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Energetic and exergetic assessment of a two-stage Organic Rankine Cycle with reactivity controlled compression ignition engine as a low temperature heat source

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ABSTRACT

The waste heat from exhaust gases and cooling water of Reactivity Controlled Compression Ignition are used to launch a two-stage Organic Rankine Cycle. Considering the chemical kinetic mechanism, a Computational Fluid Dynamic model is presented to simulate the gasoline-diesel fueled RCCI engine. In addition, the performance of ORC is simulated by applying the Engineering Equation Solver software. By linking these two codes, a detailed Computational Fluid Dynamic-thermo analysis is carried out for the proposed heat recovery system and also the potential effects of some decision parameters on the performances of the combined Reactivity Controlled Compression Ignition – Organic Rankine Cycle system are studied in detail. The obtained results show that coupling Organic Rankine Cycle to the engine, improves Fuel Conversion Efficiency, break specific of Oxides of Nitrogen and Carbon Monoxide emissions as well as exergy efficiency to compare with sole engine operation state. According to the parametric analysis, can be seen that the temperature and pinch point differences of the evaporators, expanders' efficiencies as well as the temperatures and mass flow rates of the engine exhausted gases and cooling water should be taken as the effective parameters to evaluate the proposed system in terms of the first and second laws of thermodynamic. Moreover, a comparative study is performed between Reactivity Controlled Compression Ignition engine and a conventional diesel engine as the heat source of the heat recovery system. Results indicate that the energy and exergy efficiencies of Reactivity Controlled Compression Ignition – Organic Rankine Cycle system are higher than diesel – ORC under the same operations load, although, using a diesel engine has a greater influence on the net output power of the attached cycle, regardless of the engines' power.

1. Introduction

In recent years, there is a growing recognition that the waste heat recovery strategy is well on its way to become a practical solution in order to decrease the fossil fuels consumption and environmental pollution [1]. Among the various techniques introduced on the waste heat recovery concept, perhaps there is no effective technology like ORC in the power generation from low and medium temperature heat sources. The most important advantage of the ORCs is their proficiency to be successfully applied in different aspects of waste heat recovery from gas turbines and other industrial processes. For example, Safarian and Aramoun [2] studied performance of basic as well as three modified Organic Rankine Cycles namely modified ORC incorporating turbine bleeding, regenerative ORC and modified ORC incorporating both turbine bleeding and regeneration. Their results showed that the integrated ORC with turbine bleeding and regeneration has the highest thermal and exergy efficiencies (22.8% and 35.5%) and the lowest exergy loss (42.2 kW) due to decrease in cold utility demand and high power generation. From the other application of ORC can be referred to Berzai's et al. work [3]. They applied an active waste heat recovery system such as ORC for the side walls of the aluminum electrolysis cells to utilize of the extracted heat in power generation. This will potentially lead to energy efficiency improvement in the primary aluminum production industry and an enhanced aluminum production rate.

Many attempts have been done for improving the ORC's performance. Working fluid plays an important role on the ORC performance enhancement. Pure fluids and mixtures are utilized as working fluid in the organic Rankine cycles. The effects of 10 groups of mixtures on the performance of ORC were analyzed by Kange et al. [4]. The results showed that R245fa/R600a (0.9/0.1) was the most preferable mixture among the working fluids within the scope of this research. The effect of different zeotropic mixtures on various configurations of geothermal

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Nomenclature

$\dot{m}$	Mass flow rate [kg/s]
$\dot{Q}$	Heat flow [kW]
$\dot{w}$	power [kW]
$\dot{E}$	Exergy [kW]
e	specific exergy [kJ/kg]
T	temperature [K, °C]
h	enthalpy [kJ]
s	entropy [kJ/K]
X	mass fraction
R	specific gas constant for air [kJ/kg-K]
Y	mole fraction
C_P	specific heat at constant pressure [kJ/kg K]
Q	heat [kJ]

Subscripts

i	inter
e	exit
dest	destruction
ph	physical
ch	chemical
eng	engine
HT	heat transfer
SYS	system

Abbreviations

ORC	Organic Rankine Cycle
RCCI	reactivity controlled compression ignition
FCE	fuel conversion efficiency
IMEP	indicated mean effective pressure
IHE	internal heat exchanger
PTORC	parallel two ORC
STORC	series two ORC
PPTD	pinch point temperature difference
LTC	low temperature combustion
HCCI	homogeneous charge compression ignition
CFD	computational fluid dynamic
CDC	convention diesel combustion
NOx	oxides of nitrogen emissions
CO	carbon monoxide emissions
CO_2	carbon dioxide emissions
UHC	unburned hydro carbons
SOI	start of injection
ATDC	after top dead center
PR	premixed ratio
HC	hydro carbons
EGR	exhausted gas recirculation
CI	compression ignition
SI	spark ignition
BSFC	brake specific fuel consumption
DDM	droplet discrete model
IVC	intake valve closing
EVO	exhaust valve opening
TDC	top dead center
EES	engineering equations solver
BS	break specific
SS	symbolizes sum
AHRR	apparent heat release rate
LHV	low heat value

Greek symbols

η_{II}	second thermodynamic low efficiency

powered ORC systems was studied by Sadeghi et al. [5]. Based on their results, zeotropic mixtures in comparison to a pure fluid such as R245fa, increase the power production about 24.79–27.76 (%) in different configurations of the ORC system. Nemati et al. compared the performance of the ORC for waste heat recovery of a transcritical refrigeration cycle running by CO_2 and Ethane as working fluid and concluded that waste heat recovery leads to a significant improvement in system's performance [6]. Furthermore, various investigations have also been done to improve the performance of ORCs by focusing on the cycle configurations. The comparison of a simple ORC, an ORC with an IHE (internal heat exchanger), a regenerative ORC, and a regenerative ORC with an IHE from the energy and exergy point of views was performed by Yari [7]. The results demonstrated that the highest amount of the first law efficiency was around 7.65% belonging to the ORC with an IHE and using R123 as the working fluid. Li et al. [8] represented a novel system to decrease the exergy destruction in the evaporator. They implemented two evaporators for this aim and compared the results with those of simple ORC. They concluded that thermal efficiency increases and exergy destruction decreases with this new configuration. They also proposed a new configuration with two evaporators (STORC) in [9]. They compared this new configuration (STORC) with the previous one (PTORC) and they found that STORC has higher net power and presents excellent systematic performance.

As mentioned before, ORC is a practical solution for waste heat recovery from internal combustion engines. Srinivasan et al. [10] has evaluated the exhaust waste heat recovery potential to improve fuel consumption efficiency (FCE), brake specific emissions (NOx and CO_2) and exergy efficiency in the LTC, a dual fuel engine with ORC bottoming cycle. By this configuration, they have reported that FCE can increase from 20% to 40% in the half load operation mode by applying 8% EGR and also both NOx and CO_2 emissions have been reduced about 18% on average as compared with the engine individual operation mode. Maogang et al. [11] has presented energy and exergy analysis of the exhaust gas recovery from CI engine by applying a hybrid system consisting of ORC and Kalina cycles as the bottoming cycle in the steady state condition. They have shown that this configuration can increase energy and exergy efficiency in comparison with traditional bottoming cycles such as Rankine cycle. Nemati et al. [12] have utilized the waste heat of a heavy duty marine engine for producing fresh water and electricity, simultaneously. They have studied the system performance from the viewpoint of exergoeconomic and finally optimized the system performance by considering cost and exergy efficacy as two objective functions. Zhang et al. [13] has studied a small-scale dual loop ORC cycle for waste heat recovery of a light duty diesel engine. Their results have shown that the net power of the low temperature cycle is higher than that of the high temperature cycle and also the total net power has been increased about 2% by this configuration in comparison with the diesel engine single operation. Guopeng et al. [14] has developed a model on the basis of diesel engine and ORC as bottoming cycle. They have indicated that in various engine operation modes, 7.5–9.5% of the exhaust gases and jacket water's wasted heat can be recovered. Also, the recovery and exergy efficiencies have been improved about 9.2 and 21.7%, respectively. The test results obtained by Yang et al. [15] on the Diesel-ORC system in the engine laboratories have indicated that when the engine speed is adjusted at 2200 RPM, the output power of the combined system would be maximum and equal to 308.6 kW which is 28.6 kW higher than that of single engine operation without ORC cycle. In addition, they have reported that the thermal, waste heat recovery