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Design of Parabolic Trough Collector

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Abstract - *The objective of this study is to optimize the design parameters of a parabolic trough solar collector system to maximize its thermal efficiency. Specifically, the project aims to investigate the impact of various factors such as aperture area, geometrical concentration ratio, absorber tube diameter, and tracking mechanism on the performance of the collector. The parabolic trough solar collector, with its wide temperature range up to 400°C, is pivotal in concentrated solar power technology.*

***Key Words*: Parabolic trough solar collector (PTSC), Aperture area, Rim angle, Aperture width, Trough length, Thermal losses.**

1.INTRODUCTION

The parabolic trough solar collector (PTSC) has garnered significant attention among researchers due to its adaptable temperature range, cost-effectiveness, and established commercial status. This paper focuses on exploring the various facets of PTSC technology. Its primary components encompass the reflector, receiver tube, tracking mechanism, working fluid, and structural support system to ensure overall durability.

Fig -1: Parabolic Trough Collector

2. PROBLEM DEFINITION

Large amount of solar energy is not being used and being wasted without utilization. Concentrated solar power is very useful in wide range of applications and parabolic trough collector proves to be a very effective technique of harnessing the solar power.

3.DESCRIPTION

Typically, commercially available collectors vary in aperture area (1–6 m2), geometrical concentration ratio (10–80), and rim angle (70°–120°). The absorber tube, crucial for heat absorption, features varying diameters (2.5 cm to 5 cm) and is often surrounded by a concentric glass cover with a specified annular space. Reflectors, pivotal for optical efficiency, are commonly crafted from materials like highly polished glass, aluminum foil, stainless steel, acrylic mirror, or borosilicate glass. Materials such as aluminum, stainless steel, and copper are preferred, often coated with a selective surface to optimize energy absorption and minimize heat loss. Circulation of the working fluid within the absorber tube, typically done via pumps or blowers, prevents localized overheating. Tracking mechanisms, crucial for directing sunlight onto the absorber surface, range from manual to automatic adjustment systems based on concentration ratios. Conventional fluids like synthetic oil, water, or air are commonly utilized in PTSC-based systems.

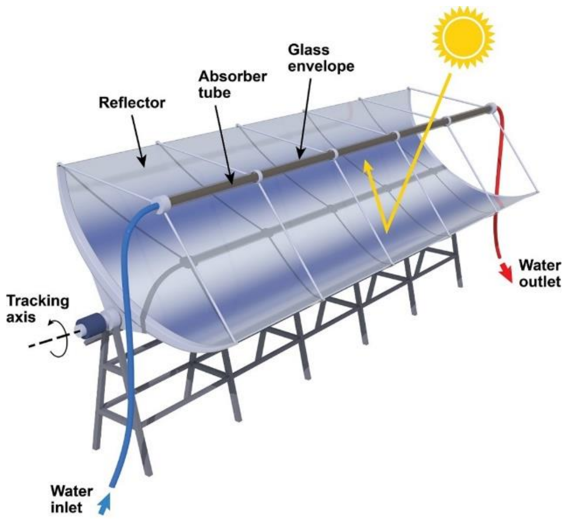

Fig -2: PTC Working

3.CALCULATION FOR PTC.

Assuming aperture width and length,

a = 1 m (aperture width)

l = 2 m (trough length)

$Ap = a * l = 2\ \text{m}^2$ (Aperture area)

Considering rim angle, $\emptyset_r = 96°$

Assuming outside & inside diameter of absorber pipe,

d_o= = 3.75 cm = 0.375 m

d_i = 3.25 cm = 0.325 m

Wall thickness = 0.5 cm = 0.005 m

To find focal length,

$$\frac{a}{f} = \frac{4}{\tan(\phi_r)} + \sqrt{\frac{16}{\tan(\phi_r)^2} + 16}$$

The equation for PTSC depth or height (H) can be obtained by putting $x = \frac{a}{2}$ in the equation of parabola $y = \frac{x^2}{4f}$, Thus we obtain:-

$$H = \frac{a^2}{16f}$$

Now,

Effective aperture area = $(a - d_o) * l(6)$

Surface area of concentrator is given by,

$$A_s = \left\{\frac{a}{2}\sqrt{1 + \frac{a^2}{16f^2}} + 2f\ln\left(\frac{a}{4f} + \sqrt{1 + \frac{a^2}{16f^2}}\right)\right\} \times l$$

Reflector or Trough Radius,

$$r = \frac{2f}{(1 + cos\emptyset_r)}$$

Geometrical concentration ratio (C) is one of the important geometrical parameters for concentrating type of solar collector which remains constant once the system gets manufactured. It signifies the system's ability to concentrate solar energy, and its value varies from unity to 10^5.

$$C = \frac{Effective\ aperture\ area}{Absorber\ tube\ surface\ area} = \frac{((a-do)*l(6))}{\pi * do * L}$$

Theoretical maximum concentration ratio,

$$C_m = \frac{1}{sin(\theta_a)}$$

Where,

θ_a= 0.267^0 (half of the angle subtended by sun on earth)

$$C_m = 215$$

Now, Thermal efficiency of solar collector,

$$\eta_{\text{th}} = \frac{Useful\ energy}{Available\ energy} = \frac{Q_u}{Q_a}$$

Where useful energy is given by,

$$Q_u = \dot{m}C_p(T_o - T_i)$$

Where,

C_p = 4184 JKg^{-1} K^{-1} (Specific capacity of fluid which is water)

ΔT= $(T_o - T_i)$ K

Now here, mass flow rate,

$$\dot{m} = \rho A_{cs}\, u$$

Where,

ρ=Density of fluid (water) = 1000 Kg/m^3

Cross sectional flow area of pipe, $A_{cs} = \pi * r_i^2$

Considering a full flow pipe therefore Hydraulic Diameter (D_h) will be same as absorber tube internal diameter,

$$D_h = 0.03253$$

Wetted perimeter (p) is given by,

$$D_h = \frac{4 * A_{cs}}{p}$$

Now, mass flow rate,

$\dot{m}$= $\rho A_{cs}u = Re * \frac{\mu\pi D_h}{4}$

Considering,

u = average velocity of fluid

ρ = Density of fluid Kg/m^3

Now, Reynold's number is given as

$Re = \frac{\rho u D_h}{\mu}$

Now, useful energy is given by

$$Q_u = \dot{m}\, C_p(T_o - T_i)$$

To Calculate Available Energy,

$$Q_a = A_{ap} * I_b$$

Where,

A_p = Aperture area

I_b = Beam Radiation

Beam Radiation is given as,

$$I_b = I_0\left(A_o + A_1 \times e^{\frac{-k}{\cos(\theta_z)}}\right)$$

Where, A_o, A_1 & k are constants given as

$$A_o = 0.2538 - 0.0063(6 - A'')^2$$

$$A_1 = 0.7678 + 0.0010\,(6 - A'')^2$$

$$k = 0.249 + 0.081\,(2.5 - A'')^2$$

A'' = Altitude of observer in km

Now,

$$I_0 = S\left(1 + 0.33\left(\frac{360 \times n}{365}\right)\right)$$

Where,

I_o = Extra-terrestrial hourly Beam radiation

S = 1367 Wm^{-2} (Solar Constant)

n= 1-365 (A day number in year)

Now, zenith angle is given by,

$$\cos(\theta_z) = sin(\emptyset_r) \times sin(\delta) + cos(\emptyset) \times cos(\delta) \times cos(\omega)$$

Where,

δ = declination angle

ω = hour angle

$\emptyset$ = latitude of location

Also,

Presuming Solar noon at 12 pm , ω = 0° Earth rotates after each hour by 15° ,Therefore if we consider 1 pm than the hour angle will be 15°

Thus with the Aperture area which was assumed as 2 m^2 we will obtain an Available energy Qa in Kw which will be generated in that area having Beam radiation (I_b) whose value will be different according to different locations. Therefore to generate a temperature difference (ΔT), Q_u is useful energy i.e. required Energy.

To generate this required energy, the required Aperture area (Ap) will be,

$$\left(A_p\right)_{Req} = Q_u \times A_p$$

Thus after obtaining the required aperture area, the length to width ratio can be kept or taken as 10:3.

Remaining parameters can be obtained easily from the formulas mentioned above to construct a PTC for required generation of energy.

Now friction factor given by Filonenko relationship,

$$f_f = (0.79 \ln Re - 1.64)^{-2}$$

We know that,

Pr= 6.9 (for water)

Mean fluid temperature is given by,

$$T_{fm} = \frac{T_i + T_o}{2}\ °\mathrm{C}$$

Now from empirical relation of Dittus-Boelter in smooth surface tube,

$$Nusselt\ number(Nu) = 0.023Re^{0.8}\mathrm{Pr}^n$$

Where,

n=0.4 & 0.3 (for heating and cooling fluid respectively)

Applicable for generally: 0.6≤Pr≤ 160 , Re≥ 10^4 and fully developed flow i.e. $\frac{1}{d_i} >$ (10-60).

Mean temperature of tube wall,

$$T_{wm} = \frac{T_i + T_a}{2}\ °\mathrm{C}$$

Now, Nusselt number from Sieder & tater equation for large temperature variation is given by,

$$N_u = 0.027R_e^{0.8}P_r^{1/3}\left(\frac{\mu_{\mathrm{fm}}}{\mu_{\omega m}}\right)^{0.14}$$

Now pressure drop can be calculated with the help of relation with friction factor,

$$f_f = \frac{2\Delta p D_h}{\rho u^2 L}$$

And Head due to friction (h_f) is given by,

$$h_f = \frac{f_f L u^2}{2 g D_h}$$

Now extra power required by pump due to pressure drop is given by,

$$W_p = \frac{\dot{m} \Delta p}{\rho \eta_p}$$

Where,

W_p = extra power required by pump

η_p = isentropic efficiency= 80% (Assumed)

The friction factor can be evaluated & validated with Blasius equation & Filonenko equation,

$$f_f = \frac{0.184}{Re^{0.2}}$$

for, 2 x 10^4 < Re < 2 x 10^6

Now, for convective transfer between fluid and tube, can be evaluated by energy balance equation

$$\dot{m} C_p (T_0 - T_i) = h A_s (T_{wm} - T_{fm})$$

Where A_s= Internal surface area = πD_hL

Optical efficiency is a measure of the extent of the perfectness of the system, which is represented mathematically as follows,

$$\eta_{\text{opt}} = r \gamma T \alpha K(\theta)$$

Where,

r= reflectivity of reflector= 90% (Assumed for aluminum foil)

γ= intercept factor =1 (Assuming 100% of absorber tube is covered by sunlight)

T= transmissivity of cover =80% (for glass)

α= absorptivity of absorber = 1 (black paint)

$K(\theta)$=1

CALCULATING THERMAL LOSSES

From energy balance equation on absorber tube by assuming steady state condition

Absorbed solar heat flux=Useful energy + Thermal losses

$$Q_{ab} = Q_u + Q_l$$

Also absorbed solar heat flux can be evaluated as

$$Q_{ab} = Q_a * \eta_{opt}$$

Therefore, Thermal losses associated with absorber tube exterior surface to envelope interior surface

$$Q_l = Q_c + Q_r$$

Where Q_c and Q_r are heat losses due to convection and radiation respectively

$$\therefore Q_l = h_{a-g}(T_{\omega m} - T_c) c \pi d_0 L + \frac{\sigma \pi d_0 L C T_{\omega m}^4 - T_c^4)}{\frac{1}{\varepsilon_a} + \frac{d_0}{d_c}\left(\frac{1}{\varepsilon_c} - 1\right)}$$

Where, h_{a-g} is the convective coefficient of heat transfer between absorber and glass envelope.

The relationship between h_{a-g} and effective thermal conductivity can be obtained by equating expressions for heat exchange as follows

$$h_{a-g}(T_{\omega m} - T_c) \pi d_0 L = \frac{2\pi K_{\text{eff}} L (T_{\omega m} - T_c)}{\ln\left(\frac{d c_i}{d_0}\right)}$$

Therefore, Heat loss Q_l can be rearranged as

$$Q_l = \frac{2\pi K_{\text{eff}} L (T_{\omega m} - T_c)}{\ln\left(\frac{d_{ci}}{d_0}\right)} + \frac{\sigma \pi d_{ao} L \left(T_{\omega m}^4 - T_c^4\right)}{\frac{1}{\varepsilon_a} + \frac{d_0}{d_{ci}}\left(\frac{1}{\varepsilon_c} - 1\right)}$$

Where,

T_c =Temperature attained by cover = 42°C (at noon assumed)

ε_c= Emissivity of cover = 0.89 (For glass)

ε_a=Emissivity of absorber = 1 (black body)

d_{ci}= Internal diameter of envelope

d_{ao}= External diameter of absorber

d_{co}= External diameter of envelope

σ = Stefan boltzman constant = 5.67 x 10^{-8} W/m^{2}K^4

Here, K_{eff} which is the effective thermal conductivity can be expressed as

$$K_{\text{eff}} = 0.317 k \frac{\ln\left(\frac{d_{ci}}{d_{co}}\right)}{b^{3/4}\left(\frac{1}{d_0^{0.6}} + \frac{1}{d_{\text{ci}}^{0.6}}\right)^{5/4}} Ra^{1/4}$$

Where,

k = 0.7491 (Constant)

b =Radial gap= $\frac{(d_{co}-d_o)}{2}$

The Rayleigh number can be presented as,

$R_a = G_r x\, P_r = \frac{\{g\beta(T_{wm}-T_c)\}b^3}{v^2}$ x P_r

Where, Properties are taken at average temperature $\frac{(T_{wm}+T_c)}{2}$

v = kinematic viscosity of fluid

β = coefficient of volumetric expansion

g = Acceleration due to gravity = ***9.81 m/s²***

Similarly thermal losses from the glass envelope to the environment can be evaluated by,

$$Q_l = h_{g-0}(T_c - T_a)\pi d_{co}L + \sigma\varepsilon_c\pi d_{co}L\left(T_c^4 - T_{sky}^4\right)$$

Where,

T_a= Ambient temperature

T_{sky} = Sky temperature

$$T_{sky} = 0.0553\, T_a^{1.5}$$

The convective coefficient of transfer of heat between glass envelope and environment is obtained as

$$h_{g-0} = 4V_{\text{wind}}^{0.53}\, d_{co}^{-0.42}$$

Where, V_{wind} = 3.7 m/s

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