Applied Thermal Engineering 50 (2013) 816–825

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Thermodynamic analysis and optimization of a solar-driven regenerative organic Rankine cycle (ORC) based on flat-plate solar collectors

Man Wang [a], Jiangfeng Wang [a,*], Yuzhu Zhao [b], Pan Zhao [a], Yiping Dai [a]

[a] Institute of Turbomachinery, School of Energy and Power Engineering, No.28 Xianning West Road, Xi'an Jiaotong University, Xi'an 710049, China
[b] China HuaDian Electric Research Institute, Hangzhou 310030, China

HIGHLIGHTS

► A solar-driven regenerative ORC using flat-plate solar collectors is simulated.
► Sensitivity analysis of parameters and parameter optimization are conducted.
► The daily average efficiency is defined to evaluate the system performance.

ARTICLE INFO

Article history:
Received 2 February 2012
Accepted 10 August 2012
Available online 23 August 2012

Keywords:
Flat-plate collector
Optimization
ORC
Parametric analysis
Solar energy

ABSTRACT

This paper presents a regenerative organic Rankine cycle (ORC) to utilize the solar energy over a low temperature range. Flat-plate solar collectors are used to collect the solar radiation for their low costs. A thermal storage system is employed to store the collected solar energy and provide continuous power output when solar radiation is insufficient. A daily average efficiency is defined to evaluate the system performance exactly instead of instantaneous efficiency. By establishing mathematical models to simulate the system under steady-state conditions, parametric analysis is conducted to examine the effects of some thermodynamic parameters on the system performance using different working fluids. The system is also optimized with the daily average efficiency as its objective function by means of genetic algorithm under the given conditions. The results indicate that under the actual constraints, increasing turbine inlet pressure and temperature or lowering the turbine back pressure could improve the system performance. The parametric optimization also implies that a higher turbine inlet temperature with saturated vapor state could obtain the better system performance. Compared with other working fluids, R245fa and R123 are the most suitable working fluids for the system due to their high system performance and low operation pressure.

1. Introduction

With the increasing development of science and technology, demand for energy is surging at an unprecedented pace. Considering the growing consumption of conventional primary energy (coal, petroleum, natural gas) and environment-related concerns, recovering low temperature heat sources has become an inevitable option to solve the energy and environment problem.

ORC as a promising energy conversion technology in the field of low grade heat utilization has been studied by many researchers for decades [1,2]. In recent years, some researchers have paid more attention to employing organic Rankine cycle to utilize solar energy for its abundant and sustainable resource. Li and Pei et al. [3] proposed a low temperature solar thermal electric system which consisted of compound parabolic concentrator (CPC) with a small concentration ratio and organic Rankine cycle with R123. Phase change materials (PCMs) were added to the system to store collected energy maintaining the stability of power output. They [4] also employed regenerative organic Rankine cycle instead of basic ORC to improve the system efficiency. Quoilin et al. [5] presented the design of a solar organic Rankine cycle installed in Lesotho. The system consisted of parabolic trough collectors, a thermal storage tank, and a small-scale ORC system using scroll expanders. With conservative hypotheses and real expander efficiency curve, the overall electrical efficiency of the system could reach 7% and 8%. From the above mentioned investigations, the concentrating collectors were usually used to collect solar radiation and they were more expensive than the flat plate collector.

* Corresponding author. Tel./fax: +86 029 82668704.
E-mail address: jfwang@mail.xjtu.edu.cn (J. Wang).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2012.08.013

Nomenclature

A	area, m^2
C	specific heat capacity, kJ kg^{-1} K^{-1}
D	diameter, m
F'	collector efficiency factor
F_R	heat removal factor
h	enthalpy, kJ kg^{-1}; convective heat transfer coefficient, W m^{-2} K
I	hourly radiation, W m^{-2}
k	thermal conductivity of the insulation
L	length, m
m	mass flow rate, kg s^{-1}
M	number of glass covers
n	the day of the year
p	pressure, MPa
Q	heat rate, kW
R	tilt factor for radiation
s	entropy, kJ kg^{-1} K^{-1}
S	incident solar flux, W m^{-2}
T	temperature, °C
U	loss coefficient, W m^{-2} K^{-1}
W	power, kW; pitch of tube, m

Greek letters

α	absorptivity
β	collector tilt angle, °
δ	declination, °; thickness, m
ε	emissivity for long wave length radiation
η	efficiency
θ	angle of incidence, °
ρ	destiny, kg m^3; reflectivity
τ	transmissivity; time, s
ϕ	latitude, °
ω	hour angle, °

Subscripts

a	ambient
b	beam radiation; bottom
c	covers
cond	condenser
d	diffuse radiation; daily
i	inside
in	input
instant	instant
fi	inlet of solar collector
fo	outlet of solar collector
load	load
loss	loss;
L	heat storage tank
net	net
o	outside
out	output
p	absorber plate
pm	average value
pw	water
P	pump
R	Rankine cycle
s	side; isentropic
t	top; tank
T	turbine
u	useful
w	water
w1	water

Wang et al. [6] conducted an experimental study to investigate the performance of a low-temperature solar Rankine cycle using R245fa as working fluid. A flat plate solar collector and an evacuated solar collector were used to collect solar radiation together, and a rolling-piston expander was mounted in the system. They [7] also built another experimental system consisting of a flat plate collector, a throttling valve, a pump and an air cooled condenser, to investigate the performance of solar Rankine cycle. Some researchers [8–18] coupled a solar-driven ORC with a reverse osmosis (RO) desalination sub-system to achieve the water purification from seawater or to remove the salt and other substances from the water. The solar-powered ORC transformed the solar radiation into mechanical power and the useful shaft power was used to drive the high pump of the RO unit. The existing installed solar ORC system usually didn't contain a thermal storage system. If the solar-ORC-RO systems used the thermal storage system to store the solar energy, they could operate continuously day and night, avoiding startup and shutdown of ORC system frequently.

In a solar-powered ORC system, choosing suitable working fluids is also a critical factor for achieving an efficient and safe operation. Not only thermophysical properties, but also chemical stability, environment impact and cost need to be considered to match the application. Therefore, much attention has been focused on the working fluid selection for solar-powered ORC system. Tchanche et al. [19] conducted the selection of most suitable fluids for a low-temperature solar ORC. By evaluating and comparing 20 potential working fluids, they pointed out that R134a appeared as the most suitable for small solar application. Rayegan et al. [20] developed a procedure to compare capabilities of working fluids employed in solar Rankine cycles with similar operation conditions. Results showed that 11 fluids were suggested to be used in solar ORCs that used low or medium temperature solar collectors.

Since the pure fluids were vaporized at a constant temperature, resulting in a thermal mismatch between working fluid and sensible heat source, mixture fluids were recommended to be used in ORC for its varied temperature evaporation behavior. Wang et al. [21] analyzed some zeotropic mixtures theoretically in low temperature solar Rankine cycles for power generation, and pointed out that using zeotropic mixture could obtain a significant increase of thermal efficiency and extend the range of choosing working fluids. They [22] also conducted a comparative study of pure fluids and zeotropic mixtures in the experimental condition. The results showed that the collector efficiency and thermal efficiency of zeotropic mixtures (R245fa/R152a) were higher than that of R245fa and indicated that zeotropic mixtures had the potential for overall efficiency improvement. Bao et al. [23] proposed a novel auto-cascade low-temperature solar Rankine cycle using zeotropic mixture (isopentane/R245fa) as working fluid. Results showed that the thermal efficiency of the proposed cycle using a mixture of 32% R245fa was significantly higher than that of the single stage low temperature solar Rankine cycle.

In this study, we have developed a solar low-temperature regenerative ORC power generation system based on flat plate collector using selected organic working fluids, namely, R245fa, R123, isobutane, R134a. In order to obtain a steady power output when the solar energy is insufficient in cloudy days or at nights, a thermal storage tank has been integrated into the system. A daily average efficiency as a modified system efficiency is defined to evaluate the system performance exactly instead of the instantaneous efficiency. A parametric analysis is conducted to examine the