International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2018): 7.426

Study of Direct Steam Generation by Parabolic Trough Solar Concentrators

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Abstract: ***The main topic of this work is solar energy which has been used for various applications throughout its history. In 1912, the world's largest solar powered pumping plant to date was built by Frank Shuman and the system was placed in Maadi, Egyp. The plant was shut down in 1915 because of World War I and also due to cheap oil prices. There are many areas beside electricity production where solar energy can be utilized efficiently. Solar thermal energy has been used for water heating purposes in residential appliances for years. Solar energy is one of the renewable technologies which harness the energy of solar irradiance to produce electricity using photovoltaic (PV) or concentrating solar power (CSP), to have heating or cooling (either passive or active) or to meet direct lighting needs. Process heat for industrial use represent a considerable consumer of energy worldwide, almost 30% of total energy demand worldwide is used up by thermal industry processes. A substantial amount of the process heat application is used to generate saturated steam. Solar Direct Steam Generation (DSG) is made possible by solar concentrating technology, and allows for integration with existing fossil based systems. Compared to indirect steam generation, DSG introduces the opportunity of capital cost saving in addition to enhanced performance and lower heat losses. The environmental aspects of not having to use thermal oil in the process are another big advantage of DSG. DSG, however, presents its own challenges regarding the controllability and stability of the system due to the two phase flows in the absorber tube in addition to the dynamics of the steam drum.***

Keywords: Solar Energy, PTC: Parabolic Trough Collector, DSG: Direct Steam Generation, CSP: Concentrating Solar Power, DISS: Direct Solar Systems, INDITEP, MNS: Molten Nitrate Salt, SEGS: Solar Electric Generation System, TES: Thermal Energy Storage, HTF: Heat Transfer Fluid, Shuman Collector.

1. Introduction

Although access to cheap energy has become essential to the functioning of modern economies, several global energy challenges still do exist. Energy challenges such as: energy security and energy access take place due to the fact that the global energy market is dominated by fossil fuels, which are non-renewable and not evenly distributed or accessible to different regions around the world. A formula that is modified from the Klass model approximates fossil fuels reserve depletion times for oil, coal and gas to be 35, 107 and 37 years respectively [1].

Despite the official figures of considerable natural gas exports, Egypt is a net importer of some liquid fuels. Such fuels are imported with the international price yet sold in the local market at a heavily subsidized price which entails a pronounced burden on the economy. In the search for a liquid fuel to fill the gap between supply and consumption, bio-fuels from non-edible oil feed-stock rank high since they are renewable, carbon dioxide neutral and thereby conserve the environment in addition to the fact that they should not be affected, price wise, by the cost of food oils [2].

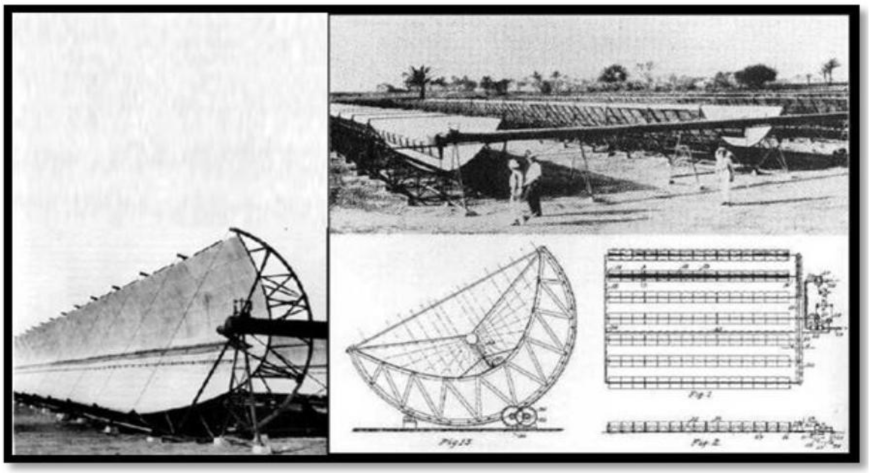

Figure 1.1: First solar thermal facility in Egypt [3]

1) Solar Direct Steam Generation

Direct steam generation (DSG) means that the steam is generated directly in the solar field and not indirectly through the heat transfer from a distinct HTF. Figure 2.6 illustrates a standard DSG steam generation system with its main components. The heat transfer medium that flows through the receivers of the solar field is the working fluid of the Rankin cycle itself. Of course, this working fluid is normally water. Water is, indeed, quite an ideal HTF if we can consider the suitability criteria for HTFs mentioned above. Only the criterion of the high evaporation temperature does not apply, but this criterion is of no importance in the case of direct steam generation, because evaporation is just intended. For small systems and temperature levels below 400°C, however, organic working media may be an alternative; they allow acceptable plant efficiencies also at low operation temperatures.

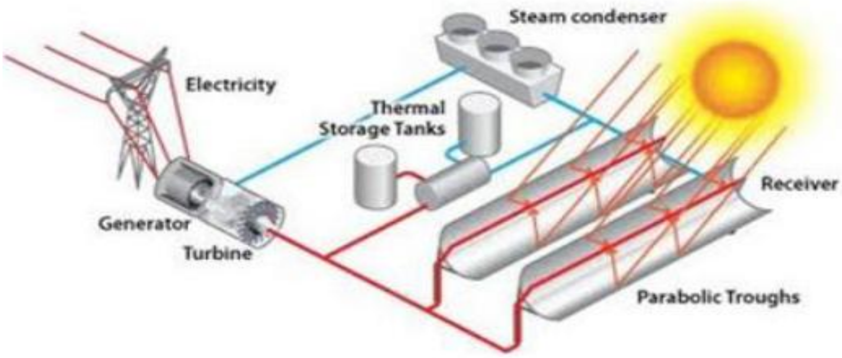

Figure 2.2: Direct steam generation system [6]

2) Direct Steam Generation Techniques

According to [7], a minimum feed flow rate must be guaranteed in the solar field to avoid high temperature gradients in the cross-section of the absorber tubes, so that acceptable flow conditions can be achieved. In order to accomplish this, three different operation modes for producing steam in DSG can be chosen and they are described below. Steam may be produced in the absorber tubes of the PTC in three different ways without causing dangerous temperature gradients. Every option demands different investment costs and offers variants for the overall behavior of the power plant during transients. These three options are once-through mode, injection mode and recirculation mode as illustrated in Figures 3.1, 3.2 and 3.3.

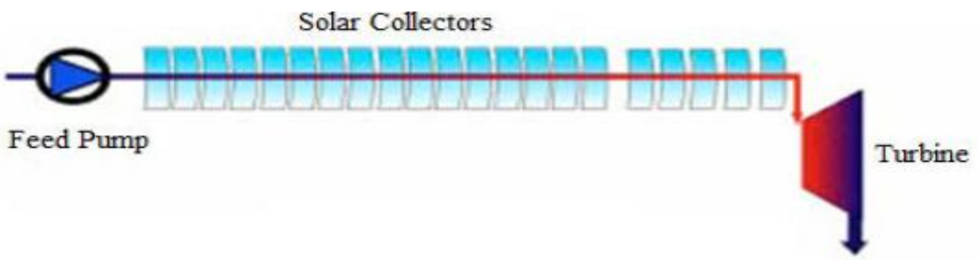

Figure 3.1: Schematic diagram of the once-through mode [].

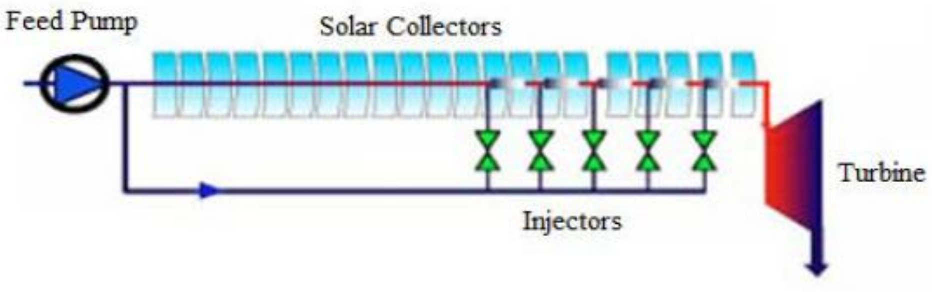

Figure 3.2: Schematic diagram of the injection mode [7].

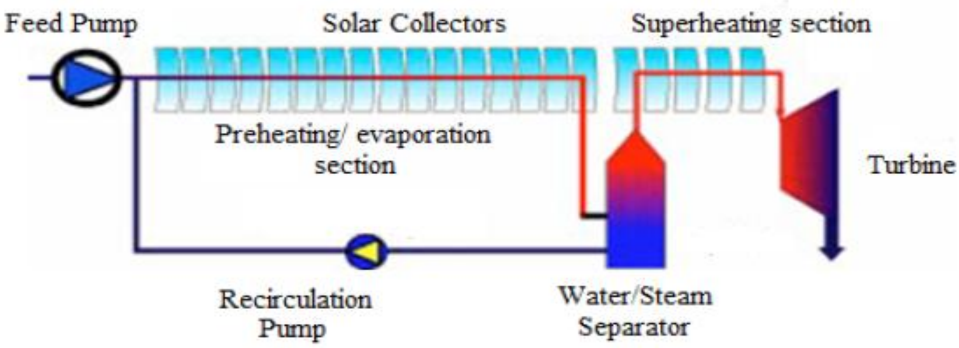

Figure 3.3: Schematic diagram of the recirculation mode [7].

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Table 3.1: Recirculation against once-through and injection concepts

	Recirculation	Once-through	Injection
Advantages	• Very robust operation • Commercially applied • Good controllability • Good flow stability	• Easily scalable • Fast startup • Low investment • Least complexity • Good performance	• Good controllability • Flow stability equally good to recirculation
Drawbacks	• Relatively high investment • Relatively high design effort • Higher complexity	• Not that robust • End of evaporation not fixed • Flow stability is a major issue • Hardest to control	• Higher complexity • Relatively high investment

3) Computer Code

A computer code is developed in order to simulate the same DSG solar collector array simulated in the INDITEP project shown in Figure 4.1. Design point parameters and temperatures of ET-100 collectors used in the model are presented in Table 4.1 and Table 4.2 [8].

As shown in Table 4.3, one collector length is 98.5m and every collector is made of 8 modules having 12.27m in length. In the mathematical model, every module is divided by 10 sub-modules having 1.227m in length. The mathematical code is developed to model a single collector as a sum of 80 sub-modules. It is assumed that every sub-module's absorber temperature is constant throughout the sub-module. One sub-module outlet conditions are equal to the inlet conditions of the continuing sub-module as shown in Figure 4.10. Inlet conditions of one array are taken as the same given in [8], which are shown in Table 5.4.

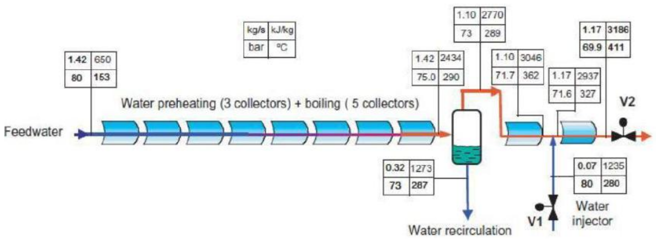

Figure 4.1: Schematic Representation of Solar Array in INDITEP project [8]

Table 4.1: Design point parameters

Direct solar irradiance	875 W/m²
Geographical longitude of the site	W 5° 58'
Geographical latitude of the site	N 37° 24'
Air temperature	20 °C
Incidence angle of solar radiation	13.7°

Table 4.2: Parameters of ET-100 parabolic trough collectors

Overall length of a single collector (m)	98.5
Number of parabolic trough modules per collector	8
Gross length of every module (m)	12.27
Parabola width (m)	5.76
Outer diameter of steel absorber (m)	0.07
Inner diameter of steel absorber pipe (m)	0.055
Length of pipe connecting adjacent collectors (m)	5
Number of 90° elbows between adjacent collectors	4
Number of ball joints between adjacent collectors	4
Net collector aperture per collector (m²)	548.35
Peak optical efficiency	0.765
Cross section of the steel absorber pipes (m²)	2.40E-01
Innner roughness factor of the steel absorber pipes	4.0E-05
Relative roughness of the steel absorber pipes	7.23E-04

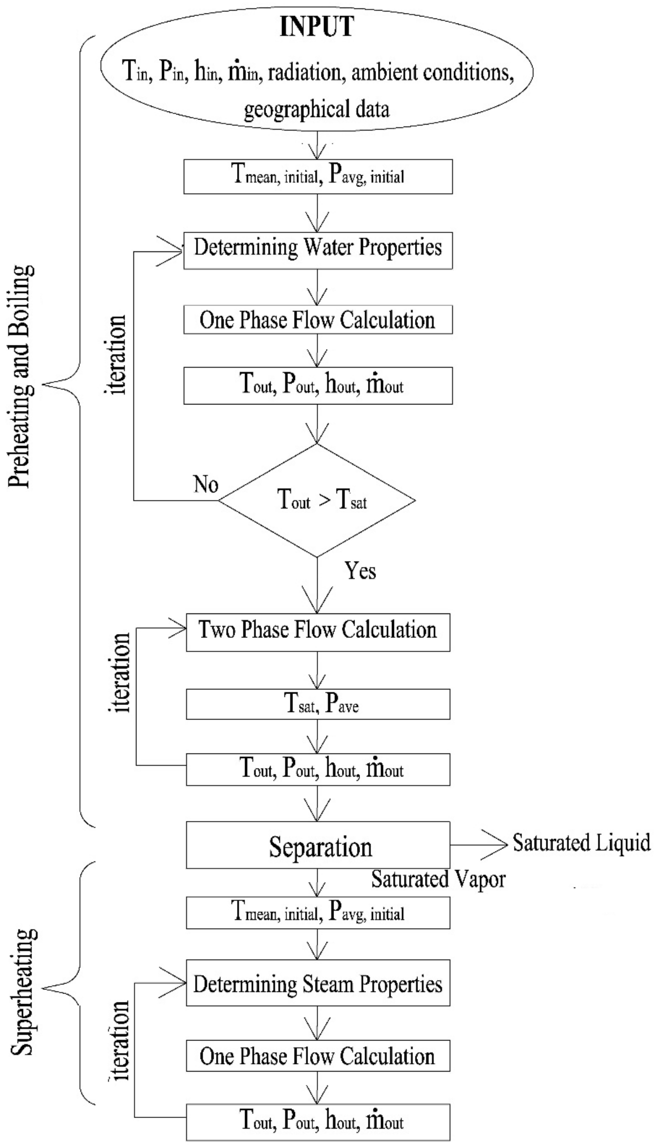

Figure 4.2: Flow chart of the Q-Basic code [8].

2. Results and Discussion

2.1 Introduction

The model presented and benchmarked against the published data in Chapter 2 is used for parametric studies in this chapter. In order to give information about the performance of the solar array simulated for different inlet conditions, simulations are run for different for variable DNI's and working pressures. For the simulations presented in this chapter, all other conditions stated in Chapter 2 are conserved.

It is important to state that the superheating section of the DSG plant is out of this study's scope and not included in the parametric studies. The reason is to neglect water injection to the second superheating collector in order to make a correct comparison.

2.2 Results of Study

For the parametric studies, simulations are performed for working pressures of 20, 30, 50, 70, 100 and 120 bars. All the other parameters are fixed and the same as in Chapter 2. Another parametric study is done for varying DNI from 200W/m^2 to 1000W/m^2 with 200W/m^2 increments. In order to state the amount of steam power produced, the term thermal power is used in this chapter.

$$Thermal\ Power = h_{cond} * \dot{m}_{cond} \ \ldots\ldots (5.1)$$

Another term used in this chapter is efficiency. The efficiency of the entire system is calculated as,

$$\mu_{sys} = \frac{(\dot{m}_{cond} * h_{cond}) - (\dot{m}_{in} * h_{in})}{DNI * \cos\theta * A} \ldots (5.2)$$

In Equation 5.2, A is the sum of aperture areas of all the collectors. The concept of this study is to understand the behavior of a DSG plant under different conditions of operating pressures and various DNI values. The study focused on obtaining the values of both thermal power and efficiency of the produced steam based on different inlet and working conditions.

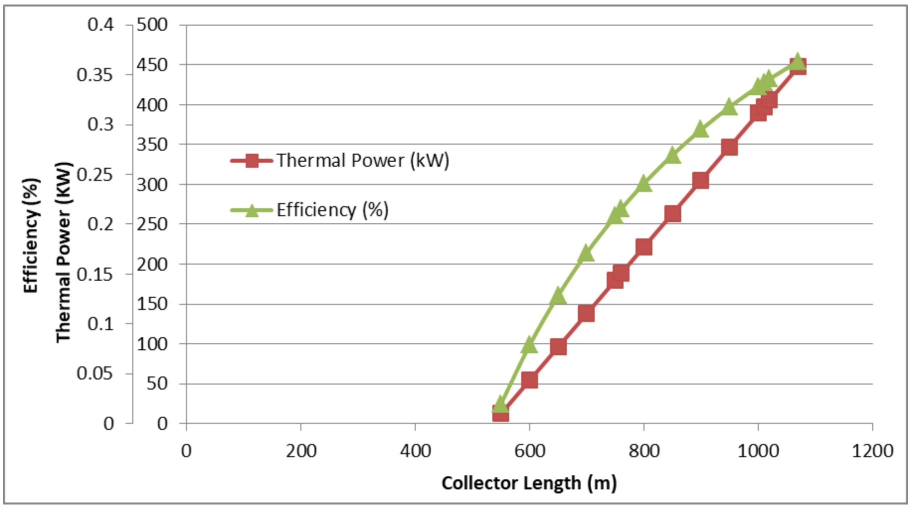

Figure 5.1: Thermal power produced and efficiency for variable collector length at 20 bar inlet pressure and 200 W/m^2 DNI

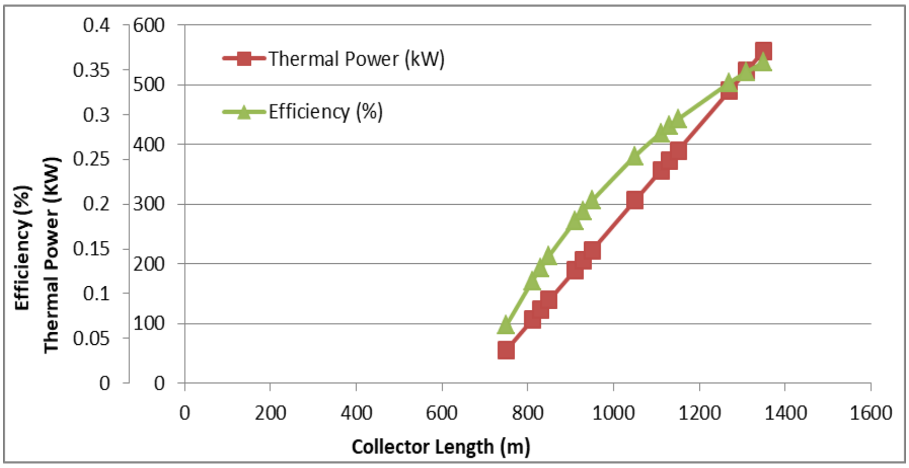

Figure 5.3: Thermal power produced and efficiency for variable collector length at 50 bar inlet pressure and 200 W/m^2 DNI

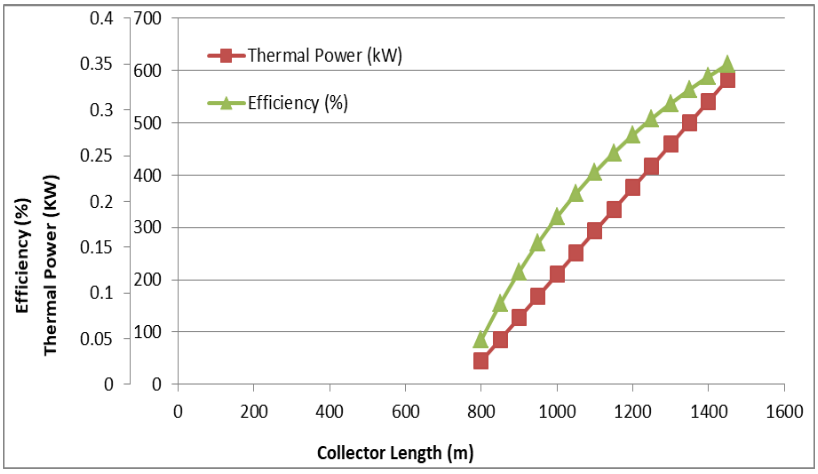

Figure 5.4, thermal power produced and efficiency for variable collector length at 70 bar inlet pressure and 200 W/m^2 DN

3. Conclusions

Based on the results of studying systems of this research. the main conclusions are presented as follows:

1) For the same working pressure within the range choses for this model (20, 30, 50, 70, 100 and 120 bars), the more the value of the solar DNI applied, the lesser total collector length is required to obtain saturated steam. For instance, for a working pressure of 20 bar, at 200W/m^2 DNI a 250m collector tube is required, while for a 1000 W/m^2 only 210m collector tube would be necessary.
2) A higher working pressure for the same solar DNI corresponds with higher efficiency and consequently more saturated steam mass flow rate until it reaches constant value at 50 bar. For instance, a working pressure of 20 bar and 800 W/m^2 produces 0.14Kg/s steam, a working pressure of 30 bar produces 0.18Kg/s and a working pressure of 50 bar produces 0.2Kg/s saturated steam. If we raise the working pressure father it won't have any effect on the flow rate of saturated steam produced.
3) For the same working pressure and solar DNI, the efficiency of the DSG system raises rapidly with increasing the total collector length. For instance, at a working pressure of 50 bar, 200 W/m^2 solar DNI, and a total collector length of 810m the efficiency reached 11.4%. When the total collector length increased to 1350m , the efficiency jumped to 35.87%.
4) For the same working pressure and solar DNI, the produced thermal power increased dramatically with the increase of total collector length. For instance, at a working pressure of 70 bar, 200 W/m^2 solar DNI and 170m collector length the efficiency reached only 9.34%. When the total collector length was raised to 290m , the efficiency increased to be 35.35%.
5) Increasing the working pressure, under the same conditions of solar DNI, corresponds with increasing the required value of total collector length to obtain saturated steam. For instance, at working pressure of 20 bar and 200 W/m^2 the required total length of the collector tube was 1070m. When the working pressure was increased to 30brar, the requitred total length reached 1200m. At a working pressure of 100bar, the required total length of collector tube reached 1500m.
6) The previous point makes us state that for the application of industrial process heat, it is not recommended to raise the working pressure of the DSG system. This may differ when discussing the application of large scale power production.
7) The efficiency of the DSG system designed for the purpose of process heat has an almost constant efficiency no matter the applied working pressure. For instance, at a working pressure of 20 bar and 400 W/m^2, the corresponding efficiency with the total collector length sufficient to produce saturated steam (510m) was 34.72%. At a working pressure of 50bar and 400 W/m^2solar DNI, the efficiency at 680m total collector length was 36.25%.

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