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Investigation of a hybrid ORC driven by waste heat and solar energy

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ABSTRACT

The objective of this work is to present a hybrid Organic Rankine Cycle (ORC) driven by solar energy and waste heat. Parabolic trough collectors coupled to a storage tank feed the heat recovery system which also utilizes waste heat of low-grade temperature (150 °C – 300 °C). Four different working fluids (toluene, cyclohexane, MDM and n-pentane) are examined in the regenerative ORC. The system is designed properly in order the maximum electricity production to be produced with the highest possible exploitation of the waste heat source. The examined model is investigated under steady-state conditions with a developed thermodynamic model in EES (Engineering Equation Solver). According to the final results, toluene leads to the highest electricity production, with cyclohexane, MDM and n-pentane to follow. The electricity production with toluene is found to be ranged from 479 kW to 845 kW and the system efficiency from 11.6% to 19.7%, with waste heat source temperature variation from 150 °C to 300 °C respectively. Moreover, it is found that higher waste heat source temperature leads to a higher fraction of the waste heat input in the ORC for all the working fluids.

1. Introduction

The last years, a lot of research has been focused on the energy domain due to several problems as the rising energy demand, the global warming, the fossil field depletion and the increasing price of electricity [1,2]. Solar energy, wind energy, geothermal energy, biomass, as well as waste heat are the main alternative energy sources which can substitute the conventional fossil fuels [3]. These alternative energy sources are abundant, cheap and environmental-friendly choices [4] which can lead to sustainable energy systems.

The Organic Rankine Cycle (ORC) is one rapidly developing technology which is ideal for electricity production with low-grade energy sources. Numerous literature studies and applications can be found with solar energy [5], waste heat [6], geothermal energy [7] and biomass utilization [8] for producing significant amounts of electricity with ORCs. Various organic fluids are used in these systems as toluene, cyclohexane, n-pentane, MDM, MM, R245fa, R123zde, propane, butane, etc. [9–11] because of their lower critical point compared to the water/steam working fluid. Moreover, the majority of these organic fluids has special saturation curve in the T-s diagram, a fact that reduces the need of superheating and the combination with low-grade sources is ideal [12].

Solar energy utilization has been examined in many ORCs from small up to great scale. Ferrara et al. [13] examined various types of solar driven ORC (with regeneration, superheating and re-heating) with parabolic trough collectors (PTCs) and they investigated different working fluids. Their analysis was focused on small scales (about 20 kW_{el}) and according to their results, acetone is the best working fluid for achieving efficiencies up to 20%. Chacartegui et al. [14] examined a 5 MW_{el} parabolic trough plant integrated with an Organic Rankine cycle power block and thermal storage. Two different heat storage layouts are tested; indirect with Hitec XL both as heat transfer fluid and as a storage medium, and indirect system with Therminol VP-1 as heat transfer fluid and Hitec XL as a storage medium. According to the results, toluene was proved to be the best organic fluid with 31.5% system efficiency and the indirect system was found to have the greatest interest. Casartelli et al. [15] examined the performance of a 5 MW_{el} ORC power plant with parabolic trough collectors for various operating temperatures. They found that toluene is the most suitable working fluid, especially for temperature levels close to 400 °C. The levelized cost of electricity production was calculated to 180 €/MWh, an attractive value for solar-driven systems. Desai and Bandyopadhyay [16] investigated various working fluids in a solar driven ORC with parabolic trough collectors and Fresnel mirrors. They stated that the utilization of R113, water, isohexane, cyclohexane, hexane, benzene, OMTS, and HMDS are promising solutions for the PTC power plants. Cocco and Cau [17] examined a solar driven ORC with PTC and Fresnel mirrors for 1 MW_{el} power production. The final results proved that PTC is a better choice than Fresnel mirrors and the system efficiency can reach up to 24%. Tzivanidis et al. [18] examined also a solar driven

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Nomenclature

A_{col}	collecting area, m^2
c_p	specific heat capacity, kJ/kgK
D	diameter of the tank zone, m
G_b	solar beam radiation, kW/m^2
h	specific enthalpy, kJ/kg
L	height of the tank zone, m
m	mass flow rate, kg/s
m_a	specific mass flow rate in the solar field, kg/sm^2
MW	molecular weight, kg/kmol
p	pressure, bar
P_{el}	net electricity power, kW
P_G	electricity production in the generator, kW
Q	heat rate, kW
Q_{lin}	heat input in the ORC from the thermal oil, kW
Q_{in}	heat input in the ORC, kW
Q_{win}	heat input in the ORC from the waste heat source, kW
s	specific entropy, kJ/kgK
T	temperature, ^oC
U_T	tank total heat loss coefficient, kW/m^2K
V	tank volume, m^3
W_p	organic fluid pump power, kW

Greek symbols

ΔT	temperature difference, K
η	efficiency, –
ρ	density, kg/m^3

Subscripts and superscripts

am	ambient
c	condenser
col	collector
crit	critical
hex	waste heat exchanger
high	high
l	thermal oil
lin	thermal oil inlet
lout	thermal oil outlet
low	low
in	inlet
is	isentropic
G	electrical generator
loss	heat losses
max	maximum
mg	electrical generator
o	organic fluid
out	outlet
pum	organic fluid pump
rc	recuperator
sat	saturation
sol	solar
st	storage tank
sys	system
u	useful
w	waste heat
win	waste heat source inlet
wout	waste heat source outlet

Abbreviations

ECO	economizer
EES	Engineering Equation Solver
EVAP	evaporator
HRS	heat recovery system
ORC	Organic Rankine Cycle
PP	pinch point
PTC	parabolic trough collector

ORC with PTC for the climate of Athens. They finally found that cyclohexane is the best working fluid by the energetic and financial point of view, while toluene is the second working fluid.

Waste heat is the next heat source which is widely applied on ORCs. Waste heat can be produced by internal combustion engines, gas turbines and thermal processes. Various temperature levels can be found in waste heat sources, from 100 °C up to 500 °C. Chen et al. [19] examined a cascade ORC driven by waste heat from a diesel engine. They found cyclopentane to be the best working fluid with a thermal efficiency of 11%. Song and Gu [20] examined a cascade ORC with waste heat from engine and jacket cooling water. They found cyclohexane to be the best working fluid for the high-temperature loop and R245fa for the low-temperature loop. The efficiency of the high-temperature loop is found close to 15% and of the low-temperature loop close to 8%. The same authors [21] stated that the utilization of cyclohexane and R141b mixture (50–50%) is able to increase the performance of a waste heat recovery system with ORC by 13.3%, compared to the system with pure cyclohexane. The use of mixture working fluids is also examined by Shu et al. [22]. They examined various combinations of working fluids and they stated that the mixture with 70% benzene and 30% R11 leads to the higher thermal efficiency of a waste heat engine recovery. Song et al. [23] examined a waste heat recovery system for about 1 MW_{el} with toluene, cyclohexane and benzene. According to their results, all the working fluids lead to similar thermal performance close to 21%.

It is obvious that there are numerous studies in the literature about ORCs driven by solar energy and waste heat sources separately. However, there is a lack of studies which combines these two alternative energy sources in ORC for achieving higher performance. The objective of the present study is to examine the combination of these two heat sources in the same heat recovery system of an ORC. The basic idea is to exploit the waste heat source in the best way, by minimizing the outlet waste heat source temperature. This goal leads to maximum heat utilization of this heat source and to higher heat input in the system. In conventional waste heat recovery systems, this technique is not followed because it leads to lower saturation temperature in the ORC and consequently to lower system efficiency. For facing this problem, solar energy utilization with waste heat is suggested in order to exploit the waste source in the best way and simultaneously to operate with high saturation temperature in the ORC.

In this study, parabolic trough collectors coupled with a storage tank are selected as the most efficient technology, according to the previous literature review [17]. Four different working fluids are examined. Toluene, cyclohexane, MDM and n-pentane are selected as usual and high efficient working fluids, according to the previous literature review. More specifically, toluene and cyclohexane are among the most efficient working fluids for high-temperature levels (close to 300 °C) and their investigation has high interest in the present system. The waste heat source is examined in the range from 150 °C to 300 °C and it is selected to be warm air in order to eliminate possible limitations about the minimum outlet temperature of the system. In the examined cases, the saturation temperature is examined parametrically and the system is optimized in order the maximum possible electricity to be produced. The analysis is performed in EES with a developed thermodynamic model.