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Simulation Concentrator type of Compound Parabolic Trough Solar Collector in the Solar Thermal Power Plant (STPP) for Conditions of Iraq

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ABSTRACT

The mathematical model CFD, presented in this study, which was designed to evaluate the performance and characteristics of STPP in Baghdad city (Iraq) with the compound parabolic concentrator (CPC) as a variant of the solar collector. For the purpose of performance analysis and simulations, many expensive and complex programs are usually used, but these tools are directed to perform initial assessments of performance efficiency and feasibility of the project in terms of the output temperature of the solar field and output power generation. To study the solar stations properly, accurate information about the weather, climate and work environment should be available, as well as extensive data on the solar radiation values of the geographical area on which the project will be set up.

Introduction

The increasing fluctuations of oil and gas prices led the countries policy to strive to use free and naturally energy; of course affordable energy from the sun for electricity generation and Iraq is no exception to this trend. The evaluation of performance efficiency and modeling of STPP was carried out for the conditions of Baghdad city with solar local data to determine the possibility of interest from the establishment of such solar plants. This seems clear as stated in the literature [1, 2], some simulation studies have been carried out for parabolic troughs using expensive and complex software packages, as well as prototypes of measurement systems for maximum solar radiation. This model shows the behavior of the system in areas with significant fluctuations in solar activity, particularly solar radiation during the day and these are general characteristics of the tropics regions, and because the solar concentrates type of parabola have exceptional characteristics, proved useful to be used in such areas. The city of Baghdad is located in an area where the solar radiation is variable widely, primarily due to change in climate factors such as clouds, rain, dust, water vapor and other factors [3, 4]. It is known that solar concentrators can receive diffused solar radiation significantly increases the efficiency of solar collectors.

Theoretical Study and Simulation

For this study, theoretical and thermodynamic analysis of the CPC and as well as the absorption tube was performed by mathematical fluid dynamics simulation (CFD): Microsoft Developer Studio (Fortran95) and Tecplot7 program. The results obtained were used in the created model. The molten salt was utilized as heat transfer fluid in the analysis. It is advisable to use heat transfer fluid type VP-1, because it has many advantages: Medium of accumulation heat, chemical stability, the ability to achieve maximum work temperatures [5].

Table 1 shows the initial data for simulation and mathematical modeling. In order to preferable comprehend to solar resources as a wherewithal of energy production and it is necessary to study many of the solar characteristics.

Table 1. Data used in STPP system model.

Variables	Symbol	Values	Unit
Receiver inner diameter	D_i	0,115	m
Receiver outer diameter	D_o	0.125	m
Emittance of receiver	ε_r	0.31	
Emittance of collector	ε_c	0.88	
Length	L	1	m
Wind speed	V	3	m/s
Sky temperature	T_{sky}	2	°C
Air temperature	T_a	10	°C
Collector width	X_{coll}	1.524	m
Collector length	L_c	12	m
Fluid temp entering absorber	T_o	140	° C
Mass flow per collector	$\dot{m}_{coll}$	2	kg/s
Specific Heat (water)	Cp_{water}	4.18	kJ/kg °C
Wind convection coefficient	h_a	300	W/m^2 °C

To know these characteristics, we must expand our knowledge about: use and forecasting of solar radiation data [4]. It is necessary to realize that the most important factors that portray solar energy: Solar insolation and radiation. The density of solar energy, which is measured current, is known as solar radiation and its unit of measured in kilowatt per square meter, and the total amount of solar radiation falling on a given site for a specific period of time is known by solar insolation, that measured in kilowatts or megawatts per square meter per day [6]. Within the atmosphere, the solar radiation may be classified as direct, scattered and total. Radiation reaching the Earth and coming from the sun without dispersion during the passage through the atmosphere is called direct radiation (beam radiation). The type of radiation that is exposed to a change in direction when it is dispersed within the atmosphere and attributed the reason for

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the impact of dust, clouds and particles of water vapor that suspended in the sky called diffuse radiation It is necessary to take into account the kind of solar radiation that the solar thermal power plant can assemble easily and efficiently as well as the availability of its data extensively. Solar concentrators type of parabolic trough collectors need a continuous tracking system for solar radiation because they can benefit only from direct solar radiation, while it is not necessary to provide such tracking systems to the sun in the case of the use of compound parabolic trough collectors because they can collect both types: direct and diffuse solar radiation. There is great similarity between the solar power plants, especially the thermal ones and the conventional stations in terms of operation. The most important difference between them is that the solar plants use concentrated sunlight to produce super heating steam, which is used to rotate the turbine and thus produce electricity instead of fuel such as oil, gas, coal or other types which are used in conventional power stations. In addition, solar radiation is available free to using, it also has disadvantages, notably: being oscillating and uneven in all regions of the earth, and also vary in intensity from one region to another [7]. It is possible to design solar thermal power plant in more than one way, as well as to build and operate them depending on the conditions governing the working environment. Fig. 1 is a diagram of a parabolic STPP.

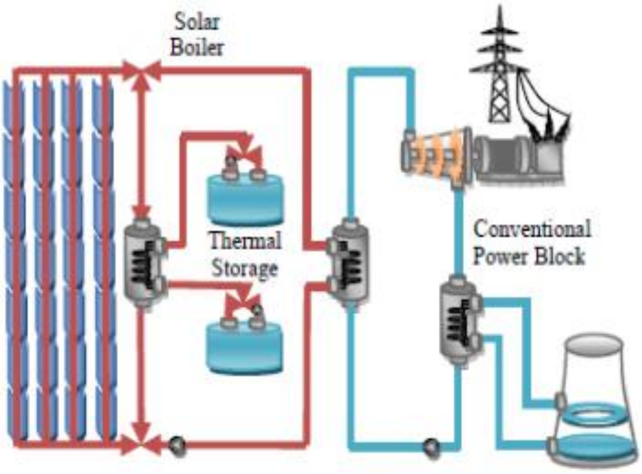

Figure 1. Diagram of a parabolic solar thermal power plant.

Solar thermal power plants comprises the following essential parts: series of collectors and sun tracking system (if necessary), an absorber, a type of fluid work (HTF), a heat transfer devices like as: steam condensers, thermal interchangers, et cetera, thermo mechanical components such as: steam generator and turbine to convert the thermal energy stored in the heat transfer fluid into a mechanical energy to rotate the turbine and then to electric energy by the electric generator and if necessary, in some cases, it is used heat accumulation system for the purpose of operating the solar stations in times of the night or when the weather is not suitable [8, 9]. In 1966 prof. Roland Winston has developed a new type of solar concentrator called the compound parabolic based on a series of studies accomplished in the field of optics without visualization [10]. When using solar concentrates parabola type for the purpose of solar radiation concentration has been observed that these rays do not fall when it reflected in focus, but these solar radiation are located below or above focus in the case of the tilt of these concentrates at an angle different from the angle of the fall of solar radiation, this is evident in Figure 2b, [11, 12]. If half the parabola reflects the radiation above the focal line It has been found a solution to this problem by excluding this part and substitution it by concentrator of a similar shape reversing the solar radiation below the focal line, in this case, the new solar concentrators will focus the solar radiation along the focal lines of the two parts of the parabola, regardless of the angle at which the solar radiation falling. Fig. 2c, can be illustrated the basic structure of the new proposed solar concentrates. The receiving angle θ, It is the angle that can benefit from solar radiation if it falls within it.

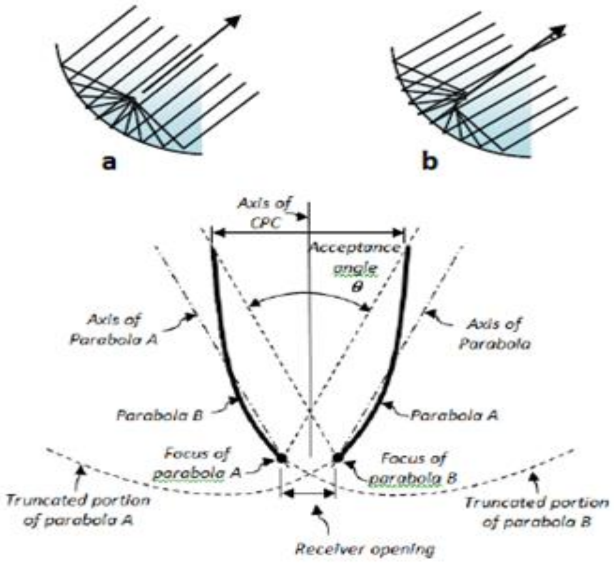

Figure 2. Parabola capturing solar radiation parallel to its axis (a), not parallel to its axis (b) and the basic shape of the CPC.

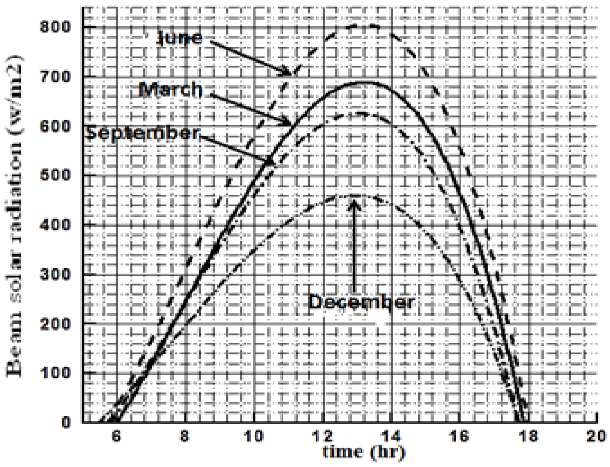

Figure 3. Monthly average of hourly heat gain in collector fields.

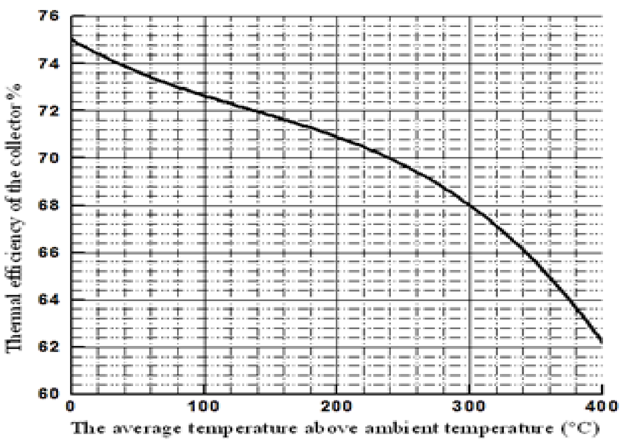

Figure 4. The influence of the average temperature above the ambient temperature in the thermal efficiency of the collector.

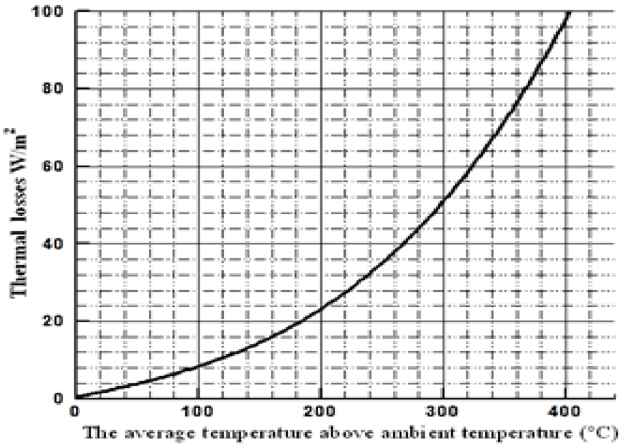

Figure 5. The influence of the average temperature above the ambient temperature in the thermal losses.

Mathematical Model

It is no secret that the solar radiation that falls on the surface of the Earth is very large but low intensity so it is necessary to find a way to use it to generate energy and for this reason should focus this radiation using different types of solar concentrators. The concentration factor of the parabolic trough can be defined according to the second law of thermodynamics as the ratio of inlet area of aperture A_{aper} to the area of aperture in the outlet $A_{receiver}$:

$$CR=\frac{A_{aper}}{A_{receiver}}=\frac{n_{ref}}{\sin 0.5\theta} \quad (1)$$

where n_{ref} is the refractive index, which can approximately be considered equal to 1 for a medium such as air [11].

The optical characteristics of the CPC depend on half-angle concerning the collector that have been clarified previously and whether the solar radiation falls within this angle or not. The theoretical efficiency of a CPC can be evaluate by computing the number of reversals, $\langle n\rangle_i$, which occur to solar radiation before arrival to the absorber. By analyzing the solar radiation that arrives the solar concentrates type of CPC, the number of reversals between the surface reflection and absorption tube is obtained. Mathematical formulas and a set of algebraic relationships can be used to obtain the average number of reversals, which solar radiation is exposed, clearly, the number of reversals depends on a half-acceptance angle of CPC [11]:

$$\langle n\rangle_i=\frac{1}{2}(1+\sin 0.5\theta)\times\left(\frac{\cos 0.5\theta}{\sin^2 0.5\theta}+\ln\frac{(1+\sin 0.5\theta)(1+\cos 0.5\theta)}{\sin 0.5\theta\left(\cos 0.5\theta+\sqrt{2(1+\sin 0.5\theta)}\right)}-\frac{\sqrt{2}\cos 0.5\theta}{(1+\sin 0.5\theta)^{\frac{3}{2}}}\right)-\frac{(1-\sin 0.5\theta(1+2\sin 0.5\theta)}{2\sin^2 0.5\theta} \quad (2)$$

After studying all the relevant factors that relate to the performance of the solar concentrator, It is appropriate to calculate the absorbed solar radiation per square meter of CPC [4]:

$$S=\rho_{cpc}^{\langle n\rangle_i}\alpha_r\tau_r\left(I_{b,cpc}+I_{d,cpc}\right)CR \quad , \quad (3)$$

$$I_{b,cpc}=FI_b\cos 0.5\theta$$

$$I_{d,cpc}=\frac{I_d}{CR} \quad \text{for} \quad (\beta+0.5\theta)<90^o,$$

$$0.5I_d\left(\frac{1}{CR}+\cos\beta\right) \quad \text{for} \quad (\beta+0.5\theta)>90^o, \quad (4)$$

$$(\beta-0.5\theta)\le\tan^{-1}(\tan\theta_z\cos\gamma_s)\le(\beta+0.5) \quad (5)$$

where ρ_{CPC} is the reflection coefficient of the CPC, αr is the coefficient of permeability for the receiver, τr is the absorption coefficient for the receiver, I is the correction factor for the angle of incidence, and F=1 and it is a control function, if the direct solar radiation if fall on the reflector and equal zero If it is incident out and F is a control function, the angle between the axis of collector and the zenith angle is called β.

The thermal losses of solar thermal power plant occurred due to two type of heat transfer are convection and radiation from the collector to the environment, and thermal conductivity, from the collector to the supporting structures, which are very small usually and therefore can be neglected. The metal absorption tube is surrounded by glass cylinder evacuated of air and as a result, there is no heat loss through the metal tube wall.

The coefficient of thermal loss is evaluated using the following mathematical equation [4]:

$$\frac{Q_{loss}}{A_{receiver}}=h_w(T_r-T_a)+\varepsilon\sigma(T_r^4-T_{sky}^4)+U_{cond}(T_r-T_a) \quad (6)$$

$$=(h_w+h_r+U_{cond})(T_r-T_a)=U_L(T_r-T_a)$$

$$\therefore \quad U_L=\frac{Q_{loss}}{A_{receiver}(T_r-T_a)}$$

Where Q_{loss} - heat loss, $A_{receiver}$ - the area of the receiver, T is the temperature, h is the coefficient of convective heat transfer, σ is the Stefan-Boltzmann constant and is equal to 5.67 * 10^{-8} (W/m^2 k^4), ε is the emissivity. The subscripts r and a indicate the reservoir and the ambient, respectively. Thus, to obtain U_L, all other factors of equation (6) must be known. Duffy [4] presented an iterative way for obtaining Q_{loss}. Duffy states that for a certain length of the collector, the heat transfer from the receiver (at T_r) to the inside of the cover (at T_{ci}) through the cover (at T_{co}) and then to the environment (T_a and T_{sky}) is given by the following relationships:

$$Q_{loss}=\frac{2\pi k_{eff}L}{\ln(\frac{D_{ci}}{D_r})}(T_r-T_{ci})+\frac{\pi D_r L\sigma(T_r^4-T_{ci}^4)}{\frac{1}{\varepsilon_r}+\frac{1-\varepsilon_c}{\varepsilon_c}(\frac{D_r}{D_{ci}})} \quad (7)$$

$$Q_{loss}=\frac{2\pi k_c L}{\ln(\frac{D_{co}}{D_{ci}})}(T_{ci}-T_{co}) \quad (8)$$

$$Q_{loss}=\pi D_{co}Lh_w(T_{ci}-T_a)+\varepsilon\pi D_{co}L\sigma(T_{co}^4-T_{sky}^4) \quad (9)$$

Where D is the diameter, L is the length. The subscripts ci, co represents the inner and outer side of the cover, respectively. If the annulus is evacuated, then k_{eff} ≈0 The procedure for solving the previous equations by the iterative method is performed by calculating T_{co}, then estimating Q_{loss} from (9) and substituting this value in (8), calculating T_{ci}. Then, according to (7), the expected T_{co} is checked, by comparing the calculated Q_{loss} by (9) and (7). The external convective coefficient h_w is calculated by simultaneous solution of the following equations [4]:

$$Nu=0.3\,\mathrm{Re}^{0.6}=\frac{h_w D_{co}}{k} \quad (10)$$

where k is the thermal conductivity, and Re is the Reynolds number calculated by the formula:

$$\mathrm{Re}=\frac{\rho VD}{\mu} \quad (11)$$

where ρ is the density of the medium, V is the wind speed and μ is the dynamic viscosity.

Although properties of heat transfer fluid are varies with temperature, It is recommended that always work with an average coefficient of heat transfer, depending on the temperature rate anticipated in the power plant. Under the conditions of turbulent flow for Reynolds number greater than 2200, can be use the following formula to calculate the coefficient of heat transfer fluid. [13].

$$h_{fi} = \frac{Nu\,k}{d} \quad (12)$$

where d is the diameter of the pipe, Nu - Nusselt number, and which can be calculated from the following relation:

$$Nu = 0.025\,\mathrm{Re}^{0.79}\,\mathrm{Pr}^{0.42}\,P \quad (13)$$

assuming p = 1.023, the Prandtl number Pr is determined by the formula:

$$\mathrm{Pr} = \frac{\mu C_p}{k} \quad (14)$$

where, μ, Cp and k: fluid viscosity, specific heat and thermal conductivity, respectively.

Results and Discussions

In the work, a thermal analysis of the CPC was carried out using the programs of the mathematical model CFD. Based on the finite difference method (FDM), the results were used in the simulation of the solar power plant. As a heat transfer fluid, molten salt is used, which provides a number of advantages such as: chemical stability, the possibility of achieving higher operating temperatures and the possibility of using it as a medium for accumulating thermal energy [14]. A calculated analysis of the STPP system was carried out for four months (March, June, September and December) with the calculation of solar and rain weather conditions. Using this data, performance of the system can be observed by evaluating the results obtained from the constructed simulation model. By the model, you can define: solar radiation, the temperature leaving the collector area and the corresponding output power of the system. It is important to recognize that some parameters of the system were considered constant: the mass flow rate of the water and steam, the number of collectors, the mass flow rate and the temperature of the heat transfer fluid. These parameters are carefully controlled in the STPP, which is ensured by means of a control system.

Conclusions

The performance and power of the STPP depends on the weather conditions. In sunny weather, STPP generates maximum energy. When the weather changes (rainy season), the STPP operates in the transitional regime. When the weather conditions fluctuate for 5-10 min, this case the transient processes. If the solar transients last for a long time, for example, an hour or two, (December 2016), the system's performance is significantly reduced, but if the solar transients occur during periods of rain, the power produced by the system drops to almost zero. Some aspects have been studied, but have not been included in the simulation model for simplicity, since in most cases it can be neglected, for example: losses in the piping system, the optical losses of solar collectors, and others. The simulation model was successfully verified using data for the installation of solar energy generating systems SEGS VI presented in [5].

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