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DESIGN OF AN ABSORBER PIPE FOR SOLAR TROUGH COLLECTOR

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Abstract— **this paper presents a review of the design parameters, mathematical techniques and simulations used in the design of trough solar systems, along with a review on their applications. It deals with the design of an absorber pipe for a solar power plant system with trough collector. The pipe is designed for 1 KW power-generating unit accounting for collector performance and ambient parameters in north Sudan.**

It was found that the ambient temperature and wind speed have small effects on the output useful heat required in the present design.

Keywords— **absorber pipe, design, trough collector, useful heat, radiation, concentration**

I. INTRODUCTION

A parabolic trough is a type of solar thermal collector that is straight in one dimension and curved as a parabola in the other two, lined with a polished metal mirror. The sunlight that enters the mirror parallel to its plane of symmetry is focused along the focal line, where objects are positioned that are intended to be heated. In a solar cooker, for example, food is placed at the focal line of a trough, which is cooked when the trough is aimed so the Sun is in its plane of symmetry.

For other purposes, a tube containing a fluid runs the length of the trough at its focal line. The sunlight is concentrated on the tube and the fluid heated to a high temperature by the energy of the sunlight. The hot fluid can be piped to a heat engine, which uses the heat energy to drive machinery, or to generate electricity. This solar energy collector is the most common and best known type of parabolic trough.

When heat transfer fluid is used to heat steam to drive a standard turbine generator, thermal efficiency ranges from 60-80%. The overall efficiency from collector to grid, i.e. (Electrical Output Power)/ (Total Impinging Solar Power) is about 15%, similar to PV (Photovoltaic Cells) but less than Stirling dish concentrators. Large-scale solar thermal power plants need a method for storing the energy, such as a thermocline tank, which uses a mixture of silica sand and quartzite rock to displace a significant portion of the volume in the tank. It is then filled with the heat transfer fluid, typically a molten nitrate salt.

As of 2014, the largest solar thermal power systems using parabolic trough technology include the 354 MW SEGS plants in California, the 280 MW Solana Generating Station with molten salt heat storage, the 250 MW Genesis Solar Energy Project, the Spanish 200 MW Solaben Solar Power Station, and the Andasol 1 solar power station[1] and [2].

Solar energy is one of the promising alternative sources of energy for most of the countries in the world. It may become one of the most important power sources for those countries where sunlight is plentiful, and it is already in practical use in many regions in the globe. In clear weather the sun sends electromagnetic radiation equivalent to 7.95 joules of energy, down to each of square centimeter of earth surface every minute perpendicular to the rays of the sun [3]. This mean that in the tropical countries the sunlight's falling on square kilometer of the ground provide enough energy which could be used to run large power stations if it could well be absorbed and used.

II. SOLAR POWER PLANT USING TROUGH SYSTEM

Trough power plant systems uses linear parabolic concentrators to focus the sun light on receivers tube which are located on the focal line of the concentrator is shown in Fig. 1. Oil is pumped through the tube at constant flow rate, and then delivered to the heat exchanger. The heat exchanger is used as steam generator to drive a conventional steam turbine / generator [4], [5], [6] and [7].

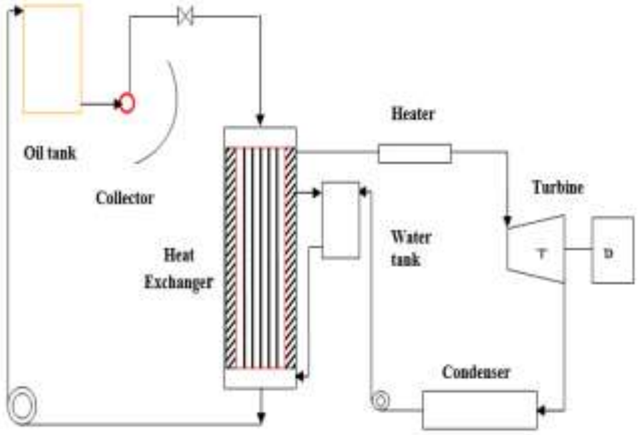

Fig. 1 Solar Power Plant with Trough System

In solar power plant application, it is desirable to deliver energy at high temperature. Energy delivery temperature can be increased by decreasing the area from which heat losses occur. This is done by interposing an optical device between the sources of radiation and the energy-absorbing surface .The collector with parabolic cross section is the most suitable for this purpose.

The size of the collector is proportion to the power required from the system. The width of the collector defines the concentration ratio. This ratio is to be selected to suit the required temperature of the receiver. The length of the collector is limited by maintenance consideration, and other design parameters such as tracking system if it is used. If the pipe is very long the heat capacity that is carried on the fluid passing through it, represents an appreciable factor in energy balances during transient operation. In case that the power required is large, segments collectors may be used.

The collectors are made from sheet metal, steel or aluminum and are supported in steel frame. The collector has reflective surface. As the reflectance of the surface increases, the absorbed energy will increase. Different reflective materials may be used for this purpose .The mirror surface is the best reflective material that can be used, although it is expensive.

III. ABSORBER (RECEIVER)

Different types of receivers may be used with parabolic concentrators. It may be flat, convex, concave or circular tube. The metal circular tube is most suitable receiver type. Black painted copper or stainless steel tube is used for the purpose. It may be covered or uncovered .The covered receiver is usually surrounded by evacuated cylindrical envelope. This will decrease the thermal losses of the absorber surface. On the other hand the covered receiver is regarded to be much expensive.

The outer diameter of the receiver tube is related to the concentration ratio, and the inner diameter defines the flow rate of the oil in the tube.

IV. HEAT TRANSFER OIL

The oil used in solar power plant is a heat carrier, the selection of a suitable oil depends on the following factors:

- Thermal properties, heat capacity, thermal conductivity, viscosity, and density.
- Working temperature.
- Availability and cost.
- Effects to the collector system, i.e. Corrosion.

Heat transfer oil-Shell Thermal oil [4] is used for this design. The properties of this oil are low viscosity, high thermal stability; low volatility .This oil is suitable for use in closed circulating system with back oil temperature up to 320 ^{o}C.

V. ABSORBER PIPE DESIGN

The absorber pipe is a metal tube located at the focus of a cylindrical trough (collector). It receives constant amount of heat from solar radiation. The working fluid passes through it, gain heat from the hot surface by convection. Fig. 2 below shows an Absorber Pipe with Trough Collector.

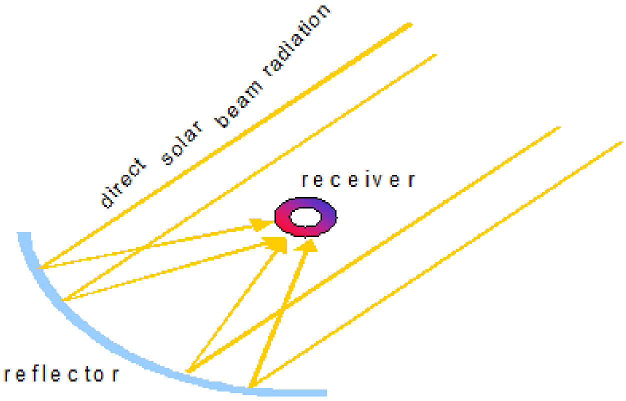

Fig. 2 an Absorber Pipe with Trough Collector

The aim of the design of the absorber pipe is to find suitable dimension for a pipe that could absorb amount of heat enough to generate power of 1KW. This could be achieved when the heat transfer oil is heated from approximate inlet temperature 100 ^{o}C to approximate outlet temperature 200 ^{o}C [4].

The design will be based on the following equations:

$$Q_U = F_R A_a[S-(A_r/A_a)U_L(T_i-T_a)] \qquad (1)$$

$$Q_U = \mathrm{m}C_p(T_o-T_i) \qquad (2)$$

Q_U	Useful heat required
S	Absorbed radiation per Unit area.
A_a/A_r	The concentration ratio
U_L	Overall losses factor
F_R	Heat removal factor
A_a	Reflective area

A. Useful Heat Required (Q_U):

The useful heat required is about (Qu = 3715 W). Consider Losses of heat in the system items such as heat exchanger, turbine, generator and condenser.

B. Absorbed Radiation per Unit Area (S):

The absorbed radiation per unit area is given by the following equation:

$S = Ib.\ \rho\ (\gamma, \tau, \alpha)\ K$

Ib. = beam radiation for concentrator

ρ = Reflectance of concentrator

(γ, τ, α) K = Factor for angle of incidence

For design purposes the approximate average value for S is between 400 to 500 w/m^2.

C. The Concentration Ratio A_a/A_r:

The concentration ratio is the ratio between the area of the aperture and the area of the receiver. This ratio may be used to define the receiver temperature. The ratio 150:1 is selected to give approximate receiver temperature of 500C^0. See Fig. 3 which illustrates the concentration ratio against receiver temperature [3].

D. Overall Losses Factor U_L:

For uncovered receivers the value of overall losses factor U_L could be found from the following equation:

$$U_L = h_w + h_r + U_{cond} \qquad (3)$$

Where, h_w is the coefficient of heat transfer due to the wind .This factor will increase as the wind increases and it can be estimated from the following relations.

$$Nu = 0.3\ Re^{0.6} \qquad (4)$$
$$Re = \rho v d/\mu \qquad (5)$$
$$h_w = \mathrm{Nu} K_f/D_o \qquad (6)$$

For calculating h_w, the properties of the air is taken at the average temperature of the receiver and the ambient.

h_r is the radiation coefficient from the receiver and the ambient and is found from the following equation:

$$h_r = 4\sigma\varepsilon T^3 \qquad (7)$$

Where, T is the receiver surface temperature and is measured in Kelvin.

Fig. 3 below shows the concentration ratio against the receiver temperature [5].

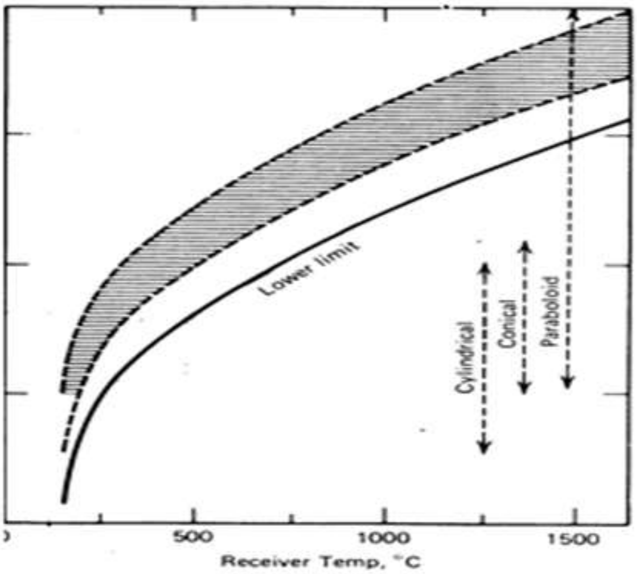

Fig. 3 the Concentration Ratio VS Receiver Temperature

E. Heat Removal Factor F_R:

This factor is calculated from the equation

$$F_R = F_E F_{FF} \qquad (8)$$

Where, F_E is the collector efficiency

$$F_E = U_O/U_L \qquad (9)$$

U_o Is the overall heat transfer coefficient based on the outside diameter of the receiver from the surrounding to the fluid.

$$U_O = \left[1/U_L + D_O/D_i \times h_{fi} + D_O \ln(D_O/D_i)/2K\right]^{-1} \qquad (10)$$

h_{fi} is the inner convection heat transfer coefficient .It depends on the oil flow rate.

For laminar flow in the absorber pipe (Re < 2100)

$$h_{fi} = 0.027(K_f/D_i) \times \mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.33} \qquad (11)$$

F_{FF} is the collector flow factor

$$F_{FF} = \left[\frac{m\ C_p}{A_r U_L F_E}\right]\left[1 - exp\left\{\frac{A_r U_L F_E}{m\ C_p}\right\}\right] \qquad (12)$$

F. Covered Absorber Pipe:

To improve the performance of the absorber pipe. It is usually surrounded by evacuated glass tube. For this case the cover glass tube has less surface temperature than the inner metal tube.

$$U_L = \left[A_r/(h_w + h_{r,r-a})A_a\right] + \left[1/h_{r,c-a}\right] \quad (13)$$

$$h_{r,c-a} = 4\sigma\varepsilon T^3 \quad (14)$$

Where, T is the cover surface temperature in Kelvin**.**

h $_{r,\ r\text{-}c}$ is the radiation heat transfer coefficient between the inner metal tube and glass tube and is given by the following equation:

$$h_{r,r-c} = \left[\frac{\sigma(T_r^2 - T_c^2)(T_r - T_c)}{(1-\varepsilon_1)/\varepsilon_1 + 1/F_{1-2} + (1-\varepsilon_2)A_r/\varepsilon_2 A_c}\right] \quad (15)$$

G. Design Procedure:

- Assume suitable value for concentration ratio.
- Define suitable value for the dimension of the receiver pipe, inner and outer diameter (Selected from standard copper pipe manual).
- Define suitable value for the collector width.
- Define suitable value for the glass tube cover if found.
- Assume suitable value for the collector length.
- Calculate the useful energy Q_U.
- If Q_U is not the required value change the length and recalculate Q_U.
- The dimension of the receiver pipe and collector width may be modified if necessary and Q_U is recalculated.

H. Initial Design Value:

Concentration ratio = 200
Absorber pipe inner diameter = 0.012m
Absorber pipe outer diameter = 0.014m
Diameter glass tube cover = 0.05 m
Width of the collector = 2.4 m
Length of the collector = 6m
Oil flow rate = 0.012 kg/s

I. Design Parameter:

For this design the following values will be considered

Wind speed 3.25 m/s (average value in north Sudan)
Ambient temperature 38 °C (average value in north Sudan)
Surface receiver temperature 350 °C
Cover temperature 54 °C
Property of air 40 °C
Emittance of cover $\varepsilon_1 = 0.88$
Emittance of absorber surface $\varepsilon_2 = 0.9$
Thermal conductivity of copper (K=380 W/m°C)

J. Sample Calculation:

$$\mathrm{Re} = \rho V d/\mu = 0.715 * 3.25 * 0.05 / 2.64E-5 = 8763$$

$$Nu = 0.3\,\mathrm{Re}^{0.8} = 0.3 * 8763^{0.6} = 69.6$$

$$h_w = Nu\,K_f / D_c = 45.5 * .0386 / .05 = 37.9\ W/m^2\ {}^\circ C$$

$$h_{r,r-a} = 4\sigma\varepsilon T^3 = 4 * .88 * 0.567E-8 * 623^3 = 48.26\,W/m^{2\circ}C$$

From equation 6.6.3

$$h_{r,r-c} = 22.46\ w/m^2C$$

From equation (15),

$$h_{r,r-c} = 22.46\ \mathrm{W/m^2}C$$

Absorber pipe area (receiver),

$$\mathrm{A_r = 3.14 * D_o * L = 0.2637m^2}$$

Collector area taking into account the shading of center part

$$\mathrm{A_a = (2.4 - .05)6 = 14.32\ m^2}$$

$$\mathrm{A_r / A_a = 0.2637 / 14.32 = 0.018}$$

$$\mathrm{U_L = [026\ (37.9 + 48.26)*14.432 + 1/22.46] = 20.93\ w/m^2C}$$

$$\mathrm{h_{fi} = 0.027\ (K_f / D_i)(Re)^{0.8}\ Pr^{0.33}}$$

$$\mathrm{h_{fi} = 53.44\ w/m^2C}$$

$$\mathrm{U_o = [1/U_L + D_o / h_{FI} D_i + D_o Ln\ (D_o / D_{IA2} / 2K)]^{-1}}$$

$$\mathrm{= 15.04\ w/m^2C}$$

$$\mathrm{F' = 15.04 / 20.93 = 0.72}$$

$$\mathrm{mcp / A_r U_L F' = 8.45}$$

$$\mathrm{F'' = 8.45\,[1 - Exp\ (-1/8.45)] = 0.94}$$

$$\mathrm{F_R = F'F'' = 0.94 * 0.72 = 0.68}$$

$$\mathrm{Q_U = F_R\,A_a\left[S - (Ar/Aa)\,U_L\,(T_I - T_a)\right]}$$

$$\mathrm{Q_U = 0.68 * 14.32 * (450 - 0.018 * 20.93) * (200 - 38) = 3760\ W}$$

This calculation is programmed on Microsoft Excel Sheet and is shown in table 1.

VI. INFLUENCE OF AMBIENT CONDITION

The design of the absorber pipe is made at the following constant average environmental factors:

Wind speed 3.25 m/s
Ambient temperature 38 °C

These factors vary with geographical locations .This variation will change the useful heat output (Q_U).The variation of the useful heat output (Q_U) with these factor are shown in Tables 1 and 2 and Figs. 4 and 5.The ambient temperature and wind speed have small effects on the output useful heat required in the present design.

Table -1 Variation of the Useful Heat Output (Q_U) with Ambient Temperature

Qu(W)	3802	3819	3839	3851	3864	3877	3898
Ambient Temp.(°C)	16	20	26	30	34	38	42

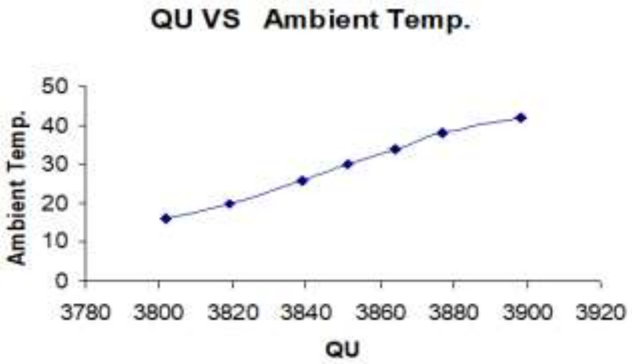

Fig. 4 Variation of the Useful Heat Output (Q_U) with Ambient Temperature

Table -2 Variation of the Useful Heat Output (Q_U) with Wind Speed

Qu(W)	3885	3858	3850	3839	3822	3806	3800
Wind Speed (m/s)	1.8	2.4	2.7	3	3.6	4.2	4.5

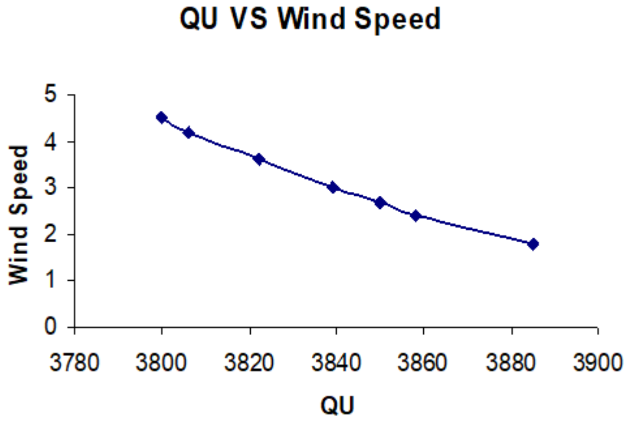

Fig. 5 Variation of the Useful Heat Output (Q_U) with Wind Speed

VII. CONCLUSIONS

For one KW power system the suitable dimensions for the absorber pipe are

Outer diameter	0.014m
Inner diameter	0.012m
Length	6.000m
Glass cover	0.050m

The pipe is made of copper with thermal conductivity 380W/m^oC.

It was found that the ambient temperature and wind speed have small effects on the output useful heat required in the present design.

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