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Thermodynamic and economic performance improvement of ORCs through using zeotropic mixtures: Case of waste heat recovery in an offshore platform

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A B S T R A C T

This paper presents a comparative thermodynamic and economic analysis of two kinds of organic Rankine cycles (ORCs) with pure and zeotropic mixtures for recovering waste heat from the exhaust gases of large diesel engines used in the offshore platforms of phase 12 of South Pars Gas on Persian Gulf. The mixtures of three hydrocarbons with two refrigerants in two cycle arrangements (simple ORC and ORC with internal heat exchanger) at different evaporation temperatures are investigated to optimize three indicators. The results showed that both the energy and exergy efficiencies are maximized at particular mass fractions of refrigerants. The ORC with mixture of R236ea/Cyclohexane (with a ratio of 0.6/0.4) has the best performance as its energy and exergy efficiency are 14.57% and 37.84%, respectively. These values are increased to 16.81% and 40.75%, respectively by adding IHE to system. The minimum amount of the specific investment cost for the most cases is achieved at the mass fractions of 0.1 and 0.5 and it is greater for the ORC with IHE. Also the payback period of investment is calculated for comparison of economic value of systems and it is observed that its amounts for the ORC with IHE are greater than simple one.

1. Introduction

By the growing industrialization over the last decades, global energy consumption has increased to a level never reached before, which has led to many serious environmental problems such as climate changes, air pollution, acid rain and ozone layer depletion. Due to the energy shortage and emission problems, the issues of energy saving and energy efficiency improvement has received more attention recently and has become a field of intense research and development. Utilization of Organic Rankine Cycle (ORC) is one of the proposed solutions to increase the energy usage and to reduce environmental emissions. Waste heat recovery is one of the applications of this system. As an example, by recovering waste heat from exhaust gases of an engine, the efficiency of the engine will be greatly enhanced.

In an ORC, the working fluid is an organic compound instead of water in the traditional steam cycle. Lower boiling point temperature and higher vapor pressure of organic fluids make better conformity with low and medium temperature heat sources compared to water. Also the ORC technology has many other advantages such as possibility of local and small scale power generation, simplicity of components and startup procedure, no need to operator attendance, easy maintenance

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Nomenclature

Abbreviations

CEPCI	chemical engineering plant cost index
GWP	global warming potential
IHE	internal heat exchanger
ODP	ozone depletion potential
ORC	organic Rankine cycle
PP	payback period
SIC	specific investment cost

Greek letters

ΔH_{vap}	heat of vaporization (kJ/kgK)
η	efficiency (%)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ε	effectiveness of internal heat exchanger (%)

Symbols

$\dot{E}x$	exergy destruction (kW)
$\dot{E}$	exergy (kW)
$\dot{m}$	mass flow (kg/s)
$\dot{Q}$	heat absorbed or released (kW)
$\dot{W}$	work (kW)
A	heat transfer surface area (m^2)
B_o	boiling number
C	cost (k$)
h	specific enthalpy (kJ/kg) or heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/mK)
L	length (m)
MM	molar mass (g/mol)
N_u	Nusselt number
P	pressure (MPa)
P_r	Prandtl number
R_e	Reynolds number
s	specific entropy (kJ/kgK)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
V	velocity (m/s)
x	vapor quality

Subscripts

$+IHE$	with internal heat exchanger
$1pH$	single phase
$2pH$	two phase
BM	bare module
c	condenser
cd	condensation dew point
cr	critical point
e	evaporator
eb	evaporation bubble point
f	working fluid
g	exhaust gas
I	energy efficiency
i	equipment i
IHE	internal heat exchanger
II	exergy efficiency
in	inlet
l	liquid
$LMTD$	logarithmic mean temperature difference
net	net output
out	outlet
p	pump
pp, c	condensation pinch point
pp, h	evaporator pinch point
t	turbine
TBM	total bare module
TCI	total capital investment
tot	total
v	vapor
w	cooling water

procedure, long life, lower cost and applicability with various kinds of heat resource. Low thermal efficiency than that of the steam cycle and organic fluid defects (i.e. flammability, toxicity, environmental concerns and their high cost) are the main drawbacks of the ORC technology [1,2]. Therefore, many studies have been accomplished to find suitable organic working fluids for the ORC system. Wang et al. [3] analyzed the performance of the ORC system using nine different pure organic working fluids which has recovered waste heat from internal combustion engines on the vehicles. The results showed that R245fa and R245ca were the most environmentally friendly working fluids. Shu et al. [4] investigated alkanes-based working fluids and found that they may be more attractive for the ORC system in engine exhaust heat recovery. Tian et al. [5] considered twenty low boiling organic fluids and reported that the R141b, R123 and R245fa perform better. Chacartegui [6] analyzed the performance of low temperature ORC by using toluene, cyclohexane, isopentane, isobutene, R113 and R245, and the results showed that the first two perform better. Roy et al. [7] optimized an ORC system with R12, R123, R134a, and R717 as working fluids and found that the ORC with R123 has maximal thermal efficiency as well as minimal irreversibility.

Utilization of the pure fluids including single chemical compounds causes larger irreversibilities in the heat transfer processes due to isothermal temperature profile in the evaporation and condensation. Using of the zeotropic mixtures as working fluid enhance the temperature matching between fluids in heat exchangers and can partly solve this issue. The effects of mixtures used in the ORC are investigated in the work of M. Chys [8]. The results showed that the cycle efficiency increases at the specific heat sources, compared with pure fluids. Wang et al. [9] experimentally investigated the use of zeotropic mixtures and R245fa for a solar ORC and found that the zeotropic mixtures can produce higher collector efficiency and thermal efficiency compared to R245fa in the experimental condition. Heberle et al. [10] examined the performance of isobutane/isopentane and R227ea/R245fa mixtures in a geothermal ORC. Investigation showed that the second law