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Exergy analysis of parabolic trough solar collectors integrated with combined steam and organic Rankine cycles

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ABSTRACT

In this paper, detailed exergy analysis of selected thermal power systems driven by parabolic trough solar collectors (PTSCs) is presented. The power is produced using either a steam Rankine cycle (SRC) or a combined cycle, in which the SRC is the topping cycle and an organic Rankine cycle (ORC) is the bottoming cycle. Seven refrigerants for the ORC were examined: R134a, R152a, R290, R407c, R600, R600a, and ammonia. Key exergetic parameters were examined: exergetic efficiency, exergy destruction rate, fuel depletion ratio, irreversibility ratio, and improvement potential. For all the cases considered it was revealed that as the solar irradiation increases, the exergetic efficiency increases. Among the combined cycles examined, the R134a combined cycle demonstrates the best exergetic performance with a maximum exergetic efficiency of 26% followed by the R152a combined cycle with an exergetic efficiency of 25%. Alternatively, the R600a combined cycle has the lowest exergetic efficiency, 20–21%. This study reveals that the main source of exergy destruction is the solar collector where more than 50% of inlet exergy is destructed, or in other words more than 70% of the total destructed exergy. In addition, more than 13% of the inlet exergy is destructed in the evaporator which is equivalent to around 19% of the destructed exergy. Finally, this study reveals that there is an exergetic improvement potential of 75% in the systems considered.

1. Introduction

Utilization of solar energy has become crucial and it is expected to increase significantly in the near future. Therefore, there is a need to improve the performance of thermal power plants integrated with solar thermal energy. Parabolic trough solar collector (PTSC) technology is considered the most established solar thermal technology for power production. It has been used in large power plants since the 1980s in California and has demonstrated a promising renewable energy technology for the future. Hence, this technology has been selected for this study.

A number of papers had examined ORCs integrated with PTSCs for electrical power production, e.g. [1–6]. He et al. [1] considered three organic working fluids, R113, R123, and pentane, for an ORC and found that pentane had the best performance. In another study, Quoilin et al. [2] carried out thermodynamic modeling of a proposed small scale PTSC integrated with an ORC for power production, considering different design options to be located in a rural location in Berea District of Lesotho, South Africa. In a different paper, Bamgbopa and Uzgoren [3] developed a transient model for a simple ORC in which the working fluid was R245fa and found that the heat exchanger was the critical part of the model. In a different study, the performance of a low temperature solar thermal electric system using an ORC and a compound parabolic trough was examined by Gang et al. [4]. It was shown that the overall electrical efficiency was about 8.6% when a solar irradiation of 750 W/m^2 was assumed. They further examined their system for selected cities and considered an improved design of the oil and organic fluid heat exchanger [5]. Derscha et al. [6] carried out a study that compared the performance of integrated solar combined cycle systems (ISCCs) with a solar electric generating system (SEGS) and found that ISCCs provided a better option than SEGS.

A few studies considered integrating ORC with PTSC for cogeneration or trigeneration, e.g. [7–13].

Li et al. [7] assessed the performance of their system for both power and water production through reverse osmosis (RO) and their system had efficiency between 18% and 20%. In a different study, Nafey and Sharaf [8] conducted thermodynamic analysis for both power and water desalination using RO. They selected four refrigerants for the PTSC case: dodecane, nonane, octane, and toluene and found that toluene was the best option. In another study, Sharaf et al. [9] conducted thermo-economic analysis of PTSC integrated with an ORC and a multi-effect distillation. Two scenarios of generation were considered in their study: the first one was with only water production and the second one was with both power

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Nomenclature

A_{ap}	aperture area, m^2
A_c	area of the receiver cover, m^2
A_r	area of the receiver, m^2
Cp	specific heat, kJ/kg K
Col_s	total number of solar modules per single row (in series)
Col_r	total number of solar collectors rows
D	diameter, m
ex	specific exergy, kJ/kg
Ex	exergy, kW
Ex_d	exergy destruction, kW
F_R	heat removal factor
F_1	collector efficiency factor
G_b	solar radiation intensity, W/m^2
h	enthalpy, kJ/kg
HTF	heat transfer fluid
h_c	convection heat coefficient, kW/m^2 K
h_r	radiation heat coefficient, kW/m^2 K
IP	exergetic improvement potential, kW
k	thermal conductivity, kW/m
$\dot{m}_r$	mass flow rate through the receivers in one row, kg/s
$\dot{m}_{rt}$	total mass flow rate though all receivers in parallel, kg/s
$\dot{m}_{st}$	mass flow rate in the steam Rankine cycle, kg/s
Nus	Nusselt number
ORC	organic Rankine cycle
P	pressure, kPa
Pv	vapor pressure, kPa
$\dot{Q}$	heat rate, kW
$\dot{Q}_{u,o}$	overall useful heat rate through all the collectors, kW
S	entropy, kJ/kg
SRC	steam Rankine cycle
SRC-A	steam Rankine cycle with atmospheric condensing pressure
SRC-V	steam Rankine cycle with vacuum condensing pressure
T	temperature, K
T_s	temperature of the sun, K
U_o	overall heat loss coefficient, kW/K
U_L	solar collector heat loss coefficient between the ambient and receiver, kW/K
v	velocity, m/s
w	collector width, m
Y_D	exergetic fuel depletion ratio
$Y_D{}^*$	irreversibility ratio
z	height (elevation), m

Greek letters

α	absorbance of the receiver
η	efficiency
ϵ_{cv}	emittance of the receiver cover
ϵ_r	emittance of the receiver
γ	intercept factor
K_γ	incidence angle modifier
σ	Stefan–Boltzmann constant, kW/m^2 K^4
ρ_c	reflectance of the mirror
τ	transmittance of the glass cover

Subscripts

0	atmospheric conditions
d	destruction
el	electrical power
ev	evaporator
ex	exergy
g	generator
i	inlet
j	property value at state j
o	organic
op	ORC pump
ot	ORC turbine
r	receiver
rt	all the receivers (collectors in parallel)
st	steam
u	useful

and water production. It was found that the first option is more attractive. Delgado-Torres and García-Rodríguez [10,11] conducted thermodynamic analysis of a thermal system consists of an ORC, a PTSC, and an RO. Initially, they analyzed the system assuming only water production through RO [10] and then they extended their study to include both electrical and water production [11]. The main objective of their study [11] was to examine the effect of different organic fluids on the aperture area of the PTSC. In another study, the energetic performance of PTSC integrated with an ORC in which the waste heat from the ORC is used for cogeneration was conducted by Al-Sulaiman et al. [12]. It was found that there was an energy efficiency improvement, when trigeneration was used, from 15% to 94% (utilization efficiency). On the other hand, using exergy analysis, Al-Sulaiman et al. [13] found that there was an exergetic efficiency improvement from 8% to 20% when trigeneration is used as compared to only power generation. Al-Sulaiman [14] conducted energy analysis of PTSC integrated with a steam Rankine cycle as a topping cycle and an ORC as a bottoming cycle. His study considered the energetic performance of his system and the effect of selected parameters on the size of the solar collector field.

It can be observed from the literature review that there is no exergy analysis that has been conducted on parabolic trough solar collectors integrated with combined steam and organic Rankine cycles. Furthermore, with fossil fuel depletion and significant increment of CO_2 emissions, finding an improved thermal power system driven by a renewable energy, such as solar energy, is becoming more crucial. Therefore, the current study is original and of significant importance. The objective of the current study is to examine, in detail, the exergetic performance of a thermal power system driven by parabolic trough solar collectors that are integrated with combined steam and organic Rankine cycles. The steam Rankine cycle (SRC) is the topping cycle while the ORC is the bottoming cycle. Severn refrigerants for the ORC were considered: R134a, R152a, R290, R407c, R600, R600a, and ammonia. In this study, key exergetic parameters are examined: exergetic efficiency, exergy destruction rate, fuel depletion ratio, irreversibility ratio, and improvement potential.

2. System descriptions

The current study considers two systems. The first one is a PTSC integrated with an SRC, as shown in Fig. 1. Two operating conditions were considered for this system: vacuum condensing pressure and atmospheric condensing pressure. The second system is a combined vapor cycle, which is similar to the first; however, an ORC, as a bottoming cycle, is integrated with SRC that has condensing atmospheric pressure (SRC-A), as a topping cycle, as shown in Fig. 2. The ORC is integrated with an SRC-A since there is a