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Parametric optimization and heat transfer analysis of a dual loop ORC (organic Rankine cycle) system for CNG engine waste heat recovery

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ABSTRACT

In this study, a dual loop ORC (organic Rankine cycle) system is adopted to recover exhaust energy, waste heat from the coolant system, and intercooler heat rejection of a six-cylinder CNG (compressed natural gas) engine. The thermodynamic, heat transfer, and optimization models for the dual loop ORC system are established. On the basis of the waste heat characteristics of the CNG engine over the whole operating range, a GA (genetic algorithm) is used to solve the Pareto solution for the thermodynamic and heat transfer performances to maximize net power output and minimize heat transfer area. Combined with optimization results, the optimal parameter regions of the dual loop ORC system are determined under various operating conditions. Then, the variation in the heat transfer area with the operating conditions of the CNG engine is analyzed. The results show that the optimal evaporation pressure and superheat degree of the HT (high temperature) cycle are mainly influenced by the operating conditions of the CNG engine. The optimal evaporation pressure and superheat degree of the HT cycle over the whole operating range are within 2.5–2.9 MPa and 0.43–12.35 K, respectively. The optimal condensation temperature of the HT cycle, evaporation and condensation temperatures of the LT (low temperature) cycle, and exhaust temperature at the outlet of evaporator 1 are kept nearly constant under various operating conditions of the CNG engine. The thermal efficiency of the dual loop ORC system is within the range of 8.79%–10.17%. The dual loop ORC system achieves the maximum net power output of 23.62 kW under the engine rated condition. In addition, the operating conditions of the CNG engine and the operating parameters of the dual loop ORC system significantly influence the heat transfer areas for each heat exchanger.

1. Introduction

As a primary power machine used in the transportation industry, IC (internal combustion) engines typically utilize fossil fuels. In recent years, environmental degradation caused by particulate emissions from IC engines has received extensive attention. Simultaneously, emission regulations are becoming progressively stricter to improve air quality. Clean alternative fuel is a good option for traditional IC engines. Among all types of alternative fuels, CNG (compressed natural gas) is considered one of the most promising options because of its low emission levels, low price, and abundant reserves [1]. In China, CNG engines have been widely used in buses, heavy-duty trucks, and power units. However, CNG engines also produce a large amount of waste heat while they are running. The thermal efficiency of an engine is difficult to improve markedly using existing technologies. Waste heat recovery technologies do not only enhance the energy utilization efficiency of IC engines, but also reduce hazard emissions [2].

ORC (organic Rankine cycle) technology has been widely studied for low grade waste heat recovery because of its simple configuration, high efficiency, and capability to operate efficiently under low and medium grade heat sources [3–6]. After the energy crisis of the 1970s, ORC technology has been gradually applied to the waste heat recovery of IC engines [7–9]. In recent years, an increasing

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Nomenclature

$\dot{W}$	power (kW) or channel width (m)
$\dot{Q}$	heat transfer rate (kW)
$\dot{m}$	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg) or convective heat transfer coefficient (W/m^2.K)
s	specific entropy (kJ/kg.K)
T	temperature (K)
P	pressure (MPa)
K	overall heat transfer coefficient (W/m^2.K)
A	heat transfer area (m^2)
Nu	Nusselt number
d	diameter (m)
r	fouling resistance (m^2.K/W)
Re	Reynolds number
Pr	Prandtl number
l	length (m)
c_t	temperature difference correction factor
f	resistance coefficient
F	forced convective heat transfer enhancement factor
S	suppression factor
x	quality
p_r	reduced pressure
q	heat flux (W/m^2)
M	molecular weight (kg/kmol)
i_{fg}	enthalpy of vaporization (J/kg)
q''_{wall}	imposed wall heat flux (W/m^2)
G	mass velocity (kg/m^2.s)
D	port diameter (m)
N	number
b	channel spacing (m)
Bo	boiling number
r_{bw}	back work ratio

Greek symbols

β	rib effect coefficient or chevron angle
α	heat transfer coefficient (W/m^2.K)
λ	thermal conductivity (W/m.K)
η	efficiency
δ	fin height (m)
ε	correction factor or effectiveness of the heat exchanger
ρ	density (kg/m^3)

Subscripts

exp1	expander1
H	high temperature
H1–H7	state points in HT cycle
ise	isentropic
pre	preheater
p1	pump1
eva1	evaporator1
exh	exhaust
a–d	state points in exhaust gas
exp2	expander2
L	low temperature or all the mass flow rate taken as liquid
L1–L8	state points in LT cycle
in	inner
out	outer
con	condenser
p2	pump2
int	intercooler
eva2	evaporator2
cool	coolant
tot	total
th	thermal
max	maximum
min	minimum
ft	fin-and-tube
wf	working fluid
l	liquid
v	vapor
tp	two-phase
fb	film boiling
nb	nucleate boiling
pla	plate
h	hydraulic
eq	equivalent
out	outlet

Acronyms

ORC	organic Rankine cycle
CNG	compressed natural gas
GA	genetic algorithm
HT	high temperature
LT	low temperature
IC	internal combustion
EGR	exhaust gas recirculation
ODP	ozone depletion potential
GWP	global warming potential
CFCs	chlorofluorocarbon
HCFCs	hydrochlorofluorocarbons
PPTD	pinch point temperature difference
LMTD	logarithmic mean temperature difference
BSFC	brake specific fuel consumption
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
IHE	internal heat exchanger
WHRE	waste heat recovery efficiency

number of scholars have focused on studying this promising field [10–16]. Vaja et al. conducted a thermodynamic analysis to efficiently recover the waste heat of a stationary IC engines. Three working fluids and cycle configurations were considered for the parametric and performance analyses of the ORC system. The results showed that a 12% increase in overall efficiency could be achieved compared with the engine alone [17]. Srinivasan et al. investigated the exhaust waste heat recovery potential of a dual fuel combustion engine using a bottoming ORC system. Potential improvements in fuel conversion efficiency and brake specific emissions were quantified. The results showed that fuel conversion efficiency could be improved by an average of 7% points via hot EGR (exhaust gas recirculation) and ORC turbocompounding [18]. Usman et al. evaluated the positive and negative effects of installing an ORC system in a light-duty vehicle. The results showed that if the negative effects were considered, the maximum power enhancement was 5.82% at a vehicle speed of 100 km/h [19].

A simple ORC configuration can only be used to recover the waste heat of a single heat source, which will result in a low power output and a high cost. The waste heat of an IC engine is released