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Research Paper

Energy and exergy analysis of an integrated organic Rankine cycle-vapor compression refrigeration system

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HIGHLIGHTS

- The performance of ORC-VCR system is investigated from energy and exergy analysis viewpoint.
- The integrated ORC-VCR system powered by low-grade thermal energy.
- Fourteen common and new HFCs, HCs, FCs, HFEs, and HFOs are suggested as working fluids.
- The influences of various operating parameters on the system performance are evaluated.
- R602 achieves the best system performance.

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ABSTRACT

In the present study, the performance of an integrated organic Rankine cycle-vapor compression refrigeration (ORC-VCR) system is investigated from the viewpoint of energy and exergy analysis. The system performance was represented by system coefficient of performance (COP_S), system exergy efficiency ($\eta_{e,sys}$), turbine pressure ratio (TPR), and total mass flow rate of the working fluid for each kW cooling capacity ($\dot{m}_{total}$). Many common and new hydrocarbons, hydrofluorocarbons, fluorocarbons, hydrofluoroethers, and hydrofluoroolefins were suggested as working fluids. The influences of various parameters such as the boiler, condenser, and evaporator temperatures, along with compressor and turbine isentropic efficiencies, on the system performance were also investigated. The results revealed that the best system performance was attained with the uppermost critical temperature dry working fluid. Among all suggested candidates, R602 is shown to be the most suitable working fluid for the ORC-VCR system from system performance and environmental issues viewpoints. However, due to its flammability, extra precautions should be taken. The highest COP_S, $\eta_{e,sys}$, TPR, and the corresponding $\dot{m}_{total}$ using R602 are 0.99, 53.8%, 12.2, and 0.005 kg s^{-1} kW^{-1}, respectively at a condenser temperature of 25 °C and the typical values for the rest parameters.

1. Introduction

Recently, there are considerable efforts in utilization of renewable energies as geothermal heat, wind energy, solar energy, and waste heat as clean energy sources for refrigeration or electricity production [1]. Waste heat of industrial activities can be recovered in order to enhance the efficiency of the energy systems. The heat-driven organic Rankine cycle (ORC) is a promising cycle for conversion of thermal energy to mechanical work or electrical energy. The ORC can be integrated with a vapor compression refrigeration (VCR) cycle to produce electricity or refrigeration [2].

The selection of working fluids for organic Rankine-vapor compression refrigeration (ORC-VCR) system is significant. Several studies have been conducted to choose working fluids according to system thermal efficiency [3,4]. Saleh [3] proposed ten pure substance, namely R1270, R290, RC318, R236fa, R600a, R236ea, R600, R245fa, R1234ze(E), and R1234yf as working fluids for ORC-VCR system activated by low-grade thermal energy. The results showed that R600 is the optimum working fluid for the system. The performance of an ORC-VCR system driven by waste heat utilizing R600a, R600, R601, and R245fa as working fluids was analyzed theoretically by Cihan [5]. The results indicated that R601 is the most suitable fluid for the system. The performance of an ORC-VCR system powered by low-grade thermal energy utilizing R1270, R600a, R290, and R600 as working fluids was also

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Nomenclature

ALT	atmospheric lifetime, years
CFCs	chlorofluorocarbons
COP	coefficient of performance
CPR	compressor pressure ratio
e	specific exergy, (kJ kg^{-1})
$\dot{E}$	exergy rate (kW)
FCs	fluorocarbons
GWP	global warming potential
h	specific enthalpy (kJ kg^{-1})
HCs	hydrocarbons
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
HFEs	hydrofluoroethers
HFOs	hydrofluoroolefins
LFL	lower flammability limit, % by volume in air
M	molecular mass (g mol^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
NBP	normal boiling point (°C)
ORC	organic Rankine cycle
ODP	ozone depletion potential
P	pressure, kPa
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
TPR	turbine pressure ratio
$\dot{Q}$	heat transfer rate (kW)
VCR	vapor compression refrigeration
$\dot{W}$	power (kW)

Greek letters

η	efficiency

Subscripts

b	boiler
c	condenser
comp	compressor
crit	critical
d	destroyed
eva	evaporator
e	exergy
exp	expansion valve
f	flow
in	input
j	component or state point number
mix	mixing chamber
out	output
pump	pump
sys	system
turb	turbine
total	total
x	quality
0	dead state
1, 2, 3 …	system state points

studied theoretically by Li et al. [6]. The results revealed that R600 is the best candidate for the system. Aphornratana and Sriveerakul [7] investigated an ORC–VCR system powered by low-grade thermal energy. They concluded that the system using R22 provided better COP than the system using R134a. Bu et al. [8,9] studied the performance of an ORC-VCR system using R123, R134a, R245fa, R600a, R600 and R290 as working fluids. The system was powered by geothermal energy for air conditioning, or powered by fishing boats waste heat for ice production. The results indicated that R600a is the most suitable working fluid. A combined refrigeration power system uses an ammonia-water binary working fluid driven by low-grade heat was investigated experimentally by Han et al. [10]. The cooling output was 11.67 kW, and the corresponding coefficient of performance (COP) was 0.465. Wang et al. [11] examined theoretically and experimentally an ORC-VCR system powered by waste heat and using scroll based expander. The system coefficient of performance (COP_S) reached nearly 0.5. Yue et al. [4] investigated a combined ORC with an automobile air conditioning system for waste heat recovery using R134a, R245fa, cyclopentane, and n-propane as working fluids. The results revealed that R134a is the most efficient working fluid. Molés et al. [12] studied an ORC-VCR system activated with low-temperature heat source using two working fluids for the VCR and two different fluids for the ORC. The results revealed that the best working fluids for the refrigeration and power cycles are R1234ze(E) and R1336mzz(Z), respectively.

The abovementioned researches concerning screening suitable working fluids for ORC-VCR systems have concentrated on maximizing the system thermal efficiency. Nevertheless, exergy analysis is a more practical criterion to assess the thermal heat source utilization. Many studies have been concentrated based on energy and exergy analyses of combined systems. An exergy analysis of a combined ORC and ejector refrigeration cycle utilizing isobutene-pentane zeotropic mixture with different composition was carried out by Yang et al. [13]. The results revealed that the proposed cycle generates more output power, but it makes less refrigeration and has larger exergy efficiency compared with the conventional cycle. Wang and Yang [14] performed both first and second law analyses of a hybrid combined cooling heating and power system powered by biomass and solar energy. The results indicated that the exergy and energy efficiencies are 16.1% and 57.9%, respectively. The energetic and exergetic assessment of different combinations of working fluids for ORC-VCR system powered by low-grade heat were conducted by Nasir and Kim [15]. They concluded that R134a was the most suitable candidate for ORC and isobutane for VCR cycle, having COP values in the range of 0.172–0.217, and cooling exergetic efficiency values in the range 24.99–26.76%, at the lowest and the highest outdoor temperatures. Demierre et al. [16] examined experimentally the performance of an ORC-VCR system used as a heat pump to provide 40 kW heating. The overall exergetic efficiency ranged from 0.37 to 0.45, according to the working conditions. The energetic and exergetic analyses of an ORC-VCR system driven by low-grade waste heat utilizing various candidates for power and refrigeration generation were carried out by Li et al. [17]. Among all candidates, R134a was recommended to be the most suitable one. Kim and Perez-Blanco [18] analyzed an ORC-VCR system for both power and refrigeration cogeneration using different candidates. Their results showed that butane and isobutane gave the best performance. The thermodynamic and economic analyses on an ORC driven by waste heat for industrial activities waste heat recovery using different working fluids were conducted by Mirzaei et al. [19]. The results indicated that m-xylene, P-xylene, and Ethylbenzene have higher net output power, higher efficiency, and lower total cost compared with other investigated working fluids. The potential of zeotropic mixture application in an ORC for low-grade heat recovery was investigated by Satanphol et al. [20]. The results indicated that among the studied mixtures, the blend of R-218/227ea/C318/245fa (32.1/13.4/38.8/15.7) attained the maximum cycle performance. The performance of ORC for heat recovery using 36 pure substances and 36 binary zeotropic mixtures as working fluids was evaluated by Scaccabarozzi et al. [21]. The results indicated that the use of mixtures leads to an increase of the exergy efficiency by approximately 2.5% (about 3.5% increase in net output power).

From the abovementioned review, it is obvious that there is no