
4. Add any additional features: Use other tools and features to add any additional details or features to the model, such as fillets, chamfers, or cutouts.
5. Switch to the "Drafting" workbench: Select the "Drafting" workbench to create the drawing view of the hyperboloid model.
6. Create a new drawing: Create a new drawing by selecting "File" > "New" > "Drawing."
7. Insert the view: Insert the hyperboloid model view onto the drawing by selecting "Insert" > "Existing Component" > "From Part."
8. Define the view: Define the view by selecting "View" > "Properties." Specify the scale, orientation, and visibility of the view as needed.
9. Add dimensions: Add dimensions to the drawing by selecting the "Dimension" tool and selecting the appropriate points or edges on the hyperboloid model.
10. Add annotations: Add annotations to the drawing by selecting the "Annotation" tool and specifying the text or symbols to include.
11. Save the drawing: Save the drawing file for future use or export it to other software for further analysis or simulation.

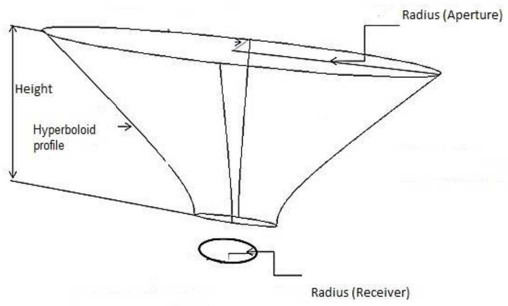

Fig 1: Schematic Sketch of circular hyperboloid model

Table 1. Circular hyperboloid Model Dimension with Various Concentration Ratio

Concentration Ratio	**Receiver Circle**	**Area (mm2)**
	Radius(mm)	π*r2
	100	31400
	Aperture Circle	**Area (mm2)**
	Radius(mm)	π*R2
CR=18	424.26	565200
CR=20	447.21	628000
CR=22	469.04	690800
CR=25	500	785000

III. RAY TRACING PROCEDURE IN ANSYS SPEOS SIMULATION MODULE

Ray tracing and flux distributions were investigated for different solar incidence angle by varying the system parameters such as concentrator height, receiver diameters and concentration ratio.

Here is the detailed procedure for performing ray tracing on an circular hyperboloid model using ANSYS SPEOS is as follows:

1. Create a 3D model of the circular hyperboloid using a CREO drafting software and file save in step file format ie. stp file. This model should include the geometry and material properties of the object, such as its dimensions, shape, and surface reflectance.
2. Import the saved CAD .stp file into ANSYS SPEOS by using the "Import" option in the "File" menu. This will create a new project in ANSYS SPEOS and load the 3D model into the project.
3. Define the properties of the light sources and the irradiance sensor that will be used in the ray tracing simulation. This can be done by selecting the "Light Sources" and "Sensors" options in the "Simulation" menu, and then defining the relevant parameters for each light source and camera.
4. Run the ray tracing simulation in ANSYS SPEOS by selecting the "Direct" option in the "Simulation" menu. This will calculate the paths of the light rays as they interact with the circular hyperboloid and generate an image based on the simulated observations of the virtual sensor and html report generated.
5. Observe the resulting image by selecting the "Results" option in the "Simulation" menu. This will show a realistic rendering of the circular hyperboloid based on the simulated behavior of light rays interacting with the object.

Overall, the detailed procedure for performing ray tracing on an circular hyperboloid model using ANSYS SPEOS involves creating a 3D model, defining the light sources and sensor camera, and running the simulation to generate a realistic rendering of the object.

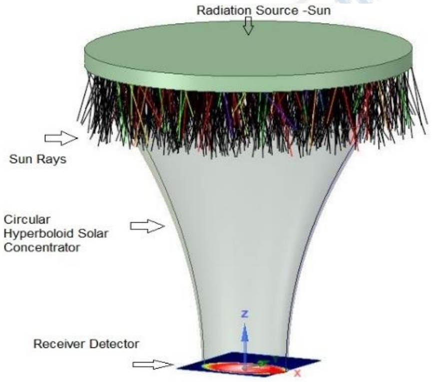

Fig 2: Ray Tracing Procedure in ANSYS SPEOS simulation module

IV. RESULT

The circular hyperboloid geometric profile model is created using CREO software, and ray tracing simulation is done by ANSYS SPEOS module. The internal reflecting material was defined as 86% because of high reflectivity of the reflecting material. In ray tracing simulation ANSYS SPEOS module software, a circle was drawn to create the source of solar radiation. The area of the circle should be higher than the aperture of the concentrator profile. The source of light was defined to be applied at different incident angles on the circular entry aperture of the circular hyperboloid geometric profile. And the source is set up to generate 10 Mega rays, each ray having a uniform radiation intensity of 1200 W/m^2. This energy corresponds to 10000 rays per 1 mm^2 resulting in a light resolution and precision in the ray tracing simulation. The light source in the solar simulation that emits a 5800 K blackbody spectrum. The intensity of the light rays generated by the source is considered as Lambertian. The radiation source and the concentrator geometric profile were drawn in the ray tracing simulation

ANSYS SPEOS module software. The receiver detector is placed at the exit of the circular concentrator to measure the total energy absorbed by the receiver of the circular hyperboloid solar concentrator.

Power at the aperture = 1200 W

Table 2. Circular Hyperboloid Model Height= 800mm

Model		CH01	CH02	CH03	CH04
CR		18x	20x	22x	25x
Absorbed power at receiver (watt) with incident angle	±0	636.3	660.3	672.6	708.8
	±15	168.2	180.3	204.9	216.5
	±30	96.2	96.8	108.5	120.6
	±45	24.3	36.1	36.9	48.6
	±60	9.2	10.5	12.5	15.2
	±75	4.5	5.3	5.9	6.5

Table 3. Circular Hyperboloid Model Height= 900mm

Model		CH05	CH06	CH07	CH08
CR		18x	20x	22x	25x
Absorbed power at receiver (watt) with incident angle	±0	672.3	720.6	780.6	816.5
	±15	192.3	216.5	228.5	252.9
	±30	108.9	120.2	122.6	145.2
	±45	36.2	38.56	49.5	62.5
	±60	13.5	26.1	37.2	49.5
	±75	7.2	12.3	13.6	13.5

Table 4. Circular Hyperboloid Model Height= 1000mm

Model		CH09	CH10	**CH11**	CH12
CR		18x	20x	**22x**	25x
Absorbed power at receiver (watt) with incident angle	±0	793.5	842.3	**936.5**	877.6
	±15	244.6	260.8	**288.6**	278.6
	±30	120.6	135.6	**159.2**	141.2
	±45	38.6	50.2	**73.2**	52.3
	±60	13.4	26.2	**50.1**	39.2
	±75	12.3	14.3	**21.5**	17.5

Table 5. Circular Hyperboloid Model Height= 1100mm

Model		CH13	CH14	CH15	CH16
CR		18x	20x	22x	25x
Absorbed power at receiver (watt) with incident angle	±0	696.3	729.5	790.4	834.5
	±15	194.5	218.5	230.5	255.4
	±30	110.4	123.6	128.4	148.6
	±45	38.5	40.3	51.5	65.2
	±60	14.4	26.5	37.5	48.6
	±75	8.3	13.0	14.5	14.9

After completion of design and ray tracing simulation, the final dimensions and the final results are shown below

Table 6. Circular Hyperboloid Model CH11 (Optically Efficient Model): Height= 1000mm, CR=22x and Ray tracing simulation results

Receiver Circle	**Area (mm^2)**
Radius(mm)	$\pi * r^2$
100	31400

Aperture Circle	**Area (mm^2)**
Radius(mm)	$\pi * R^2$
469.04	690800

Incidence Angle (degree)	Absorbed power (watt)	Optical efficiency (%)
±0	936.5	78
±15	288.6	24
±30	159.2	13
±45	73.2	6
±60	50.1	4
±75	21.5	1

V. CONCLUSION

Circular hyperboloid solar concentrators with different heights, concentration ratios, and acceptance angles of different models can be highly efficient if designed and operated correctly.

By adjusting the acceptance angle, the concentrator can be designed to capture more sunlight during different times of the day or year, improving its efficiency. The optimal configuration for a particular application will depend on several factors, including the location, desired energy output, and weather patterns. Therefore, proper design and operation of the concentrator are crucial to achieve maximum efficiency.

As acceptance angle of solar radiation circular hyperboloid solar concentrators increases from ±0 to ±75, the absorbed power at receiver and optical efficiency decreases drastically. As height of circular hyperboloid solar concentrators increases from 800 mm to 1000 mm, the absorbed power at receiver and optical efficiency increases.

As acceptance angle of solar radiation of circular hyperboloid solar concentrators increases from ±0 to ±75, the absorbed power at receiver and optical efficiency decreases drastically. As height of circular hyperboloid solar concentrators increases from 800mm to 1100mm with different concentration ratio CR 18x,20x,22x,25x, the absorbed power at receiver and optical efficiency increases from height 800 mm to height 1000 mm and CR 22x. and decreases gradually to height 1100 mm. After completion of design and ray tracing simulation, the final dimensions are circular hyperboloid model CH11 (Optically Efficient Model) having height= 1000 mm, CR=22x, receiver dimensions are radius is 100 mm and aperture dimensions are radius is 469.04 mm.

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