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Thermodynamic analysis of an organic rankine cycle using a tubular solar cavity receiver

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ABSTRACT

In this study, a non-regenerative Organic Rankine Cycle (ORC) has been thermodynamically analyzed under superheated conditions, constant evaporator pressure of 2.5 MPa, and condenser temperature of 300 K. R113, R601, R11, R141b, Ethanol and Methanol were employed as the working fluid. A parabolic dish concentrator with a square prismatic tubular cavity receiver was used as the heat source of the ORC system. The effects of the tube diameter, the cavity depth, and the solar irradiation on the thermodynamic performance of the selected working fluid were investigated. Some thermodynamic parameters were analyzed in this study. These thermodynamic parameters included the thermal efficiency, second law efficiency, total irreversibility, availability ratio, mass flow rate, and net power output. The results showed that, among the selected working fluids, methanol had the highest thermal efficiency, net power output, second law efficiency, and availability ratio in the range of turbine inlet temperature (TIT) considered. On the other hand, methanol had the smallest total irreversibility in the same range of TIT. The results showed also that mass flow rate and consequently the net power output increased for higher solar irradiation, smaller tube diameter, and for the case of cubical cavity receiver (i.e. cavity depth h equal to the receiver aperture side length a).

1. Introduction

In recent years, Organic Rankine Cycle (ORC) has become a favorable technology for small-scale power generation. There are several advantages in using solar ORC, that include reduced emissions of CO, CO_2 and other pollutant gases that are responsible of the global warming, ozone depletion and other atmospheric pollutants. On the other hand, ORC can be utilized with different kinds of low-grade heat sources for power generation. Solar energy is a kind of renewable energy that can be used as a heat source for the ORC.

In early years of 1970s, the study of the solar ORCs started both theoretically [1,2] and experimentally [3]. Wolpert and Riffat [4] analyzed a low-temperature solar ORC design for electricity power generation. Delgado-Torres and García-Rodríguez [5] studied the ORC with four different types of stationary solar collectors including flat plate collectors, evacuated tube collectors, and compound parabolic collectors. In their work, they utilized twelve substances as the working fluids of the ORC system. Helvaci and Khan [6] experimentally investigated a solar thermal system, using as a flat plat collector as a heat source of the ORC system. They conducted energy and exergy analyses on the thermodynamic system. The results reveal that the higher turbine inlet pressure and higher turbine inlet temperature resulted in the higher thermodynamic efficiency of the solar ORC. Producing mechanical power by an organic Rankine cycle combined with a solar thermal collector was carried out by Marion et al. [7]. Their results demonstrate that the optimum flow rate is a linear function of the solar insolation and the net mechanical power intensely depends on the mass flow rate.

Hung et al. [8] considered different types of ORC working fluids for converting low-grade energy to electricity power. They suggested that solar pond or the ocean thermal energy could be utilized as the heat sources. Rayegan and Tao [9] developed an analysis for comparing the capabilities of different working fluids, as employed in the solar Rankine cycles. Quoilin et al. [10] simulated the component of a solar ORC by considering the main mechanical and physical properties and the phenomena taking place in the cycle. Chacartegui et al. [11] analyzed a solar ORC in which, a parabolic trough plant was applied as the heat sources.

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Nomenclature

a	receiver aperture side length, m
A	area of the tube, m^2
c_2	constant used in linear equation
c_p	constant pressure specific heat, J/kg K
d	receiver tube diameter, m
D	dish concentrator diameter, m
F	view factor
h	cavity depth, m
h^*	enthalpy, kJ/kg
$\acute{h}$	heat transfer coefficient, W/m^2 K
I_{sun}	solar irradiance (W/m^2)
$\dot{I}$	irreversibility, W
k	thermal conductivity, W/m K
m_2	slope of linear equation
$\dot{m}$	system mass flow rate, kg/s
N	number of tube sections
ORC	Organic Rankine Cycle
$\dot{Q}_{net}$	net heat transfer rate, W
$\dot{Q}^*$	rate of available solar heat at receiver cavity, W
$\dot{Q}_{loss}$	loss rate of heat loss from the cavity receiver, W
$\dot{Q}_{solar}$	rate of available solar heat at dish concentrator, W
q	heat (kJ/kg)
R	thermal resistance, K/W
s	entropy (W/kg K)
T	temperature, K
TIT	turbine inlet temperature, K
$\dot{W}$	power, W

Greek symbols

ε	emissivity
σ	Stefan–Boltzmann constant, $W/m^2 K^4$
η	efficiency
φ	availability ratio

Subscripts

0	initial inlet to receiver
ap	aperture
Ave	average
bp	boiling point
c	condenser
cav	for the cavity
col	overall for the collector
conc	concentrator
cond	due to conduction
conv	due to convection
cr	critical
Dish	dish concentrator
evp	evaporator
f	fluid
forced	due to forced convection
H	heat source of the organic Rankine cycle
inlet	at the inlet
ins	insulation
II	second law
L	cold heat sink of the organic Rankine cycle
n	tube section number
natural	due to natural convection
net	net
oil	thermal oil
out	at the outlet
outer	out of the cavity
P	pump
$\acute{s}$	surface of the inner tube
rec	receiver
rad	due to radiation
s	surface of the inner tube
t	turbine
th	thermal
∞	environment

The performance of the system was investigated at the rated and off-design conditions with different organic working fluids. Tchanche et al. [12] studied the thermodynamic properties, the environmental characteristics, and the theoretical performances of some fluids for utilizing in the low-temperature solar ORC systems.

Pi et al. [13] carried out a numerical simulation for a low-temperature solar thermal electric generation with regenerative organic Rankine cycle in which, compound parabolic concentrator was used as the heat source. Their achievements show that the regenerative cycle has positive effects on the cycle efficiency, while it has negative effects on the collector efficiency. Calise et al. [14] simulated a novel design of a solar ORC where the ORC system was coupled with a flat plate evaluated collector as a heat source. In this study the energy and economic efficiency of the simulated solar ORC was investigated under different climatic conditions.

Li et al. [15] suggested a new design of CPC and ORC to reduce the heat transfer irreversibility between a thermal oil and HCFC-123 in the heat exchangers, by keeping the stability of the electricity output. They studied the influences of the collector tilt angle tuning, the ORC evaporation temperature, and the joining between the heat exchangers and the CPC collectors, on the system performance. Wang et al. [16] carried out the performance evaluation of a thermodynamic system under off-design situations. For the purpose of collecting the solar radiation, a compound parabolic collector was applied. The results show that the increase in the thermal oil mass flow rates or decrease in the ambient temperature cause developing the off-design performance.

Schimpf and Span [17] simulated and optimized a novel solar thermal and ground source heat pump system which combined with an ORC system. A flat plat collector was used as the heat source and the situation of the heat pump and the ORC system were continually changed. Also, they discussed the economic feasibility of the aforementioned system and concluded that the conventional solar energy conversion systems coupled with a ground source heat pump was found to be economically unreasonable at all locations [18]. Roy et al. [19] analyzed the parameters of a non-regenerative ORC system, using four different working fluids. They concluded that the R-123 produces the maximum shaft work, the maximum efficiencies, and the minimum irreversibility at the constant and variable heat source temperatures.

On the other hand, Le Roux et al. [20] investigated the performance of a rectangular cavity receiver in the solar thermal Brayton cycle. They proposed a method for determining the receiver surface temperatures and receiver efficiencies for various cavity sizes. Their case has some benefits like simplicity, low receiver cost and high efficiency, since it operates at low pressure [20–26]. Generally, cavity receivers have a higher level of efficiency compared to external receivers [27].

It can be observed from the literature review that there is no report of a parabolic dish concentrator with the square prismatic cavity receiver that is employed as the heat source of the ORC sys-