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Operational profile based thermal-economic analysis on an Organic Rankine cycle using for harvesting marine engine's exhaust waste heat

Gequn Shu, Peng Liu, Hua Tian *, Xuan Wang, Dongzhan Jing

State Key Laboratory of Engines, Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, China

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ABSTRACT

Escalating crude oil price and environmental problem are attracting more interest in methods to improve thermal efficiency and reduce emission of shipping. Comparatively, The Organic Rankine cycle (ORC) offers a good solution to utilize low-medium quality waste heat from marine engine. In this paper, an operational profile based thermal-economic evaluation model is established providing reliable evaluation on Organic Rankine cycle used for waste heat utilization from marine diesel engines. Base on this model, ORC system is proposed and designed based on the ship's most typical operational condition. The effect of ship's operating condition on ORC thermodynamic performance among seven working fluid candidates is analyzed. Thermal-economic analysis is presented with increasing attention to the ship's operational profile based on the measurement data from 4-week navigation of objective passenger cruise ship. The result indicates that: considering the different thermodynamic properties, R123 is capable of outputting power at heavy load of engine, while R365mfc is more suitable at light load of engine. Taking typical operational profile into consideration, R123 suits better when ORC is designed for container ships, while R365mfc is suggested for bulk carrier and tankers. For the investigated case study, compared with estimation using nominal design output power, the electricity production cost EPC increased by around 36–41% when operational profile is included. Nominally, all working fluid candidates can satisfy 5-year payback limit except RC318. However, only R123, R365mfc and R245ca are feasible when operational profile is considered. This result makes clear that real operational profile is indispensable for assessing the feasibility of technology.

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1. Introduction

The environment issue combined with the rising of crude oil price has attracted more attention in efficient energy use of marine vessels. According to the third International Marine Organization (IMO) Green House Gas (GHG) study in 2014, the marine ship including domestic and international, from year 2007–2012, accounted on about 2.8% of global greenhouse gas emissions, accounting to about 1 billion tons annually, along with 15% and 13% of NO_X and SO_X, respectively [1]. Most of the shipping emissions are the results of fossil fuel combustion by marine engine to produce power for propulsion and auxiliary services.

Despite their high efficiency, marine engine still rejects a large amount of energy to environment through the forms of exhaust gas [2]. Part of this waste heat is recovered to satisfy the board auxiliary heat demand. However, this demand is relatively small and leaves potential for further exploitation of the available waste heat for other purposes. In particular, the waste heat recovery technology converting waste heat to electricity is treated as a considerably potential to increase energy efficiency and reduce emission of ships. Considering relatively low temperature (200–250 °C) and power outputs (<10 MW), the Organic Rankine cycle (ORC) offers a good solution to utilize low and medium quality waste heat from marine engine [3].

Extensive researches have been conducted on ORC-based waste heat recovery from marine engine. Ulrik et al. [4] compared three cycles (ORC, Kalina cycle and steam Rankine cycle) in a combined cycle application with a large marine two-stroke diesel engine and concluded that ORC has greatest potential for increasing the fuel efficiency. Marco et al. [5] presented ORC system to exploit the low-grade waste heat rejected by marine engine and three ORC configurations (simple, regenerative and two-stage) were compared. Results showed that the simple ORC coupled with the second engines cooling system seems to be the most promising option. Song et al. [6] designed the separated ORC apparatuses for the waste heat recovery from both jacket water and engine exhaust gas of marine diesel engines. The total net power output

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* Corresponding author.
E-mail address: thtju@tju.edu.cn (H. Tian).

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Nomenclature

Abbreviations

ORC	Organic Rankine cycle
EPC	electricity production cost
IMO	International Marine Organization
GHG	green house gas
WHR	waste heat recovery
ME	main engine
AE	auxiliary engine
EGBO	exhaust gas boiler
SMCR	specific maximum continuous rate
SOLAS	International Convention for the Safety of Life at Sea
ODP	ozone depletion potential
GWP	global warming potential
PPTD	Pinch Point Temperature Difference
LMTD	log mean temperature different
CEPCI	Chemical Engineering Plant Cost Index
CRF	capital recovery factor
DPP	depreciated payback period

Symbol

U	overall heat transfer coefficient (kW/m^2 K)
h	heat transfer coefficient (kW/m^2 K)
d	diameter (mm)
A	area (m^2)
T	temperature (K)
Q	heat flow rate (kW)
D	diameter (mm)
Nt	tube-side passes
Ns	shell-side passes
n	tube number
Re	Reynolds number
Cp	constant pressure specific heat [kJ/kg K]
Pr	Prandtl number
Nu	Nusselt number
k	thermal conductivity (W/m^2 K)
Bo	boiling number
G	mass flux of the working fluid
P	pressure (kPa)
L	length (m)
f_p	friction factor
s	specific entropy (kJ/(kg K))
m	mass flow rate (kg/s)
C	cost ($)
A_{nk}	annuity of the investment
h	operation hour
$\dot{W}$	power output (kW)
h	specific enthalpy (kJ/kg)
N	rational speed
i	interest rate
f_K	operation, maintenance and insurance cost factor
k	discount rate
ΔT	superheat degree (°C)
F_t	temperature corrected factor
H	head (m)
$\dot{V}$	volumetric flow rate (m^3/s)

Greek symbols

λ	thermal conductivity (W/m^{2}K)
ρ	density (kg/m^3)
μ	viscosity (Pas)
η	efficiency
χ	sailing time percentage

Subscripts and superscripts

OP	operational profile
DP	design point
shell	shell side
tube	tube side
o	outside
i	inside
eq	equivalent
l	liquid
v	vapor
des	design
in	inlet
out	outlet
ph	preheater
b	boiler
sh	superheater
exh	exhaust
wf	working fluid
eva	evaporating/evaporator
1–7	state point
con	condensation/condenser
cw	cooling water
bm	bare module
T	turbine
P	pump
is	isentropic
max	maximum
mean	mean
exc	exchanger

was found to reach 101.1 kW, which resulted in an efficiency increment of 10.2% for the marine engine. Mirko et al. [7] studied a cogeneration plant using s a supercritical ORC with R245fa to utilize the low-temperature waste heat energy of a Suezmax-size oil tanker, revealing the supercritical ORC with R245fa fluid met the demand of electricity onboard. OPCON Marine [8] had commissioned the first ORC-WHR plant aboard M/V Figaro and expect fuel savings around 4–5% for the case.

On the other hand, selecting the optimum working fluid is a complex task and the topic has received significant attention in the scientific literature. Tian et al. [9] analyzed the techno-economic performance of an ORC system used in the engine exhaust heat recovery based on various working fluid and revealed R123 and R245fa present highest output power and thermal efficiency. Shu et al. [10] performed parameter optimization of combined system of diesel engine with bottoming ORC using Alkaned-based working fluid and revealed Alkaned-based ORC is attractive for diesel engine waste gas heat recovery. Ulrik Larsen et al. [11] presented a generally applicable methodology based on the principles of natural selection to determine the optimum working fluid for marine application. Results showed that R245fa, R236ea and RC318 seem feasible with low hazard and near optimum efficiency. Another study by Ulrik Larsen et al. [12] suggested that 9% fuel consumption reductions with 6.5% NO_X reduction was achieved using a hybrid turbocharger and ORC and R365mfc performed best among refrigerants. Yang and Yeh [13] proposed an ORC system to recover waste heat from jacket water of large marine engines using six zero Ozone depletion potential (ODP) and low Global warming potential (GWP) working fluid and revealed R600a is superior to others in the optimal objective parameter.

In the above papers, simulations were performed in a nominal working point without taking ship's operational profile into

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