Energy Conversion and Management 162 (2018) 189–202

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Payback period investigation of the organic Rankine cycle with mixed working fluids to recover waste heat from the exhaust gas of a large marine diesel engine

Min-Hsiung Yang*

Department of Naval Architecture and Ocean Engineering, National Kaohsiung University of Science and Technology, Taiwan, Republic of China

ARTICLE INFO

Keywords:
Payback period
Mixtures
Mass fraction
Organic Rankine cycle (ORC)
Waste heat recovery
Marine diesel engine

ABSTRACT

The aim of this study is to investigate the payback period and the payback-period reduction of the organic Rankine cycle (ORC) with mixtures for waste heat recovery from the exhaust gas of a large marine diesel engine. Working fluids with zero-ozone-depletion potential, such as R236fa, R245fa, R600, R1234ze, and their mixtures, are selected to analyze the economic and thermodynamic performances in the conversion cycle. The optimal mass fractions of the mixed working fluids R236fa/R245fa, R236fa/R1234ze, and R600/R1234ze for the lowest payback period with the corresponding optimal expander inlet temperature and condenser outlet temperature of the ORC have been obtained. R600/R1234ze possesses the best performance in terms of payback period. Under optimal conditions, the payback period of the ORC with R600/R1234ze is the lowest and is shorter than that with R236fa, R245fa, R600, R1234ze, R236fa/R245fa, and R236fa/R1234ze by 7.55%, 6.47%, 9%, 9.17%, 0.9%, and 2.88%, respectively. To evaluate the economic potential of mixed working fluids using different types of expander such as turbine, scroll, and screw expanders properly, the relationships between the isentropic efficiencies of the expander and their corresponding optimal expander inlet temperature and optimal mass fraction are obtained. Optimal correlations are proposed to conveniently predict the optimal mass fractions of the mixtures R236fa/R245fa, R236fa/R1234ze, and R600/R1234ze in the ORC and to assess the reduction of their payback periods for the waste heat recovery of a large marine diesel engine. The results highlight the significant potential of the mixtures used in the ORC for performance improvement and demonstrate the importance of mixture assessment for reducing the payback period in further work.

1. Introduction

Owing to energy savings and reduction of carbon dioxide emission, waste heat recovery (WHR) has become an essential way for energy utilization. To prevent the marine environment from being polluted by ships, the International Convention for the Prevention of Pollution from Ships (MARPOL) had been implemented by the International Maritime Organization (IMO). Furthermore, to reduce emissions of greenhouse gases from international shipping, regulations on air pollution and emissions from ships have been addressed in Annex VI of the MARPOL Convention [1]. The energy efficiency design index (EEDI) of new ships and the ship energy efficiency management plan (SEEMP) for all ships over 400 gross tonnage are policies concerning methods of energy savings [2]. Among these methods, WHR is one of the most effective ways to increase the energy efficiency and reduce the CO_2 emission from the marine diesel engines of merchant ships [3]. Moreover, the effect of WHR for a large marine diesel engine can be enhanced by integrating multiple waste heat sources, such as exhaust gas, cylinder, and scavenge air cooling water [4]. Furthermore, the organic Rankine cycle (ORC) system has great potential in applications of WHR systems for the internal combustion engine because of the lower evaporation temperature of the organic working fluids [5].

Using pure components as the working fluids, Yang and Yeh [6] analyzed the performance of an ORC system for recovering waste heat from the cooling water system of a large marine engine. Thermodynamic and economic investigations of the ORC system for using the exhaust gas of a diesel engine were reported. The results also depicted the payback-period reductions, fuel savings, and CO_2 emission reductions. Consequently, analyses of the ORC system applied to both the cooling water and the exhaust gas also revealed enhancement of the utilization rate of the waste heat resources for a large marine diesel engine [8]. Chen et al. [9] proposed a thermodynamic analysis of a cascade ORC system using pure components as the working fluids for waste heat recovery of truck diesel engines. From thermo-economic and

* At: No. 142, Haizhuan Rd., Nanzi District, Kaohsiung City 81157, Taiwan, Republic of China.
E-mail address: mhyang@webmail.nkmu.edu.tw.

https://doi.org/10.1016/j.enconman.2018.02.032
Received 7 November 2017; Received in revised form 23 January 2018; Accepted 7 February 2018
0196-8904/

Nomenclature

A_{eva}	heat-transfer area of the evaporator, 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	friction coefficient
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	coefficients of equipment cost, $
L_t	thickness of tube wall, m
M	molecular weight of working fluid, $g\,mole^{-1}$
m	mass flow rate, $kg\,s^{-1}$
N	section number of the 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
$T_{exh,i}$	exhaust gas inlet temperature, °C
$T_{exh,o}$	exhaust gas 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 the heat exchanger, $kW\,m^{-2}\,K^{-1}$
v	specific volume, $m^3\,kg^{-1}$
W	power of the 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	difference
γ	mass fraction
η	efficiency
μ	dynamic viscosity, Pa s
ρ	density, $kg\,m^{-3}$

Subscripts

b	bulk
con	condensation, condenser
cri	critical
cw	cooling water
eva	evaporation, evaporator
exp	expander
ehx	exhaust gas
f	liquid
g	vapor
i	inside, inlet
j	section
max	maximal
min	minimal
net	net
o	outside, optimal, optimization
pum	pump
r	working fluid
sat	saturated
t	tube
th	thermal
tot	total
wall	tube wall of heat exchangers

Acronyms

PB	payback period
LMTD	logarithmic mean temperature difference
ORC	organic Rankine cycle
WHR	waste heat recovery

sizing point of views, Galindo et al. [10] presented multi-objective optimization results of a bottoming ORC coupled to a turbocharged gasoline engine. Moreover, the profitability of the project by means of the net present value and the payback were estimated. Badescu et al. [11] reported improvement of the thermal efficiency of an internal combustion engine in an ORC using R245fa as the working fluid for recovering waste heat from the exhaust gas. The effect of optimal superheating in the evaporator for R245fa on the thermal efficiency of the ORC was reported.

To increase thermal efficiency, Vaja and Gambarotta [12] investigated the performance of an ORC system for recovering waste heat from the exhaust gas and engine cooling water of an internal combustion engine. Shu et al. [13] reported that the specific fuel consumption of a diesel engine can be reduced by ~10% by recovering waste heat from exhaust gas with an ORC. The results of Song et al. [14] revealed that an increase of 10.2% in the efficiency of a diesel engine can be obtained by adding the ORC system to recover the waste heat from exhaust gas and the cylinder cooling water. Moreover, Yu et al. [15] analyzed the thermodynamic performance for an ORC system to recover waste heat from engine exhaust gas and jacket cooling water using R245fa as a working fluid. Their results indicate that ~75% and ~9.5% of waste heat from exhaust gas and from jacket water, respectively, can be recovered under engine conditions ranging from high to low loads. Yue et al. [16] investigated the improvement of overall thermal efficiency for a diesel engine combined with an ORC driven by exhaust gas. Their results showed that the overall thermal efficiency of the integrated combined power system model was higher than that of the standalone internal combustion engine system model. Moreover, Yang et al. [17] proposed thermodynamic and economic optimization models of an ORC system by applying the waste heat of exhaust gas from a diesel engine. The optimal evaporation pressure, superheat degree, and condensation temperature corresponding to the maximum net power output per unit heat-transfer area and the minimum exergy destruction rate were provided under various engine operating conditions. To depict the performance improvement of a marine diesel engine, Larsen et al. [18] introduced the relationships of thermal efficiencies and exhaust gas temperatures of the waste heat in an ORC system. Tian et al. [19] demonstrated a parameter optimization and techno-economic analysis of the ORC by evaluating the heat-transfer area of heat exchangers in WHR systems. Their results showed that, among their analyzed working fluids, R141b, R123, and R245fa present the highest thermal efficiency of the ORC. Thermodynamic analyses of a WHR