Applied Energy 165 (2016) 627–638

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Analysis of a novel solar electricity generation system using cascade Rankine cycle and steam screw expander

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HIGHLIGHTS

- Solar power system using SORC and steam screw expander is original.
- Technical requirements are reduced.
- Efficiency of 15.62% is achieved.

ARTICLE INFO

Article history:
Received 2 August 2015
Received in revised form 9 December 2015
Accepted 17 December 2015
Available online 7 January 2016

Keywords:
Screw expander
Solar electricity generation system
Steam Rankine cycle
Organic Rankine cycle
Pressure ratio

ABSTRACT

A novel solar electricity generation system (SEGS) using cascade cycle is proposed. The top and the bottom are steam Rankine cycle (SRC) and organic Rankine cycle (ORC). Particulary, screw expander (SE), which is characterized by good applicability in power conversion with steam–liquid mixture, is employed in the SRC. Steam is generated directly in the parabolic trough collectors (PTC) and expands in the SE. The heat released by steam condensation is used to drive the ORC. This type of SEGS has the advantages of avoidance of superheated steam, moderate operating temperature and pressure, low technical requirements in heat collection and storage, and suitableness for distributed power generation. Simulation of the system performance is conducted on the use of ten ORC fluids. Four hot/cold side temperatures of 473/313 K, 473/293 K, 523/313 K and 523/293 K are exemplified. The results indicate the ORC evaporation temperature corresponding to theoretical maximum solar power efficiency fails to provide a pressure ratio (PR) that matches the SE built-in PR. Off-design operation of the SE is recommended for the purpose of higher system efficiency and simpler ORC turbine. Efficiency of 13.68–15.62% for the proposed system can be achieved.

1. Introduction

Thermal electricity generation is one of the most important approaches to utilize solar energy. This industry is booming rapidly in recent years. The global operational solar electricity generation systems (SEGSs) in 2014 reached 4287 MW, and the systems under construction exceeded 2000 MW. Among the commerical SEGSs, parabolic trough collectors (PTC)-based systems are proven to be the most mature and predominant, which amount to approximately 90% of the total capacity of operational and under-construction plants [1].

PTC power plants with direct steam generation (DSG) are an alternative option for future cost reduction in SEGS. The DSG solar thermal power technology has been widely investigated [2–6]. In a DSG system, steam is directly generated in the solar field, hence avoiding the use of a boiler in the power section. The solar field recirculating pump consumption is also reduced. The collectors benefit from the constant temperature and high coefficient of heat transfer in the evaporation region of water. The feasibility of DSG technology in SEGS was manifested in the Direct Solar Steam (DISS) project funded by European Union, which had been operated for more than 6000 h [7]. DSG in the absorber tubes was deemed as a promising option to improve its competitiveness. Thermodynamic losses within oil–water/steam heat exchanger was obviated and hence higher steam temperature and higher SRC efficiency were attained. A 26% reduction in the levelized electricity cost seemed to be achievable [8]. A demonstration plant of 8 MWht was also built by Abengoa Solar [9]. The plant consisted of an evaporator field with three parallel loops and a superheater field with two loops in order to work at 8.5 MPa and 723 K. During one year operation, an innovative control strategy system that guaranteed the stability of the plant on transient conditions was validated. Different configurations of interconnections between

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http://dx.doi.org/10.1016/j.apenergy.2015.12.087
0306-2619/

Nomenclature

A	aperture area, m^2
C	heat capacity, kJ/kg K
E	exergy, kW
G	solar radiation, W/m^2
h	enthalpy, kJ/kg
m	mass flow rate, kg/s
P	pressure, MPa
T	temperature, K
v	specific volume, m^3/kg
W	power output, kW
ε	mechanic efficiency
η	system efficiency

Abbreviations

DSG	direct steam generation
HX	heat exchanger
ORC	organic Rankine cycle
P	Pump
PCM	phase-change material
PR	pressure ratio
PTC	parabolic trough collectors
SE	screw expander
SEGS	solar electricity generation system
SORC	steam–organic Rankine cycle
SRC	steam Rankine cycle
V	valve
VR	volume ratio

Subscripts

I, II	Cycle I, II
1–8	state points
0	reference state
a	ambient
b	binary phase/beam
c	characteristic
cas	cascade
ex	exergetic
g	generator
in	inlet
l	liquid phase
net	net
op	optimum
out	outlet
p	peak point/pressure/pump
s	solar/isentropic
single	single stage
T	thermal/turbine

collectors with ball joints and flexible rotation joints were evaluated. The first commercial PTC power plant with DSG technology in the world has been producing electricity since 2011 [10]. The 5 MWe solar thermal power plant located in Kanchanaburi/Thailand uses a new generation of PTC made of composite material combined with an efficient thin-glass mirror which reflects more than 95% of the sun radiation. After two years of successful operation, the power plant shows practical applicability of the DSG technology. The operation of the plant in sub-tropical climate characterized by frequent occurrence of cloudy phenomena, which sets high requirements on the transient control of PTC loops, has proven the reliability of the technology under nonideal condition for SEGSs.

Like most PTC-SEGSs with heat transfer fluid (HTF) of oil and molten salt, the aforementioned SEGSs with DSG generally use turbine-based steam Rankine cycle (SRC) for power conversion, which have some disadvantages as follows.

First, only superheated steam is allowed to enter the turbine to avoid condensation of vapor during the expansion process. If water droplets are formed, they may impinge on the blades of turbine at high speed, and cause damage and reduce mechanical efficiency. The SEGS developed in the DISS project had steam temperature of 673 K and pressure of 10 MPa at the turbine inlet [10,11]. There was a degree of superheat of about 90 K. The plant developed in INDITEP project (the logical continuation of the DISS project) had steam temperature of 673 K and pressure of 6.5 MPa at the turbine inlet [12]. The degree of superheat was about 119 K. The need of superheat significantly increases the turbine inlet temperature, while the increment in the SRC efficiency is limited. The detail will be provided in Section 5.1.

Second, the technical requirements in solar energy collection are high in order to achieve the high temperature heat source for the SRC. The glass-to-metal sealing of the PTC receiver is a type of tubular sealing, which involves not only appropriate mechanical strength but also excellent gas tightness on high vacuum conditions. Owing to the thoroughly different characteristics of metal and glass (e.g. thermal expansion coefficient and wettability), sealing failure/degradation of the receiver may be caused when the operating temperature fluctuates from about 673 K at daytime to 300 K at night. This failure/degradation proved to be a big problem in the early SEGSs [13]. To reach a temperature of 673 K, the geometric concentration ratio of PTC is generally more than 60 [14]. Large concentration ratio leads to high accurate tracking system, frequent maintenance, repair/replacement of moving parts and gears.

Third, it is difficult to store high grade heat. Thermal storage is vital to maintain the continuity of solar thermal power generation. HTF with mineral oil was used in USA SEGS I for 3 h heat storage. In the temperature range below 573 K, this technology was successful for helping the plant dispatch the generated electricity to meet the utility peak loads in the non-sunlight periods. But for later, more efficient SEGS that operated at higher solar field temperature, the mineral oil became very flammable and could not be used any more. Molten salt has been adopted as HTF in the USA Solar-Two power tower project. Due to its simple storage concept it is also suggested for use in PTC power plants [15]. Recently the world's largest solar thermal plant with molten salt storage system has come online in Arizona [16]. However, the low thermal conductivity and high melting point (which causes the freezing problem) of the salt are two obstacles which must be overcome before making full use of this storage technology.

Fourth, the plants have to be large to be economic. The capital cost per kWe of a SEGS generally decreases with the increment in installed capacity [17]. The reason is some fixed costs for a larger plant are approximately the same as those for a smaller plant, and the devices e.g. turbine, pump and generator are more efficient at higher power. Usual capacity of PTC-SEGS ranges from a few to tens of MW, some even reach two or three hundred MW. Millions of square meters of flat land is necessary, which can only be met in the Gobi desert or sparsely populated areas.

The above problems can be solved or eased by the usage of screw expander (SE) [18] and reciprocating expander [19,20]. Particularly, SE is a kind of volumetric expander which uses a rotary type positive displacement mechanism in the absence of high speed fluid. In general, it consists of a pair of helical screws and a shell casing. Fluid moves from the groove of relative small