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Organic Rankine Cycle coupling with a Parabolic Trough Solar Power Plant for cogeneration and industrial processes

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ABSTRACT

Over the last 25 years solar power plants based on parabolic trough concentrators have been developed for the commercial power industry. On the other hand, in recent years, a way to harness the solar energy is to cogenerate through Concentrated Solar Power (CSP) technology coupled to an Organic Rankine Cycle (ORC) with potential applications to industrial processes. In this work we present a study of a small CSP plant coupled to an ORC with a novel configuration since useful energy is directly used to feed the power block and to charge the thermal storage. In order to analyze this novel configuration we consider a case study with cogeneration applied to textile industrial process at medium temperature. It turns out that this configuration reduces the size of the thermal storage disposal. The performance of the solar power plant was simulated with TRNSYS to emulate real operating conditions. We show the design, study and simulation results, including the production and efficiency curves for our load profile. Our results show that our system is a promising option for applications to medium temperature processes where electrical and heat generation is required.

1. Introduction

Currently the technological development of thermal generation plants and electric power recorded a preview and amazing flexibility. Multiple generation, *i.e.* the combined generation of mechanical and thermal power (low, medium and high temperature) using fossil fuels and/or renewable energy multiplies rapidly, not only with high energy and exergy efficiencies but with very attractive economic returns and low environmental impacts.

In a few years, the large and medium users, public and private, have the possibility of having a diverse portfolio of energy with final prices depending on the season, from treasury weather and conditions of supply and demand exist, converting these energy systems in large energy and financial markets, as a necessary stage of the energy transition we experience. The incorporation of solar energy as a primary energy source in multiple generation will be key in these emerging markets, regardless of whether a country has abundant solar resources or not, because these markets will be carried over geographical boundaries, even for long distances between producers and consumers.

A parabolic trough concentrator (PTC) is a promising solar concentration technology to integrate solar energy as primary energy source. This technology converts the solar beam radiation into thermal energy in their linear focus receiver. PTC applications can be divided into two main groups. The first and most developed is Concentrated Solar Power (CSP) Plants. This technology is one of the main renewable energy alternatives for the production of electricity by solar power plants where the Rankine cycle is a common technology employed for commercial projects in the capacity range from 10 MWe to 90 MWe, and the operating temperature reached is in the range from 300 to 400 °C. CSP projects have recently become more economically appealing due to the improvements in concentrated solar power technology and cost. In particular, power plants with CSP and Organic Rankine Cycle, ORC, technologies have become a profitable choice due to the high performance, reliable and easy to use ORC power block units supplied by many worldwide manufacturers offering simple operation and low cost maintenance. Nonetheless, the question of the optimum Rankine cycle capacity remains an open issue. The second group is meant to provide thermal energy to applications that require temperatures between 85 and 250 °C. These applications use primarily industrial process heat, such as cleaning, drying,

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Symbols

A	total collector area
$AH1$	energy from auxiliary heater 1
$AH2$	energy from auxiliary heater 2
Auxiliary input	power from auxiliary sources
I_{beam}	beam solar radiation
C_p	Specific heat
E	energy
E'	energy stored typical configuration
Ex	exergy
f_{solar}	solar fraction
G	incident radiation
h	enthalpy
Q	energy
$\dot{Q}$	energy by unit time
IncRad	incident radiation on the collector
IR	irreversibility
N	number of collectors
m	mass
$\dot{m}$	mass flow rate
P	power
P	pressure
s	entropy
S_{gen}	entropy generation rate
Solar input	power from solar source
T	temperature
t	time
V_{tank}	volume of the storage tank
V'_{tank}	volume of the storage typical configuration
$\dot{W}$	power
ΔT	temperature difference
ρ	density of the heat transfer fluid
η	efficiency
η_{II}	second law efficiency

Subscripts

charging	charging
col	collector field
cool	cooler
CS	solar collector field subsystem
CSo	parabolic arrangement and storage
e	electric
ex	exchanger
dest	destroyed
Dis	discharging
in	inlet
lost	lost
max	maximum
min	minimum
oil	therminol 55
ORC	ORC power block
out	outlet
rec	recovered
s	solar, sun
st	storage
plant	plant
pump	pump
t	plant
tank	tank
TES	thermal storage tank
turbine	turbine
U	usefull from parabolic arrangement
AH1	auxiliary heater 1
AH2	auxiliary heater 2
Δ	changes

evaporation, distillation, pasteurization, sterilization, cooking, among others, as well as applications with low-temperature heat demand and high consumption rates (domestic hot water, space heating and swimming pool heating), and heat-driven refrigeration and cooling. However, one of the aims of solar-thermal engineering is to develop collectors that are suitable for applications in the temperature range between 85 and 250 °C. Up to now only very limited experience exists for this temperature interval [1–3].

In the literature some researches have addressed the study of small-scale solar thermal power combining heat and power (CHP) systems by using solar thermal collectors coupled to an Organic Rankine Cycle (ORC) heat engine. In the following, we present a brief review of literature related to the generation of thermal energy with solar ORC.

In 2010, Delgado-Torres and García-Rodríguez [4] estudied twelve substances as working fluids of the ORC and four different models of stationary solar collectors (flat plate collectors, compound parabolic collectors and evacuated tube collectors) were considered. They determined the operating conditions of the solar ORC that minimizes the aperture area needed per unit of mechanical power output of the solar cycle for each working fluid and each solar collector. Their results can be usefull in technoeconomic analysis, selection of working fluids of the Rankine cycle, sizing of systems and assessment of solar power cycle configuration. In the same year, Jing et al. [5] reported a low temperature solar thermal electric generation system that consists of a compound parabolic concentrators (CPC) and a ORC working with HCFC-123. They established the optimization of the system by considering the connection between the heat exchangers and CPC collectors, the tilt angle adjustment and the ORC evaporation temperature.

In 2011, Quoilin et al. [18] described the design of a solar ORC for rural electrification purposes. The system consisted of parabolic trough collectors, a storage tank, and a small-scale ORC engine using scroll expanders. They developed a model of each component based on experimental data for the main key components. They established a model for sizing the different components of the cycle and they evaluated the performance of the system. In their study, different working fluids were compared, and two different expansion machine configurations were simulated (single and double stage).

In 2012, Ya-Ling He et al. [6] developed a model for a typical parabolic trough solar thermal power generation system with ORC. They studied the system by using the transient energy simulation package TRNSYS [16]. They considered in their modeling the integration of several submodels for the trough collector system, a single-tank thermal storage system, an auxiliary power system and the heat-electricity conversion system. On basis of their modeling procedure they examined the influences of several designing and operating parameters on the performance of the collector field as well as the whole system. In the same year, Fahad A. Al-Sulaiman et al. reported the performance assessment of a novel system based on parabolic trough solar collectors and an Organic Rankine Cycle for combined cooling, heating and power (CCHP) [17]. They considered in their study that a portion of waste heat is used for heating through a heat exchanger and the other portion is used for cooling through a single-effect absorption chiller. They reported three modes of operation: a solar mode, which is characterized by a