Energy Conversion and Management 174 (2018) 248–259

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Global optimization of the diesel engine–organic Rankine cycle (ORC) combined system based on particle swarm optimizer (PSO)

Rui Zhao, Hongguang Zhang*, Songsong Song, Fubin Yang, Xiaochen Hou, Yuxin Yang

College of Environmental and Energy Engineering, MOE (Ministry of Education) Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Beijing Key Laboratory of Heat Transfer and Energy Conversion, Beijing University of Technology, Pingleyuan No. 100, 100124 Beijing, China
Collaborative Innovation Center of Electric Vehicles in Beijing, Pingleyuan No. 100, 100124 Beijing, China

ARTICLE INFO

Keywords:
Organic Rankine cycle
Combined system
Integrated simulation
Global optimization
Particle swarm optimizer

ABSTRACT

The organic Rankine cycle (ORC) system powered by exhaust heat has great potential in improving engine performance. Many optimizations of the only ORC system were conducted, while the existing literature pays limited attention to the optimization of the engine–ORC combined system. By considering the importance of interaction, cooperation, and influence between the engine and ORC system, a global optimization of the diesel engine–ORC combined system (herein, the combined system) is conducted in this paper with respect to power output and fuel economy. A GT-Suite model of the combined system and a GT-Suite/Simulink co-simulation model are proposed to obtain the optimum operating parameters of the engine and the ORC system under various operating conditions. Furthermore, the effects of the operating parameters, namely, exhaust valve timing, injection timing, expander speed, and pump speed, are evaluated on the combined system. In addition, models of the engine and the ORC system are calibrated, and a particle swarm optimizer (PSO) is designed and adopted for global optimization. Optimization results show improvements of 3.24% and 3.13% on the power output and brake specific fuel consumption (BSFC), respectively, with full engine load when the engine is operated at 3600 r/min. In the optimization of fuel economy with partial engine load, a maximum reduction of 5.71% on the BSFC of the combined system is obtained at 3600 r/min engine speed.

1. Introduction

With the increasing fuel costs and growing environmental concerns, numerous complex engine designs, such as turbocharging, variable valve timing, have been implemented to improve the thermal efficiency of engines [1,2]. However, considerable heat loss of engines still occurs, and waste heat from engines constitutes approximately two-third of the total energy from fuel combustion, thereby allowing further efficient waste heat recovery (WHR) [3]. Therefore, WHR is an attractive technique for further improving thermal efficiency of engines. Extensive research highlights that an organic Rankine cycle (ORC) system is one of the best performing technologies for WHR due to its simplicity, high efficiency, and reliability [4–6].

In the application of an ORC system on WHR, the selection of working fluid, which should be safe, environmentally friendly, and low cost, must be specifically considered [7–10]. According to the temperature–entropy (T–s) diagrams, fluids have the three types, namely, dry fluids, wet fluids, and isentropic fluids [11]. Hung et al. [12] parametrically analyzed and compared the efficiency and irreversibility of ORCs using various dry fluids. A 10 MW waste heat source was employed in their calculation. Dai et al. [13] compared and analyzed the optimum performance of cycles with different working fluids under the same waste heat condition. The results showed that the cycles with organic working fluids are considerable better than the cycle with water in converting low grade waste heat into useful work. Chen et al. [14] investigated 35 types of working fluids under different operating conditions. They noted that the best working fluids with the highest efficiency cycles may not be the same for other operating conditions and different working fluids. Wang et al. [15] analyzed the performance of different working fluids operating in specific regions by using a thermodynamic model constructed in MATLAB along with REFPROP. They indicated that R11, R141b, R113, and R123 manifest slightly higher thermodynamic performances than the others; however, R245fa and R245ca are the most environment-friendly working fluids for engine WHR applications.

Many studies have investigated the optimization of an ORC system by focusing on different cycle configurations for high efficiency recovery from different heat resources [16–18]. Xi et al. [19] examined

---

* Corresponding author at: College of Environmental and Energy Engineering, Beijing University of Technology, Pingleyuan No. 100, 100124 Beijing, China.
E-mail address: zhanghongguang@bjut.edu.cn (H. Zhang).

https://doi.org/10.1016/j.enconman.2018.08.040
Received 26 May 2018; Received in revised form 28 July 2018; Accepted 11 August 2018

Nomenclature

c_p	specific heat at constant pressure (kJ/kg·K)
D	diameter of tube (m)
F	constant
G	total mass velocity (kg/m^2·s)
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2·K)
k	fluid thermal conductivity (W/m·k)
N	speed (r/min)
$\dot{q}$	mass density (kW/m^2)
T	torque (N·m)
T_{ext}	exhaust valve timing (°CA)
T_{int}	injection timing (°CA)
$\dot{W}$	power (kW)
x	vapor quality
ρ	mass density (kg/m^3)

Dimensionless numbers

Bo	Boiling number
Fr	Froude number
Re	Reynolds number
N_u	Nusselt number
Pr	Prandt number

Subscript

l	liquid
com	combined system
de	desired
en	engine
ex	expander
eq	equivalent
g	vapor
n	net
p	pump
out	outlet
tol	tolerance
tp	two-phase

Acronyms

BSFC	brake specific fuel consumption
ORC	organic Rankine cycle
WHR	waste heat recovery

the performances of three ORC systems, namely, the basic ORC, single-stage regenerative ORC, and double-stage regenerative ORC systems, under the same waste heat condition. The results showed that the double-stage regenerative ORC system consistently provides the best thermal and exergy efficiencies under optimal operating conditions, followed by the single-stage regenerative ORC system, whereas the basic ORC system has the worst efficiencies. Branchini et al. [20] analyzed and compared recuperation, superheated cycle, supercritical condition, regenerative cycle and their combinations to improve ORC recovery performance. Their developed performance calculation method could be used to compare different designs of cycle configuration. Karimi et al. [21] optimized several crucial operating parameters of three systems, that is, basic ORC, regenerative ORC and two-stage evaporation ORC system, via thermodynamic, economic, and exergoeconomic optimization methods. Zare [22] compared three configurations of ORC from the thermodynamic and economic perspectives. The researcher indicated that from the thermodynamic perspective (first and second law efficiencies), the ORC with internal heat exchanger has superior performance. Meanwhile, from the economic perspective, the simple ORC is the best case among the considered cycles.

Generally, appropriate operating parameters result in good performance and low cost of ORC systems. Several researchers have dedicated their efforts in optimizing the parameters of key components of an ORC system [23–26]. Liu et al. [27] selected five key geometrical parameters of evaporator as decision variables and three parameters as optimization objectives to obtain an optimal design by using a particle swarm optimization (PSO) algorithm. Zhai et al. [28] optimized six design parameters of an ORC radial-inflow turbine for maximum turbine efficiency by using a constrained genetic algorithm. The results showed that the efficiency of the optimized turbine varies from 88.06% to 91.01%, which increases monotonously with the temperature of the heat source outlet. Moreover, with the sufficient number of simulation model designed for the ORC system, an increasing number of multi-variable and multi-objective optimizations of the ORC system were conducted using various optimizers. Guo [29] and He et al. [30] optimized the evaporating temperatures for an ORC system. The results showed that the optimum evaporating temperatures maximizes the net power output. Dai et al. [31] optimized the parameters, namely, turbine inlet pressure, turbine inlet temperature, and turbine back pressure, of a novel combined power and ejector refrigeration cycle via a genetic algorithm. The results demonstrated that the combined cycle of the three optimal parameters has a maximum exergy efficiency of 27.10%. Yang et al. [32] investigated the effects of six key parameters on the thermo-economic indicators of a dual-loop ORC system. The results showed that the thermal efficiency of the dual-loop ORC system is in the range of 8.97–10.19% over the entire operating range. Boyaghchi et al. [33] selected three objective functions and optimized seven decision variables to obtain high values of avoidable parts by using the NSGA-II optimization algorithm. The researchers found that the optimization of a system improves the system performance based on advanced exergy and exergoeconomic concepts.

Additional detailed investigation on the simulation of the engine-ORC combined system must be conducted to achieve an optimal efficiency of WHR from engine by using the ORC system [33]. Recently, a few studies have been conducted to analyze the performance of the engine and ORC combined system. Zhao et al. [34] separately developed simulation models of the diesel engine and the ORC system in the GT-Suite, which were coupled by a bridging model developed in the Simulink. The researchers indicated that the net power output increment, the BSFC reduction, and the thermal efficiency improvement of the steady engine performance of the ORC system can reach up to 4.13 kW, 3.61 g/(kW h), and 0.66%, respectively. However, the ORC system has minimal effect on the acceleration performance of the engine. Xie et al. [35] developed dynamic models of the engine and the Rankine cycle system (RCS) using GT-Suite and MATLAB/Simulink software. The researchers defined four basic operating modes and investigated the waste heat recovery behavior of the RCS during driving cycle. The results indicated that the on-road RCS efficiency (RCS-E) is as low as 3.63%, which is less than half of the design RCS-E (7.77%) at the rated operating point. Usman et al. [36] evaluated the positive and negative effects of the ORC system installation on a light-duty vehicle by using the engine exhaust data for light-duty vehicles to design an ORC-based system. The results indicated that for a vehicle operating at 100 km/h, its engine power can be enhanced by 10.88%, that is, 5.92 kW of the additional power and at a low speed of 23.5 km/h. Moreover, the engine power enhancement is 2.34%. Tian et al. [33] developed a semi-dynamic model composed of a detailed one-