Energy 93 (2015) 2208–2228

Contents lists available at ScienceDirect

Energy

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

Thermoeconomic multi-objective optimization of an organic Rankine cycle for exhaust waste heat recovery of a diesel engine

Fubin Yang [a, b], Hongguang Zhang [a, b, *], Songsong Song [a, b], Chen Bei [a, b], Hongjin Wang [a, b], Enhua Wang [c]

[a] *College of Environmental and Energy Engineering, Beijing University of Technology, Pingleyuan No. 100, 100124 Beijing, China*
[b] *Collaborative Innovation Center of Electric Vehicles in Beijing, Pingleyuan No. 100, 100124 Beijing, China*
[c] *State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Qinghuayuan, 100084 Beijing, China*

ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form
20 September 2015
Accepted 24 October 2015
Available online 19 November 2015

Keywords:
Diesel engine
Waste heat recovery
Organic Rankine cycle
Thermoeconomic analysis
Multi-objective optimization

ABSTRACT

In this paper, the ORC (Organic Rankine cycle) technology is adopted to recover the exhaust waste heat of diesel engine. The thermodynamic, economic and optimization models of the ORC system are established, respectively. Firstly, the effects of four key parameters, including evaporation pressure, superheat degree, condensation temperature and exhaust temperature at the outlet of the evaporator on the thermodynamic performances and economic indicators of the ORC system are investigated. Subsequently, based on the established optimization model, GA (genetic algorithm) is employed to solve the Pareto solution of the thermodynamic performances and economic indicators for maximizing net power output and minimizing total investment cost under diesel engine various operating conditions using R600, R600a, R601a, R245fa, R1234yf and R1234ze as working fluids. The most suitable working fluid used in the ORC system for diesel engine waste heat recovery is screened out, and then the corresponding optimal parameter regions are analyzed. The results show that thermodynamic performance of the ORC system is improved at the expense of economic performance. Among these working fluids, R245fa is considered as the most suitable working fluid for the ORC waste heat application of the diesel engine with comprehensive consideration of thermoeconomic performances, environmental impacts and safety levels. Under the various operating conditions of the diesel engine, the optimal evaporation pressure is in the range of 1.1 MPa–2.1 MPa. In addition, the optimal superheat degree and the exhaust temperature at the outlet of the evaporator are mainly influenced by the operating conditions of the diesel engine. The optimal condensation temperature keeps a nearly constant value of 298.15 K.

1. Introduction

IC (Internal combustion) engines only convert about 40% of the total fuel combustion energy into useful work, and the remaining energy is discharged into environment in the form of waste heat [1,2]. Under the background of energy crisis, how to realize the recovery of the waste heat from the IC engines has received much attention these years. Light-duty passenger vehicle exhaust system operates at gas temperatures from 500 to 900 °C, while the heavy-duty vehicle exhaust system operates at gas temperatures from 500 to 650 °C. These high temperature exhaust gases provide significant opportunities for waste heat recovery [3]. The exhaust waste heat recovery of IC engines would not just bring huge advantages for improving the fuel consumption, but also increase engine power output, further reducing CO_2 and other harmful exhaust gas emissions [4]. If approximately 6% of the exhaust heat could be converted into useful power, it would be possible to reduce the fuel consumption around 10% [5]. ORC (Organic Rankine cycle) system is considered as a promising method due to its simple configuration and high efficiency [6–9].

The concept of applying an ORC to IC engines first appeared after the 1970 energy crisis [10–12]. Compared with other waste heat recovery technologies, ORC is receiving more and more attention due to its higher thermal efficiency, simplicity and ability to operate efficiently under low and medium grade heat sources [13]. Another advantage of this technology is the use of widely available and affordable components because of the similarities between ORC

---

* Corresponding author. Beijing University of Technology, Pingleyuan No. 100, 100124 Beijing, China. Tel.: +86 10 6739 2469; fax: +86 10 6739 2774.
E-mail address: zhanghongguang@bjut.edu.cn (H. Zhang).

http://dx.doi.org/10.1016/j.energy.2015.10.117
0360-5442/

and refrigeration cycle [14]. However, it is difficult to control the ORC system due to the transient characteristic of IC engines. Another technical bottleneck is that the ORC system requires a large installation space. In addition, the exhaust backpressure will deteriorate the performance of IC engines. Currently, most of the researches are focused on working fluid selection, parameters optimization, and configuration analysis.

The properties of the working fluid have a great influence on the performance of the ORC system. The working fluid with good properties performs higher system efficiency and meets the environmental requirements. Many investigations have been conducted to select the optimal working fluid. Liu et al. presented the influence of working fluids on the performance of ORC for waste heat recovery. The effects of different types of working fluids, including wet, isentropic and dry fluids on the thermal efficiency and the total heat-recovery efficiency were evaluated. The results showed that dry or isentropic fluids are considered as appropriate for the ORC applications [15]. Wang et al. investigated the performances of ORC system with nine different pure organic working fluids for engine waste heat recovery. The results revealed that R245fa and R245ca are the most environment-friendly working fluids [16]. Andreasen et al. provided a generic method for ORCs optimization and fluid selection considering pure fluids and mixtures. It was shown that mixed working fluid can increase the net power output of the cycle [17]. Tian et al. conducted fluids selection and parameters optimization for the ORCs used in exhaust heat recovery of ICE (Internal Combustion Engine). The results indicated that R141b, R123 and R245fa present better performance than the other fluids [13]. Roy et al. presented a study of ORC system by using R12, R123, R134a and R717 as working fluid. The results showed that R123 is the most suitable choice for the investigated system [18]. Xu et al. proposed a critical temperature criterion for selection of working fluids for subcritical pressure organic Rankine cycle. In addition, a new method was developed to couple the heat source with the organic fluid, and the integrated-average temperature difference was used to quantify the thermal match in the evaporator. The results showed that the thermal efficiencies of the ORC system are well correlated with critical temperature. R245fa and R141b can be used over a wide heat source temperature range [19]. Generally speaking, the selection of working fluid is mainly influenced by the heat source temperature range. Besides, operating conditions, thermoeconomic performances, environmental impacts and safety levels should also be concerned. Therefore, no single working fluid is best for all ORC applications. Recently, many studies have shown that the critical temperature limits the application range of the working fluid [19,20]. But more comprehensive study needs to be done in the future.

In order to achieve the optimal performances of the ORC system, several key parameters including evaporation pressure, superheat degree and condensation temperature need to be optimized. Mago et al. analyzed the effects of turbine inlet parameters on the system performances. The results indicated that the fluid with the highest boiling point has the best thermal efficiency [21]. Wang et al. examined the effects of four key thermodynamic parameters, including turbine inlet pressure, turbine inlet temperature, pinch temperature difference and approach temperature difference, on the net power output and surface area of heat exchangers. The results revealed that the thermodynamic parameters have significant effects on net power output and heat transfer area of the ORC system [22]. Liu et al. investigated the sensitivity of system parameters, containing working fluid, superheat degree, pinch temperature difference in the heat exchangers, evaporating temperature, the isentropic efficiencies of the pump and the pump, to the performance of the ORC system. The results showed that the evaporating temperature has a great influence on the thermodynamic and economic performances of the ORC system [23]. Yang et al. analyzed the effects of the turbine inlet and outlet pressures on the net power output, thermal efficiency, and total cost of equipments of the ORC system. The results revealed that the thermo-economic performance of the ORC system can be improved by increasing the turbine inlet temperature in superheated state [24]. Miao et al. conducted the experimental researches by adjusting the frequency of the working fluid pump and the shaft torque of the expander. The results showed that the optimal performance of the ORC system can be controlled by these two parameters [25]. In addition, optimization algorithms are widely used in many researches to improve the system performance for finding the optimal operation parameters.

For parametric optimization, optimization algorithms are used to achieve the optimal system performance. Xi et al. examined the performances of three different ORC systems using six kinds of working fluids. The GA (genetic algorithm) is used to optimize the operating conditions and the thermodynamic parameters [26]. Wang et al. presented a working fluid selection and parametric optimization by using simulated annealing algorithm [27]. Rashidi conducted the parametric optimization of regenerative Clausius and ORC system based on artificial neural network and artificial bees colony algorithm [28].

Different performance criteria are adopted by scholars for evaluating ORC system. One type is the thermodynamic indicators. Shu et al. presented the thermodynamic analysis of a dual loop ORC system with net power output, thermal efficiency, and exergy efficiency as the objective functions [29]. Yang et al. studied the performances of zeotropic mixtures of ORC under engine various operating conditions. Variations of net power output, thermal efficiency, exergy efficiency of the ORC system were investigated [30]. Song et al. examined the waste heat recovery of a marine diesel engine using ORC technology. The maximum power output was adopted as the evaluation criterion to define the optimal system parameters [31]. Maraver provided optimization guidelines for a wide range of operating conditions and different ORC configurations in terms of the exergy efficiency [32].

In addition, another type is the economic indicators. Imran conducted the thermo-economic optimization of basic ORC and regenerative ORC for waste heat recovery. Thermal efficiency and specific investment cost were considered by using NSGA-II (Non-dominated Sorting Genetic Algorithm-II) [33]. Zhang et al. presented an investigation on the parameter optimization and performance comparison of subcritical ORC and transcritical power cycle system for low-temperature geothermal power generation. Thermal efficiency, exergy efficiency, recovery efficiency, heat exchanger area per unit power output and the levelized energy cost were selected as the performance indicators [34]. Li et al. examined the effects of pinch point temperature difference and evaporating temperature on the performance of ORC system for minimizing the electricity production cost [35]. Hajabdollahi et al. optimized the design parameters of the ORC system for diesel engine waste heat recovery. The NSGA-II was applied to maximize the thermal efficiency and minimize the total annual cost simultaneously [36].

Based on the aforementioned analysis, ORC technology which is an effective method to recover the low temperature waste heat has been widely studied, especially in working fluid selection and parameters optimization. But most of researches about the ORC are only focused on stationary heat source. Few studies have been conducted for the IC engines with large temperature span, small mass flow rate and variable heat source. In this paper, the exhaust waste heat characteristics of a vehicle diesel engine are analyzed under various operating conditions. The effects of four key parameters, including evaporation pressure, superheat degree, condensation temperature and exhaust temperature at the outlet of