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Off-design performance analysis of a solar-powered organic Rankine cycle

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ABSTRACT

Performance evaluation of a thermodynamic system under off-design conditions is very important for reliable and cost-effective operation. In this study, an off-design model of an organic Rankine cycle driven by solar energy is established with compound parabolic collector (CPC) to collect the solar radiation and thermal storage unit to achieve the continuous operation of the overall system. The system off-design behavior is examined under the change in environment temperature, as well as thermal oil mass flow rates of vapor generator and CPC. In addition, the off-design performance of the system is analyzed over a whole day and in different months. The results indicate that a decrease in environment temperature, or the increases in thermal oil mass flow rates of vapor generator and CPC could improve the off-design performance. The system obtains the maximum average exergy efficiency in December and the maximum net power output in June or in September. Both the net power output and the average exergy efficiency reach minimum values in August.

1. Introduction

Utilizing the renewable energy resources is proved to be an alternative way to solve the energy crisis and achieve the sustainable development of human beings due to their potentials in reducing fossil fuel consumption and alleviating environmental problems. Solar energy as a promising clean renewable energy has attracted much attention particularly in recent years due to its zero pollution and broad prospects in applications.

Concentrating Solar Power (CSP) system as an alternative effective way to utilize solar energy is a proven large-scale solar power technology with a variety of collector systems such as the parabolic trough, the solar dish, the solar tower or the Fresnel linear collector. However, most of the currently CSP plants typically include a condensing vapor cycle power block, requiring a minimum power of a few Mwe and high collector temperature and large-area field. Thus, the CSP cost is not yet competitive with conventional alternatives unless subsidized. In recent years, distributed energy systems have drawn much attention due to their small-scale capacity, flexibility and high efficiency. A solar-power organic Rankine cycle system with small-scale capacity compared with steam Rankine cycle has been focused on due to its low working temperature, high energy conversion efficiency and little negative impact on environment.

Since the organic working fluids have significant effect on the environment deterioration, the system operation and efficiency for solar organic Rankine cycle, some studies have been carried out on the selection of proper working fluids. Tchanche et al. [1] compared twenty working fluids from efficiencies, volume flow rate, mass flow rate, pressure ratio, toxicity, flammability, ODP and GWP and found that R134a was the most suitable working fluid for small scale solar applications. Rayegan and Tao [2] developed a procedure to select the working fluids used in solar Rankine cycles and found that eleven working fluids had been recommended in solar ORCs that used low or medium temperature solar collectors. Wang et al. [3] conducted a comparative study of pure and zeotropic mixtures in low-temperature solar Rankine cycle and found that the zeotropic mixtures had the potential for overall system performance improvement.

Except for the selection of working fluid, some researches have devoted to the sensitive analysis of key parameters and performance optimization of the solar-powered ORC. He et al. [4] conducted a simulation of a solar-powered organic Rankine cycle with parabolic trough collector using TRNSYS software. They examined the effects of several key parameters on the performance of the parabolic trough collector field based on the meteorological data of Xi'an city in China. Li et al. [5] presented a low temperature solar Organic Rankine Cycle (ORC) using R123 with compound parabolic concentrators. The influences of the collector tilt angle adjustment, the connection between the heat exchangers and the

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Nomenclature

A	area, m^2
b	width of absorber, m
Bo	boiling number
C	concentration ratio of CPC
c_p	specific heat, kJ/(kg K)
D	diameter, m
E	exergy, kW
F'	collector efficiency factor
F_R	heat removal factor
GWP	global warming potential
h	enthalpy, kJ/kg; convection heat transfer coefficient, W/(m^2 K)
I	Hourly radiation, W/m^2
k	heat transferring coefficient, W/(m^2 K)
L	length, m
m	mass flow rate, kg/s
N	number of tubes
Nu	Nusselt number
ODP	ozone depletion potential
P	pressure, kPa
Pr	Prandtl number
Q	heat rate, kW
R	tilt factor for radiation
Re	Reynolds number
s	entropy, kJ/(kg K)
S	incident solar flux, W/m^2
T	temperature, K
U	loss coefficient, W/(m^2 K); heat transfer coefficient, W/(m^2 K)
V	volume, m^3
W	power, kW
x_m	vapor quality

Greek letters

α	absorptivity of the absorber surface
β	chevron angle
δ	thickness, cm
ΔT_m	log mean temperature difference
η	viscosity, kg/(s m); efficiency, %
λ	thermal conductivity, W/(m K)
ρ	reflectivity of the concentrator surface; Density, kg/m^3
τ	transmissivity of the cover

Subscripts

0	environment
b	beam
c	cold
CND	condenser
CPC	compound parabolic collector
d	diffuse
e	effective reflectivity of the concentrator surface
eq	equivalent
exg	exergy
h	hot
in	input
l	liquid
lo	loss
load	energy input to bottoming ORC
max	maximum
min	minimum
net	net power output
oil	thermal oil
orc	organic Rankine cycle
out	outlet
S	single phase
sto	thermal storage tank
thm	thermal
TBN	turbine
u	useful
v	vapor
VG	vapor generator
w	water

CPC collectors, and the ORC evaporation temperature on the system performance were examined. The results indicated that the three factors had significant impact on the annual electricity output and should be the key points of optimization. Marion et al. [6] examined a solar-powered subcritical organic Rankine cycle with R134a, R227ea and R365mfc operating between the solar collector and a fixed temperature sink. A set of parametric studies was carried out to establish the optimum configuration.

Delgado-Torres and Garcia-Rodriguez [7] conducted a theoretical analysis of a low-temperature solar organic Rankine cycle. The overall efficiency of the solar ORC and its optimization with different collector types and working fluids were explored, and the influence of the regeneration process and cycle configuration on its performance were examined. They used the solar-powered ORC to drive a reverse osmosis desalination to produce fresh water for some water shortage areas based on the previous researches [8,9]. Many other researchers have also drawn more attention to the solar organic Rankine cycle for reverse osmosis desalination, such as Kosmadakis' work [10–12] and Nafey's work [13,14] and other's [15–17]. Wang et al. [18] carried out the simulation of a solar-driven regenerative organic Rankine cycle based on flat-plate solar collectors using different organic working fluids. They examined the effects of the key thermodynamic parameters on the system performance and conducted the parameter optimization with the daily average efficiency as its objective function using genetic algorithm.

As mentioned above, most of the researches mainly focus on the selection of working fluid, sensitive analysis and optimization design of the solar-powered ORC system and little research has been devoted to off-design performance evaluation of the system which is very significant to the reliable and economic operation of the system. Generally, it is impossible for ORC system to operate at the design point all the time due to the load requirement, operation limitations and so on. Once the ORC system operates deviating from the design point, the equipments in ORC system would undergo performance degradation, resulting in a degradation of overall system performance. The off-design behavior of system could impact the economic performance, and even the system stability under the severe conditions, such as very low load condition. Therefore, it is very important to examine the off-design performance of solar powered organic Rankine cycle.

The main objective of this paper is to carry out the off-design performance analysis of a solar powered organic Rankine cycle. The system consists of a compound parabolic collector (CPC), a thermal storage unit and an organic Rankine cycle with R245fa as the working fluid due to its good thermodynamic performance and no impact on the environment. The off-design model of the organic Rankine cycle driven by solar energy is established. The system off-design behavior is examined under the change of ambient temperature, the mass flow rate out of vapor generator and mass flow rate out of CPC. In addition, the off-design performance for