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Transient simulation for developing a combined solar thermal power plant

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A R T I C L E I N F O

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In the present article, performing a transient simulation, power expansion of a solar power plant by integrating a new collector and an auxiliary boiler is studied. The new system consists of an oil cycle, a steam cycle and a new extra oil cycle. For analysis, a computer code is developed and experiments are performed to validate the simulation program. Thermal modeling is employed to select the best capacity of different components and operational control philosophy of the new developed power plant system. Based on the selected conditions, annual power generation of solar part and fossil section are determined and compared with conventional power plants using coal and natural gas. From the results it is shown that the considered method of integration can be used for all fossil fuel power plants to reduce fuel consumption by utilizing parabolic collectors for electricity generation. Comparison of the new system with previous arrangement illustrates that various integration schemes can be easily simulated and an appropriate system to satisfy the main design objectives can be chosen. The advantages of using a new external loop to integrate parabolic solar collectors into the previously constructed fossil fuel system are also discussed.

1. Introduction

Increasing rate of energy demand all around the world is one of the major challenges for further economical and social developments. Green house effects and global warming has made it crucial to devise new green technologies and expand the current rate of renewable energy generation to reduce fossil fuel consumption [1]. Being available in vast areas around the world, solar energy is one of the most important renewable energy sources to comply with the world's growing need for energy. Due to high prices and low efficiencies encountered for developing solar thermal power plants, selecting efficient working philosophies and improving working condition of current power plants are very important to increase power generation and reduce consumption of non renewable energies [2].

A variety of models and approaches toward studying the performances of solar thermal power plants are available in literature. The behavior of a typical 30-MWe SEGS (Solar Electric Generating Systems) plant is studied by Lippke [3]. Based on extensive experimental results on a LS-2 collector, a new solar field model is derived. Price [4] developed a computer model that combines analysis of the performance of a parabolic trough solar power plant with its cost and economic parameters. Patnode [5] developed a model using the TRNSYS simulation program as a computational tool. The power block was separately modeled and also implemented in TRNSYS software. Rolim et al. [6] developed an analytic approach to simulate various parts of a large solar plant. In their study, the energy conversion of solar radiation into thermal power along the absorber tube of a parabolic collector is studied, taking into consideration the nonlinearity of heat losses and its dependence on the local temperature. The conventional Rankine cycle is treated as an endo-reversible Carnot cycle, whereby the mechanical and electric power is calculated.

The main problem of using solar thermal power plants is the unreliability encountered due to variation of environmental conditions such as cloud density and ambient temperature, and technical defects such as tracking errors. These parameters result in oscillations in the plant thermal performance [7]. Due to the unreliability of power generation of solar thermal power plants, different methods have been developed to make these plants more reliable. One of these methods is combining current solar thermal power plants with fossil fuel power generating systems to make solar power plants more reliable and develop hybrid power generating systems. Another approach to develop solar-fossil hybrid power plants is to integrate the current working fossil fuel power plants with solar power systems to reduce the role of fossil fuels in generating electric power. Large scale commercial parabolic trough collectors (PTC) can supply thermal energy that can be used to produce superheated steam for a Rankine steam turbine generator. The PTCs are frequently employed for steam generation in

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Nomenclature

A_c	collector area (m^2)
F_R	collector heat removal factor
h	enthalpy (kJ/kg)
I_t	incident solar radiation (kJ/s m^2)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}_u$	useful energy gain (kJ/s)
T	temperature (°C)
U_L	collector overall loss factor (W/m^2 K)
C_p	heat capacity (kJ/kg K)
k	thermal conductivity (W/m K)

Greek symbols

ΔT	temperature difference (°C)
$(\tau\alpha)_n$	normal transmittance absorptance
η	efficiency
ρ	density (kg/m^3)

Subscripts

set	set point temperature
in	inlet temperature

hybrid systems due to their high thermal efficiency at mid-temperatures (around 300 °C) [8,9]. Recent technological progresses have opened new perspectives for Integrated Solar-Fossil Cycle Systems. On the basis of classical thermo-economic criteria (performance/cost), several integration options are commonly cited [10–15]. These studies are mostly based on developing efficient solar combined cycles with a better fuel conversion efficiency and reducing electricity production costs. Literature shows that less attention has been paid to introducing easily applicable methods for developing current working plants to hybrid systems with slight changes in the original plant. In order to select appropriate components for the design of such developments, an estimate of the performance of the system under different working conditions must be studied both theoretically and experimentally. In this regard Kane et al. [16] performed a study on a small hybrid system. A novel concept of mini-hybrid solar power plant has been partly demonstrated both in laboratory and in situ. Laboratory tests have been also performed on the presented system which has shown adequate behavior over a broad range of conditions including in the presence of large variations of thermal supply. In their study the integration of a thermal diesel engine to the superposed organic Rankine cycles of the thermal solar plant has been successful with reasonable efficiencies considering the relatively low power range. Lentz and Almanza [17] proposed a hybrid solar-geothermal system to increase the steam flow of an existing geothermal cycle and Tao et al. [18] presented the construction and preliminary testing of a prototype combined solar concentration/wind augmentation (CSCWA) system. The performance of hybrid solar-gas absorption systems is also studied by Nguyen et al. [19].

In the current study, expansion of Shiraz solar thermal power plant to a new hybrid and reliable system is investigated both theoretically and experimentally. With extended utilization of a developed transient computer code, this paper investigates a new proposed method of developing solar-fossil hybrid power plants based on integrating the existing fossil fuel power plants with parabolic trough collectors using an external loop. This study shows that all fossil fuel power plants have the potential to be integrated with parabolic trough solar collectors by external loop integration in order to reduce both fossil fuel consumption and CO_2 emission and simultaneously increasing the power generation rate. Furthermore annual performance of Shiraz solar thermal power plant is determined and advantages of using the proposed modification without major changes of the original system are also illustrated.

2. Shiraz solar thermal power plant (STPP)

Shiraz solar thermal power plant is a pilot plant for demonstrating that design can be made and solar energy can be harnessed to generate superheat steam and electricity, and further expansions are possible with experiences developed locally from this plant. The initial design of STPP for 250 kW capacity is installed near Shiraz city, Iran. This plant consists of two cycles: an oil cycle and a Rankine steam cycle. The main collectors' field of this power plant consists of 48 collectors in 8 parallel loops. Experimental study on the installed designed system shows significant fluctuation in STPP steam generation and performance. In order to make this plant more reliable and to increase its capacity, a new large collector and an auxiliary boiler are designed. These elements are integrated into the initial power plant to increase the power generation to 500 kW [20].

3. Modeling

Solar thermal power plants rely on intermittent energy supply (the Sun), therefore it is important to model the plant's performance on a transient basis to understand what the annual performance will be. Stuetzle et al. [21] with a semi transient modeling investigated the set points for optimum operation of 30 MW SEGS VI. Their simulation consists of a dynamic model for the collectors' field and a steady-state model for the power plant. It is used to examine the linear model predictive control strategy for maintaining a specified constant collector outlet temperature at a constant set point (653.9 K) on a summer day and a winter day when the power plant was operating in pure solar mode. García-Barberena et al. [22] evaluated the effect of operational strategies on the performance of a solar thermal power plant using SimulCET code. Special attention is paid to the calculation of the solar field energy stream, as it is exclusive of solar thermal power plants and no storage systems are considered. Vargas et al. [23] developed a simplified mathematical model to numerically simulate transient performance of a solar collector driven water heating and absorption cooling plant system under different operating conditions. The basic thermodynamics problem of how to extract maximum exergy input rate from a solar collector and a gas-fired driven water heating and refrigeration plant has been considered. A transient solar system mathematical model is developed to obtain the system response in time and to calculate the second law efficiency of the entire system as functions of operating and design parameters. Yao et al. [24] performed a transient simulation on the pioneer 1 MW solar thermal central receiver system in China and studied the system performance under different working conditions. The system mainly makes use of a field of heliostats, superheated steam cavity receiver and turbine, thermal storage of oil and water/steam. Several codes have been developed for heliostat field layout design and concentrated solar flux calculation since 1970s. However, much works are needed to adapt those codes to specific features and specific needs of different projects. Thus, Yao et al. developed the code HFLD which is designed to optimize the heliostat field. Examples of similar studies for other solar systems such as desalination plants are available in literature [25,26]. The process of combining transient modeling with experimental measurements toward developing solar systems is widely being used for different solar systems. Shatat and Mahkamov [27] performed an experimental investigation of the performance of a multi-stage water