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Design and Modeling of Tubular Receiver of a Solar Tower Power Plant

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Abstract- **Energy is the basic need of the world and its growing demand shows that producing energy is one of the major challenges in the world. Renewable energy resources enable us to produce electricity that is clean and plays an important role in decreasing greenhouse gas emissions. The rising costs of fossil fuels and the energy disaster have driven the world into a mission to harness the free and naturally available energy from the sun to generate electrical energy. The solar thermal tower power plant is a type of solar concentrating technology having higher conversion efficiencies due to higher concentrations. The purpose of this paper is to model the receiver of the concentrated solar tower power plant. The design of the receiver is for a 50MW solar thermal tower power plant with water as a working medium. At the start, detailed calculations are carried out to calculate the design parameters of the receiver like diameter, number of panels, number of tubes per panel, etc. Based on these calculations 3D model of these components is developed using the CAD software and assembly of one panel is carried out. panels and their connections are assembled to form the final assembly and the final design is presented.**

Index Terms—**Renewable energy, Concentrating solar energy, Tubular receiver, Solar tower power plant, HTF Simulation.**

I. INTRODUCTION

Fossil fuel resources are diminishing step by step and natural resources are depleting at an increasing pace as globalization and industrialization have developed [1-3]. The search for new energy resources will not only overcome this problem but enhance the process of industrialization. There are different forms of natural resources and some fundamental types are fossil fuel, hydropower, wind power, solar energy, tidal power, and nuclear power. Solar energy is important amongst these as it is a quite abundant and promising form of future energy [4, 5]. There are different techniques to harness this solar energy like photovoltaic and concentrating solar technologies. Among concentrating solar technologies, the solar thermal tower power plant is the most promising and efficient [6, 7].

A. History

The first-ever solar thermal power plant was established in 1968 in Italy, under Professor Giovanni Francia. The similarities of this plant to the recent plant are of having a central receiver, which is encircled by a field of mirrors known as heliostats. In 1982, the United States Department of Energy, with the help of industry partners, put Solar One into action, a 10 MW demonstration project for central receivers. The project has demonstrated the functionalities of the solar tower systems. After four years, in 1986, the largest solar thermal power plant was established in California. The solar field had rows of mirrors that focused solar energy on the tubes in which High Temperature Fluid (HTF) was flowing. The HTF was used to heat the water and generate steam that generated electricity with the help of a turbine.

In 1996, the US Department of Energy, with the coalition of an industrial partner put “Solar Two” in process. “Solar Two” which was the improvement of the “Solar One”, was established in 1999, this plant demonstrated that how solar energy can be greatly utilized and stored even there is no sunlight i.e. in the night or cloudy atmosphere. In June 2010, 34 CSP systems with a total of 880.45 MW were installed worldwide [8].

II. PRINCIPLE AND CLASSIFICATION

The solar thermal power generation can be divided into two categories that are direct and indirect generation as shown in Fig. 2. The most innovative amongst indirect technologies is Concentrated Solar Power (CSP) technologies [9, 10]. In the CSP technologies, the sunlight is focused to a certain point or line to generate very high temperatures.

This heat is absorbed by the HTF and transferred to the working fluid for electricity generation in the power block working on the Rankine cycle, Brayton cycle, or a combined cycle [12-15]. This power generation process is similar to the fossil fuel power plant except the heating source is the sun instead of fossil fuels. Concentrating Solar Power technologies can be of different forms like a parabolic trough, linear Fresnel reflector, solar tower, and parabolic dish engine [16-18]. The solar tower power plant has the following components:

FIGURE 1. External receiver Supcon solar power plant [11]

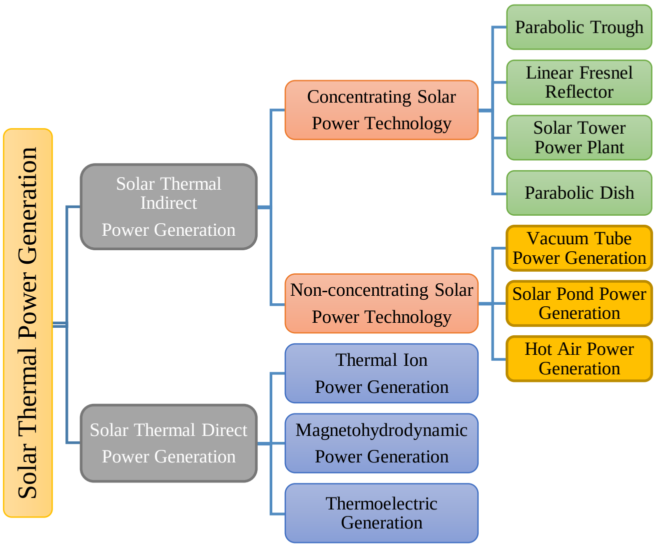

FIGURE 2. Classification of Solar Thermal Power Generation technologies

A. *Solar Tower Power Plant*

The solar tower power plant is the major type of concentrated solar technology having higher efficiencies due to higher concentrations.

1) Working Principle

The solar tower power plant has tracking mirrors called heliostat installed in a field, concentrates the sunlight on the receiver placed on the top of the central tower. Energy absorbed by the receiver generates steam that is then used to run a turbine to generate electricity[19-21].

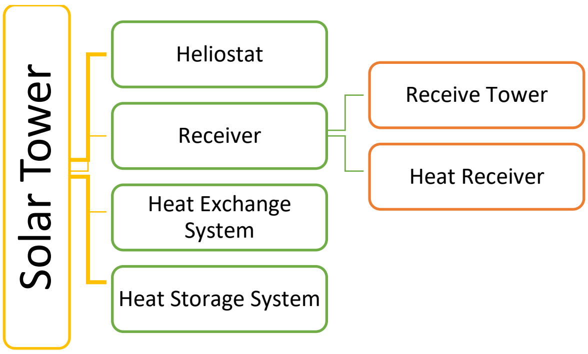

FIGURE 3. System arrangement of the Solar Tower

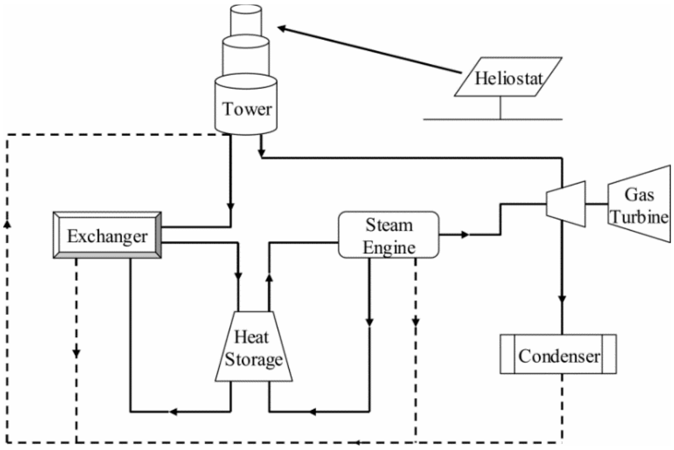

FIGURE 4. Schematic representation of CSP [22]

2) System composition

This system is composed of four main components i.e. Heliostat, Heat storage system, Heat Exchange system, and Receiver. Figure 3 shows the composition of the solar tower power plant [23-26].

3) Schematic representation

Schematic representation of concentrated solar power plant (CSP) is given in Fig. 4.

B. *Receiver*

The receiver is the main part of the solar tower power plant that captures the thermal energy from the heliostats. It plays an important role in the generation of steam [27, 28].

1) Types of receivers

Following are the main types of CSP receivers

a) Volumetric
- (i) Pressurized air receiver
- (ii) Open volumetric air receiver

b) Tubular
- (i) External receiver
- (ii) Cavity receiver

Types of a solar tower receiver are shown in Fig. 5 and Fig. 6, and details are labeled.

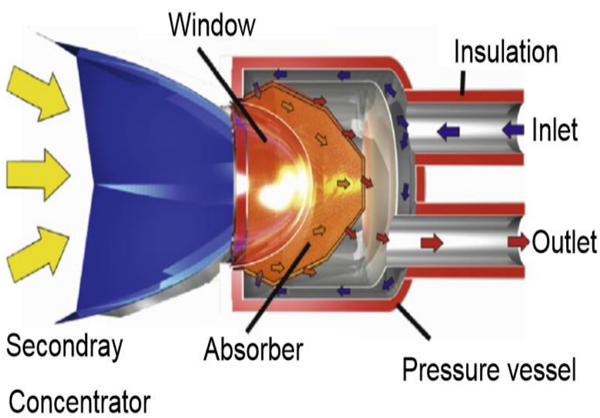

FIGURE 5. Volumetric receiver with details labeled [29]

FIGURE 6. External receiver mounted on tower [30]

C. External cylindrical receiver

The prime focus of this paper is to design and model external cylinder receiver using CAD software. An external receiver is selected due to its wide utilization in the world. An external cylindrical receiver is presented in Fig.6.

III. DESIGN METHODOLOGY

The detailed design methodology is as follows:

A. Input parameters

In this section, first, the factors and their values are declared in Table I and Table II.

B. Design approach

The steps involved in designing the external cylindrical receiver are summarized below and presented in Fig.7.

1) Calculate the thermal power of the incident receiver with the anticipated efficiency of the receiver and receiver output, which was initially declared.

$$Q_{th,rec} = \frac{Q_{rec}}{\eta_{rec}}$$

$$= \frac{50 \times 10^6}{0.9}$$

$$Q_{th,rec} = 55.5 \text{ MW}$$

2) Select receiver fluid. Water in our case.

3) Select the specific heat for the HTF.

4) Select the allowable peak flux limit of the receiver based on the type of HTF. Then, take the average of the values to get the average allowable flux. The average allowable flux of different HTFs materials is given in Table. I.

TABLE I.
THE AVERAGE ALLOWABLE FLUX OF HTF MATERIALS

HTF	Flux limit range	Unit
Molten Salt	0.6 to 1.2	MW/m^2
Water/Steam	0.3 to 0.6	MW/m^2
Liquid Sodium	1.2 to 1.75	MW/m^2

TABLE II.
INPUT PARAMETERS AND DEFAULT VALUES

Name	Symbol	Value	Unit
Heat transfer fluid	-	Water	-
Thermal power of the receiver	Q_{rec}	50	MW
Average flux of receiver	$q_{avg\ flux}$	0.45	MW/m^2
Aspect ratio	A.R	1.5	-
Efficiency of receiver	η_{rec}	90	%
Specific heat of the water	C_p	4185.5	J/kgK
Temperature of HTF at the outlet	$T_{HTF\ hot}$	577	K
Temperature of HTF at the inlet	$T_{HTF\ cold}$	300	K
Density of water	ρ_{water}	1000	kg/m^3
Velocity of fluid	V	4	m/s
Outer Diameter of tube	d_o	23	mm
Thickness of tube	T	1.2	mm
Inner Diameter of tube	d_i	21.8	mm
Number of flow paths	$n_{flowpaths}$	2	-

As our HTF is water so our range is 0.3 to 0.6. If the average of both values is taken the average allowable flux will be

$$q_{avg\ flux} = 0.45\, MW/m^2$$

5) Design the outer body of the receiver with the help of the aspect ratio which is usually taken 1.5 for external cylindrical receivers.

A.R=1.5

6) Select the diameter of the receiver tube so that the efficiency of the receiver is increased and the pressure loss is minimized. The small diameter tends to produce greater efficiency, while on the other hand, it causes pressure losses to increase. It is usually taken 23mm for 40-50 MW.

7) Select the pipe wall thickness that is suitable for the pressure exerted by the liquid on the pipe. A thin wall will result in greater receiver efficiency. Also, it should be able to withstand the pressure. The thickness of the tube is 1.2 mm.

8) Calculate the area of the receiver by using the following formula

$$A_{rec} = \frac{Q_{th,rec}}{q_{avg\ flux}}$$

Substituting values, results will be

$$A_{rec} = \frac{55.5 \times 10^6}{0.45 \times 10^6}$$

$$A_{rec} = 123.33m^2$$

9) Calculate the diameter of the receiver by the formula given below

$$D_{rec} = \left\{\frac{A_{rec}}{\pi \times A.R \times \pi/2}\right\}^{1/2}$$

Substituting values

$$D_{rec} = \left\{\frac{123.33}{\pi \times 1.5 \times \pi/2}\right\}^{1/2}$$

$$D_{rec} = 4.08\ m$$

10) Calculate the height of the receiver by putting values in the below equation

$$H_{rec} = A.R \times D_{rec}$$

$$H_{rec} = 1.5 \times 4.08 = 6.125\ m$$

11) Calculate the mass flow rate by the following equation

$$\dot{m} = \frac{Q_{th,rec} \times \eta_{rec}}{c_p(T_{HTF\ hot} - T_{HTF\ cold})}$$

Substituting values

$$\dot{m} = \frac{55.5 \times 10^6 \times 0.9}{4185.5(577 - 300)}$$

$$\dot{m} = 43.08\ kg/s$$

12) Calculate the cross-sectional area with the help of this formula

$$A_{sec} = \frac{\dot{m}}{\rho \times v}$$

$$A_{sec} = \frac{43.08}{1000 \times 4}$$

$$A_{sec} = 0.01077\ m^2$$

13) Calculate the total number of tubes by the following equation

$$n_{tube,rec} = \frac{\pi \times D_{rec}}{d_{o,tube}}$$

$$n_{tube,rec} = \frac{\pi \times 4.08}{23 \times 10^{-3}}$$

$$n_{tube,rec} = 557.00 \approx 558$$

The number of tubes is rounded to an even number so that no difficultly is faced during the modeling stage.

14) Calculate the number of tubes per panel by the following equation

$$n_{tubes\ per\ panel} = \frac{A_{sec}}{\pi(d_{i,tube}/2)^2 \times n_{flowpaths}}$$

$$n_{tubes\ per\ panel} = \frac{0.01077}{\pi(21.8 \times 10^{-3}/2)^2 \times 2}$$

$$n_{tubes\ per\ panel} = 14.43 \approx 14$$

15) Calculate the number of panels by substituting the values in the following formula

$$n_{panels} = \frac{n_{tube,rec}}{n_{tubes\ per\ panel}}$$

$$n_{panels} = \frac{558}{14}$$

$$n_{panels} = 39.85 \approx 40$$

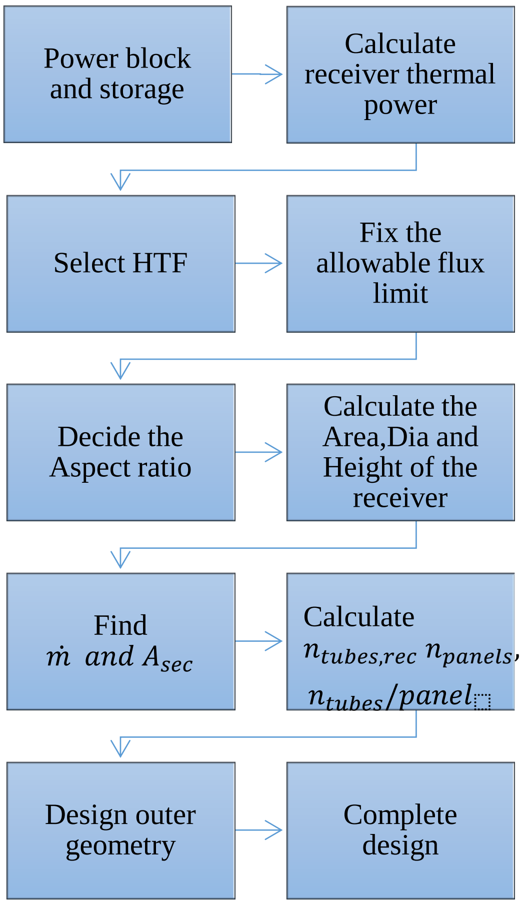

FIGURE 7. Receiver design procedure for tubular receivers

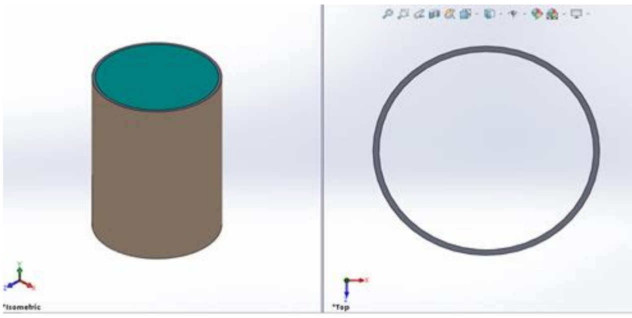

FIGURE 8. Internal body of a tubular receiver

C. Steps to design the tubular receiver

The steps involved in designing a receiver are enlisted in Fig.7.

IV. MODELLING AND ASSEMBLY OF RECEIVER

After calculating all the parameters, the next step is to make the model in CAD software. Parts are made individually and then assembled to generate the receiver 3D model. Description of parts is given below

A. Internal geometry

A central cylinder of height 6.125m and an outer diameter of 4.80m is designed. Suitable thickness is selected.

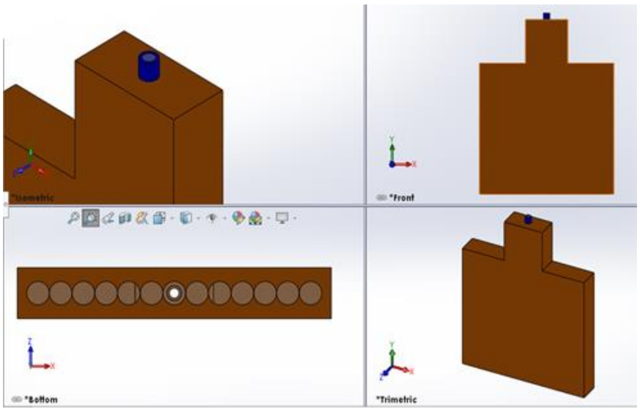

FIGURE 9. HTF inlet and outlet casing

B. HTF inlet and outlet casing

A rectangular panel of width 320mm and height 300 mm is designed. The purpose of this panel is to hold the receiver tubes and carry the fluid from the inlet to the outlet. For this purpose, the shell command is used to make the panel hollow and 14 holes are modeled on the bottom of the panel for the insertion of 14 tubes.

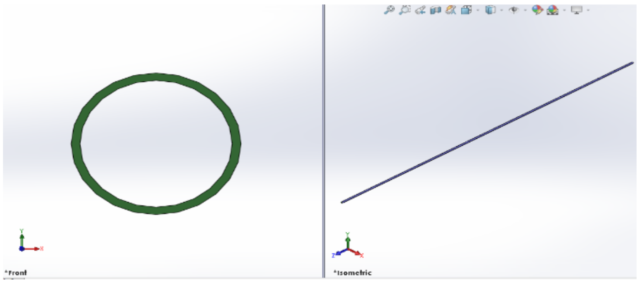

FIGURE 10. Receiver Tube

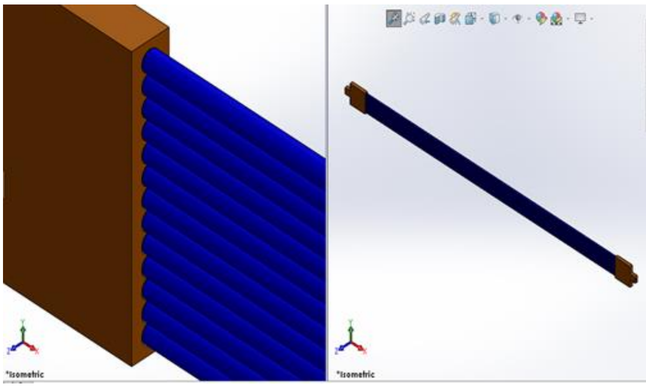

FIGURE 11. Tubes and casing assembly (Panel)

C. Tubes

Tubes of length 6m, the outer diameter of 23.0mm, and thickness 1.2 mm are designed as calculated.

D. Tubes and casing assembly(Panel)

The receiver tubes are assembled with the tube casing to complete the panel. For this purpose, one tube is assembled in the tube casing and a linear pattern is applied.

E. Fluid distributor pipe

A pipe is made for carrying the fluid from the casing of the tube to the single output.

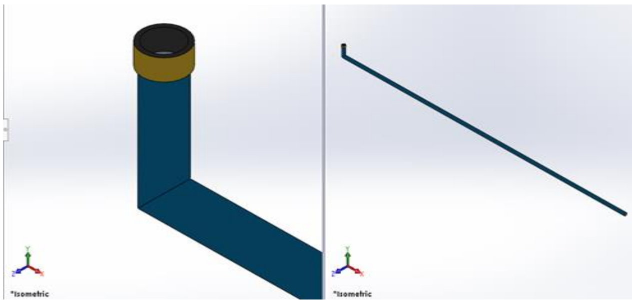

FIGURE 12. Fluid distributor pipe

F. Final receiver assembly

All the parts are joined together to get the final assembly. Some extra connecting parts are added to make the single inlet and outlet.

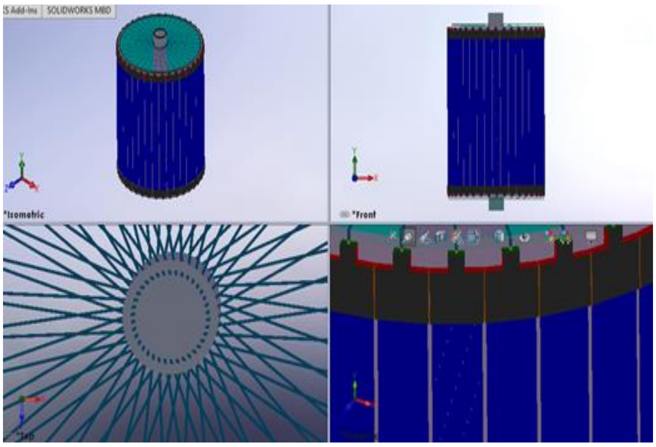

FIGURE 13. External receiver assembly

V. CONCLUSION

External Tube Central Receiver Systems are gaining importance due to their high concentration and high-cost reduction potential by increasing the capacity factor of the system with storage. This article elaborates the solar tower power plant technology, which is considered as one of the most favorable ways to harness solar energy. The technology of the receiver for solar thermal power is outlined and elaborated. A design methodology of a 50 MW solar tower receiver has been anticipated which enables us to design a solar tubular receiver for mega power plants. A procedure was established to design tubular receivers using water as HTF. Detailed calculations are completed and 3D models were developed using the CAD software.

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