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The performance analysis of the transcritical Rankine cycle using carbon dioxide mixtures as the working fluids for waste heat recovery

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ABSTRACT

The aim of this study is to investigate the economic performance improvement of a transcritical Rankine cycle system employing carbon dioxide mixtures for waste heat recovery. Five lower global-warming-potential working fluids, namely difluoromethane, fluoroethane, propane, tetrafluoroethane, and tetrafluoropropene, are selected to blend with carbon dioxide. In addition to thermodynamic analysis, the apparatus and maintenance costs of the waste heat recovery system are considered to evaluate the levelized energy cost for the economic performance study. The results indicate that the system cycled with carbon dioxide/fluoroethane exhibits the most effective economic performance, and is superior to that cycled with carbon dioxide/difluoromethane, carbon dioxide/tetrafluoropropene, carbon dioxide/tetrafluoroethane, carbon dioxide/propane, and pure carbon dioxide by 0.7, 13.89, 15.27, 20.88, and 21.52%, respectively. In the transcritical Rankine cycle operated with the carbon dioxide mixtures, not only are energy costs reduced, but the high pressure and temperature are also decreased. Furthermore, the optimal expander inlet pressures for the transcritical Rankine cycle with a minimal levelized energy cost are always smaller than those with maximal thermal efficiencies. Finally, economic performance correlations are proposed for the waste heat recovery system, utilizing various waste heat source temperatures.

1. Introduction

Owing to energy shortages and increasing CO_2 (carbon dioxide) emissions, waste heat recovery (WHR) has become an important global issue for energy utilization. The organic Rankine cycle (ORC) system, which contains lower boiling temperature working fluids, has been widely employed for low-grade waste heat energy conversion. Wei et al. [1] analyzed the influences of operating parameters on thermodynamic performance optimization in ORC for WHR. Dai et al. investigated the exergy efficiencies of the ORC [2], and reported that R236ea was a favorable working fluid because it performed with the highest exergy efficiency among those assessed. Furthermore, the benefits of power generation from residual industrial heat using the ORC were investigated by Nguyen et al. [3]. In order to reveal the effects of recovering waste heat energy from the cooling water of a large diesel engine, the economic performances of ORC systems were studied by Yang and Yeh [4]. The authors later reported that R245fa performed most satisfactorily in the WHR from exhaust gases generated by a large marine diesel engine [5]. Moreover, in the analysis of the ORC for recovering waste heat from the exhaust gas and cooling water of the diesel engine, R1234yf proved to be superior in the optimal thermo-economic performance evaluation [6].

Nevertheless, a very small temperature difference exists between the heat source and working fluid during the heating process in the ORC evaporator. This small temperature difference, also known as the pinch point, not only restricts heat energy transportation, but also obstructs the utilization of low-temperature waste heat sources. In order to overcome the pinch point limitation, a transcritical Rankine cycle (TRC) with a preferable temperature profile in the heating process was employed for WHR [7]. Schuster et al. [8] analyzed the effects of the operating parameters and various organic media on the TRC to obtain higher WHR thermal efficiencies. Thermodynamic analysis and a cost evaluation of heat exchangers were reported by Cayer et al. [9] to demonstrate TRC optimization using a low-temperature heat source. Le et al. [10] analyzed the TRC cycled with pure organic fluids to convert heat energy from water at 150 °C and 5 MPa. They found that among the analyzed working fluids, R1234ze (tetrafluoropropene, $C_3H_2F_4$) and R32 (difluoromethane, CH_2F_2) performed well with the highest values of electrical power output and thermal efficiency, respectively. Moreover, multi-utilization methods for a WHR system based on the TRC were proposed by Yang [11] to enhance the energy conversion ratio for a marine diesel engine. In Yang's analyzed results, R1234yf

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Nomenclature

A_{vap}	heat transfer area of vapor generator, m^2
B_1, B_2	bare module factor of equipment
C	cost, $
C_1, C_2, C_3	pressure factor of equipment
C_P	purchased equipment cost, $
c_p	specific heat, kJ kg^{-1} K^{-1}
$CEPCI$	chemical engineering plant cost index
C_{BM}	bare module cost, $
D	diameter, m
D_h	hydraulic diameter, m
F_P	pressure factor
F_M	material factor
g	acceleration due to gravity, m s^{-2}
h	heat transfer coefficient, kW m^{-2} K^{-1}
i	enthalpy, kJ kg^{-1}
k	thermal conductivity, kW m^{-1} K^{-1}
K_1, K_2, K_3	equipment cost coefficients, $
L_t	tube wall thickness, m
M	molecular weight of working fluid, g mole^{-1}
m	mass flow rate, kg s^{-1}
N	section number of heat exchangers
Nu	Nusselt number
P	pressure, MPa
P_r	Prandtl number
Q	heat transfer rate, kW
Re	Reynolds number
s	entropy, kJ kg^{-1} K^{-1}
T	temperature, °C
$T_{whs,i}$	waste heat source inlet temperature, °C
$T_{whs,o}$	waste heat source outlet temperature, °C
ΔT_{mean}	logarithmic mean temperature difference, °C
$T_{r,i}$	working fluid inlet temperature, °C
$T_{r,o}$	working fluid outlet temperature, °C
U	overall heat transfer coefficient of heat exchanger, kW m^{-2} K^{-1}
v	specific volume, m^3 kg^{-1}
W	power of expander or pump, kW
X	equipment type
x	mass flow rate factor
Y	capacity or size parameter of equipment, kW or m^2

Greek symbols

Δ	relative error, difference
α	pressure ratio
θ	temperature ratio
γ	ratio of levelized energy costs
η	efficiency
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}

Subscripts

con	condensation, condenser
cw	cooling water
exp	expander
f	liquid
g	vapor
i	inside, inlet
j	section
max	maximal
min	minimal
net	net
o	outside, optimal, optimization
pum	pump
r	working fluid
t	tube
th	thermal
tot	total
vap	vapor generator
wall	tube wall of heat exchangers
whs	waste heat source

Acronyms

LEC	levelized energy cost
LMTD	logarithmic mean temperature difference
ORC	organic Rankine cycle
TRC	transcritical Rankine cycle
WHR	waste heat recovery

(tetrafluoroethane, CH_2CFCF_3) and R236fa (hexafluoropropane, $C_3H_2F_6$) were recommended as favorable working fluids for the TRC [12]. In the theoretical investigation conducted by Chen et al. [13], mixed working fluids were employed as ORC and TRC working fluids to convert low-grade heat energy into power. The authors pointed out that using a zeotropic mixture as the TRC working fluid could result in a certain temperature glide during the condensation process. In addition, a comparison was carried out between the ORC and TRC systems using R245fa (Pentafluoropropane, $C_3H_3F_5$) as the working fluid to recover the waste heat from the exhaust gas of a bio-fuel engine [14]. The results indicated that both the thermal and exergy efficiency of the TRC were higher than those of the ORC.

Furthermore, a working fluid with suitable critical temperature and pressure is a key element in obtaining the conversion outcome efficiently in the TRC system. The natural medium of CO_2, which is non-flammable, non-toxic, abundant in nature, and provides superior environmental protection, has been widely considered as a TRC working fluid in low-grade thermal energy conversion [15]. Cayer et al. [16] presented an investigation of a CO_2 TRC using the industrial low-grade steam of process gases as a heat source, with energy and exergy analysis. Chen et al. [17] noted that when utilizing a low-grade heat source, the CO_2 TRC exhibited a slightly higher power output than the ORC. Shu et al. [18] also revealed that compared to the ORC system, the TRC system showed a significant advantage in terms of thermodynamics owing to the high specific heat capacity and heat transfer performance of CO_2. Moreover, Li et al. [19] compared the performance of a CO_2 TRC with that of an ORC, using R123 (trifluoroethane, $C_2HF_3Cl_2$), R245fa, R600a (isobutane, C_4H_{10}), and R601 (pentane, C_5H_{12}) as working fluids. Their results indicated that the CO_2 TRC exhibited superior economic performance to the ORC. Nevertheless, the analyzed results of Chen et al. [20] demonstrated that the R32-based TRC

Table 1
Properties of pure fluids.

Item	CO_2	R32	R161	R290	R1234yf	R1234ze
Molar mass (kg/kmol)	44.01	52.02	48.06	44.1	114.04	114.04
T_{cri} (°C)	30.98	78.11	102.1	96.74	94.7	109.36
P_{cri} (MPa)	7.38	5.78	5.01	4.25	3.38	3.63
ODP	0	0	0	0	0	0
GWP	1	675	13	3.3	4	6
Safety	A1	A2	A3	A3	A2	A2

Note: ODP: Ozone depletion potential; GWP: Global warming potential.
1: No flame propagation; 2: Lower flammability; 3: Higher flammability.
A: Lower toxicity; B: Higher toxicity.