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Parabolic trough solar collectors integrated with a Kalina cycle for high temperature applications: Energy, exergy and economic analyses

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ABSTRACT

As a promising option for future power generation is the concentrating solar power systems with various types, among which Parabolic Trough Solar Collectors (PTSC) are the most proven technology with lowest cost available today. Benefits of this renewable energy source are challenged by means of relatively low energy conversion efficiency. To overcome the dilemma, one approach is employing an efficient thermodynamic power cycle in order to enhance the overall power plant efficiency. The Kalina cycle (KC) is considered as an efficient alternative over the conventional or organic Rankine cycles in last few years. In the present work, the integration of a novel configuration of the KC, which is proper for utilizing high temperature heat sources, with PTSC is proposed and analyzed. Thermal, thermodynamic and economic models are developed to investigate the integrated system performance from the viewpoints of energy, exergy and economics. The results indicate that, exergy efficiencies of around 64% is achievable for power cycle unit while the overall power plant exergy efficiency reaches to around 14%. The results of economic analysis revealed that if a lower LCOE is to be reached increment of the number of collectors per row is more beneficial than the increment of parallel rows of the collectors.

1. Introduction

Among renewable energy resources, the solar one has received more and more attention in recent years as it is an inexhaustible, safe and clean energy. Over the last decade lots of research works have been devoted to analyze and discuss on different aspects, types and applications of solar energy systems. Solar PV/T systems [1,2], application of solar energy for air-conditioning systems [3–5], comprehensive studies on solar thermal power generation [6,7] and analyzing Concentrating Solar Power technologies (CSP) [8] have been considered in relevant scientific literature. Among different CSP technologies, Parabolic Trough Collectors (PTC) are the most mature and common systems which have been successfully employed in many places around the world [9].

The first solar electricity generation system is built in California in 1980s, since then researches on these systems have experienced great impetus investigating both the solar field and the power generation unit. Thermal modeling and simulation of PTCs is recently conducted by some researchers [10–13], who investigated different aspects of these systems from various perspectives. A detailed thermal model of a PTC is presented by Kalogiro [10] using Engineering Equation Solver (EES) and taking into account all modes of heat transfer. Padilla et al. [11] performed an exergy analysis to investigate the effects of operational and environmental parameters on the performance of PTCs, who found that the highest exergy destruction occurs due to the heat transfer between the sun and the absorber. A novel thermal model for PTCs is developed by Behar et al. [12] and validated using experimental data available from Sandia National Laboratory (SNL) tests with an average uncertainty of 0.64%. Guo and Huai [9] employed a multi-objective optimization to investigate the PTCs based on energy and exergy analyses and concluded that the exergy efficiency of the collector's field can be increased at the expense of heat losses from receiver.

With regards to various power generation units integrated with PTCs a number of papers are published recently. Regarding the available heat source temperature from PTC (up to 400 °C [14]) Organic Rankine Cycles (ORCs) and Kalina cycles (KCs) are two proper choices for power generation in this case and a lot of research papers are published on investigating ORC-based solar power plants. The performance of a low temperature regenerative ORC derived by PTCs is evaluated by Gang et al. [15], who indicated that the overall electrical efficiency of about 8.6% for a solar irradiation of 750 W/m^2 is achievable. They also examined their proposed system performance for different selected areas and assessed the influences of important operating parameters on its performance [16]. Quoilin et al. [17] conducted

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Nomenclature

A	surface area (m^2)
D_{pi}	inside receiver pipe diameter (m)
D_{po}	outside receiver pipe diameter (m)
D_{gi}	inside glass envelope diameter (m)
D_{go}	outside glass envelope diameter (m)
$\dot{E}$	exergy rate (kW)
f_{pi}	fraction factor of the receiver pipe inside
h	convection heat transfer coefficient (W/m^2 K). Specific enthalpy (kJ/kg)
k	thermal conductivity (W/m K)
h_f	HTF convection heat transfer coefficient at T_f (W/m^2 K)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
P	pressure (bar)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K)
T	temperature (°C or K)
T_f	mean (bulk) temperature of HTF (°C or K)
T_{pi}	receiver pipe inside surface temperature (°C or K)
T_{po}	receiver pipe outside surface temperature (°C or K)
T_{gi}	inside glass envelope surface temperature (°C or K)
T_{go}	outside glass envelope surface temperature (°C or K)
$\dot{W}$	power (kW)
X	ammonia mass fraction

Greek symbols

σ	Stefane–Boltzmann constant
ε_{gi}	glass envelope emissivity
ε_{go}	emissivity of the glass envelope outside surface
η_{ex}	second law efficiency
η_P	pump isentropic efficiency
η_T	turbine isentropic efficiency
η_{th}	thermal efficiency

Subscripts and abbreviations

AWM	ammonia–water mixture
CD	condenser
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiance
HTF	Heat Transfer Fluid
EV	evaporator
KC	Kalina cycle
MX	mixer
ORC	Organic Rankine Cycle
P	pump
PP	power plant
PTC	parabolic trough collector
PTSC	parabolic trough solar collectors
RE	recuperator
SEP	separator
SPL	splitter

a thermodynamic analysis of a small scale ORC integrated with PTC for a rural location in Berea District of Lesotho, South Africa. Their results showed that an overall electrical efficiency between 7 and 8% can be reached for a steady state operating condition at a nominal working point. He et al. [18] modeled and analyzed the performance of an ORC integrated with PTC for three organic working fluids including: R113, R123, and pentane and concluded that pentane yields the highest thermal efficiency. The performance of conventional steam Rankine cycle and combined steam Rankine with ORC, from energy and exergy viewpoints, is analyzed and compared by Al-sulaiman [19,20], who reported that the main source of exergy destruction is the solar collector. Chacartegui et al. [21] analyzed the performance of a 5 MW parabolic trough plant integrated with an ORC power block with two different thermal storage systems. They showed that, the indirect storage layout is the most interesting from the viewpoint of LEC (16.19 c €/kW) and productivity (28.2 GWh/y for a 5 MWe plant) for 10 h of storage. Casartelli et al. [22] analyzed the performance of a 5 MWe ORC power plant with PTC for different heat source temperatures and found that toluene is the most suitable working fluid for temperature levels close to 400 °C for which a levelized cost of electricity of 180 €/MWh is calculated. A pilot PTC with a design output of 650 kWth integrated with an ORC is constructed in Louisiana during 2012 and is evaluated under various local weather conditions by Chambers et al. [23]. Their results indicated a thermal efficiency of about 7–8% for the ORC power plant at an average Direct Normal Irradiance (DNI) of 800 W/m^2. Borunda et al. [24] proposed a PTC system coupled with an ORC for cogeneration of heat and power applied to a textile industrial process at medium temperature. Design and thermodynamic modeling of a solar plant with PTC and an ORC unit, being installed in Lesotho, is developed by Quoilin et al. [17] based on experimental data. Using real expander efficiency curves, they showed that an overall electrical efficiency between 7 and 8% is achievable. A simplified transient modeling of an ORC coupled to PTCs is conducted by Bamgbopa and Uzgoren [25], who aimed to assess the ORC response to heat input variations. The performance of an integrated steam Rankine cycle with PTC, in which four different nano-fluids are used to enhance heat transfer in the collector system, is evaluated by Toghyani et al. [26] using energy and exergy analyses. Their results showed that, the overall exergy efficiency of the system when nano-particles are employed can be increased by almost 3–11%. Desai and Bandyopadhyay [27,28] analyzed and compared thermo-economic performance of organic and steam Rankine cycles powered by parabolic trough collectors and linear Fresnel reflectors. They compared different working fluids performance for ORC and concluded that, amongst 12 working fluids for ORC, R113 can achieve the lowest LCOE with a value of 0.344 $/kWh. The performance of a 1 MWe grid-connected solar thermal power plant with PTC is analyzed by Desai et al. [29,30] from the viewpoints of thermodynamics and economics. They investigated the effects of turbine inlet pressure, temperature, solar radiation, plant size, and various cycle configurations on overall efficiency and LCOE and reported an estimated minimum LCOE of about 18.8 ¢/kWh.

The Kalina cycle (KC) is introduced as an ambitious competitor against the ORC for power generation from low and medium temperature heat sources and recently applied for different applications such as geothermal power plants and industrial waste heat recovery [31]. Rodríguez et al. [32] compared the exergetic and economic performance of a KC and an ORC for a low temperature geothermal power plant and reported that the KC generates 18% more power than the ORC with 17.8% lower levelized electricity cost. A comparison between different power cycles for medium temperature geothermal resources is presented by Coskun et al. [33], who found that the KC and the double flash cycle provide the least levelized cost of electricity. The performance of a KC driven by PTC for low temperature heat sources (a turbine inlet temperature of 106 °C) is analyzed by Wang et al. [34] who conducted a parametric analysis from the viewpoint of first law of thermodynamics to examine the effects of some key thermodynamic parameters on the system performance and reported an optimized system efficiency of 8.54%. Later for this configuration of the KC, Ashouri et al. [35] performed an economic analysis and reported that under a typical operating conditions, the system has a levelized cost of