Energy 147 (2018) 440–450

Contents lists available at ScienceDirect

Energy

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

The effects of design parameters on the dynamic behavior of organic ranking cycle for the engine waste heat recovery

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

State Key Laboratory of Engines, Tianjin University, No.92 Weijin Road, Nankai District, Tianjin, 300072, China

ARTICLE INFO

Article history:

Keywords:
Organic rankine cycle
Dynamic behavior
Design parameters
Waste heat recovery
Controller

ABSTRACT

Organic Rankine Cycle (ORC) is a suitable way to recover the waste heat of internal combustion engines. Since the engine usually operates under different working conditions, the waste heat recovery system is also under unstable state. Consequently, it is quite meaningful to research the dynamic behavior of the ORC. The dynamic math model of the ORC for waste heat recovery of a natural gas engine is established by Simulink in this paper. Based on these, the effects of design parameters of evaporating pressure, condensing pressure, exhaust outlet temperature and working fluids on the ORC dynamic behavior are researched. The results indicate that the dynamic response speed of the ORC just varies a little with the design evaporating pressure, condensing pressure and exhaust outlet temperature. By contrast, different working fluids lead to quite different dynamic response speed. As a result, when designing the ORC, the working fluid should be considered much more to match the dynamic characters of the engine working condition. Furthermore, it is found that ORCs designed under different evaporating pressure, condensing pressure, exhaust outlet temperature can apply the same PID controller, while it is not suitable for ORCs with different working fluids which have quite distinctive critical temperature.

1. Introduction

ORC (Organic Rankine cycle) is attracting more and more attentions for waste heat recovery of ICE (internal combustion engines) [1–3]. In many researches, ORC has been proved to be a potential method to enhance the engine efficiency under stable working conditions. For example, Song et al. proposed [1] two separated ORC systems with R245fa and benzene as the working fluids to utilize waste heat from both the jacket cooling water and the exhaust of a marine engine. The total net power output was found to reach 101.1 kW at most, which resulted in an efficiency increment of 10.2% for the marine diesel engine. Song et al. [2] presented an ORC with internal heat exchanger to recover exhaust energy from a stationary CNG engine. The results showed that the electric efficiency of the combined system could be improved by 6.0%, while the brake specific fuel consumption could be reduced by 5.0%. Kim et al. [3] proposed a highly efficient single-loop ORC for waste heat recovery from a vehicle engine. The novel single-loop system could produce nearly 20% additional power when the engine operated under the target condition.

As mentioned above, these researches are all based on stable engine working conditions. However, the engine work condition often need change to meet the constantly varying demand load, resulting in the change of the waste heat source. The exhaust temperature of the engine can vary from 400 to 900°C under different working conditions [4,5]. At the same time, the exhaust mass flow rate changes greatly as well. These mean the ORC also need operate under unsteady state frequently. Therefore, it is quite necessary to develop a control system in order to make sure the safety and efficiency of the ORC during the whole operating process [6]. For example, Peralez et al. [7] applied a PID controller in an ORC for the vehicle engine waste heat recovery and validated it by experiment, which indicated the superheat degree could be controlled in the safe range by the controller. Mazzi et al. [8] established a dynamic model of ORC to analyze the effectiveness of the proposed control strategy when the state of the heat source changed. The controller should cope with the varying dynamic behavior of the nonlinear ORC system, so it is quite significant to research the dynamic behavior before the design of the control system [9].

Torregrosa et al. [10] did experimental research of an ORC as the waste heat recovery system for a gasoline engine using working fluid ethanol. Both steady tests in three engine operating points and transient tests by changing the engine working conditions were

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

https://doi.org/10.1016/j.energy.2018.01.047
0360-5442/

performed to reveal the dynamic behavior of the ORC. Based on these, a simple and robust adaptive PID controller was validated. Chowdhury et al. [11] established a dynamic model of the supercritical ORC for engine waste heat recovery. The dynamic responses of the ORC system under transient heat source were investigated. It revealed the effects of the working fluid mass flow rate on the dynamic response of the evaporator outlet temperature, which is the key parameter for control of the ORC in real application. Zhao et al. [12] built a dynamic model of ORC system verified by experiment results. The transient variation of the heat resource was divided into 6 modes and they were used as the input of external condition to the dynamic ORC model. Under the 6 modes, the dynamic behavior of the ORC was analyzed. The research results showed useful meaning for understanding the dynamic behavior of ORC under varying working conditions and developing of the control strategy.

All the researches above are for an already designed ORC system and just analyzed the dynamic response behavior when certain system parameters change, such as the cooling water temperature, turbine and pump speed. According to our knowledge, there is few study about the effects of ORC design parameters on its dynamic behavior. If the system is designed under different parameters such as evaporating pressure, condensing pressure and so on, the system dynamic behavior will vary. The dynamic behavior of the ORC should match with the engine working condition characters. For instance, automotive engines of which working conditions change frequently should match with the fast-responding ORC. By contrast, the ORC with slow response speed can be applied in large marine engines, owing to their relatively stable working conditions. If the effects of the design parameters are known, the system can be designed to have the matched dynamic behavior as far as possible. Besides, the varying of the dynamic behavior due to the different design parameters also has effects on the control design. Therefore, in order to study these problems, the dynamic math model of the ORC as the WHRS (waste heat recovery system) for a natural gas ICE is established by Simulink. Based on the model, the following contributions are done in this paper: the effects of the design parameters (evaporating pressure, condensing pressure, exhaust outlet temperature and working fluids) on the dynamic behavior of the ORC are analyzed and compared, illustrating which has the greater effects. Finally, the effects of these design parameters on the PID controller are revealed, which contributes to the design of the control system.

2. System description

The structure of the engine-ORC combined system is shown as in Fig. 1. The exhaust of a natural gas engine with rated power of 1000 kW is the heat source of the ORC. As the power plant, the engine speed keeps 600 rpm all the time while its load varies with the user demand. The main parameters of the engine and exhaust got from our heat balance experiment under seven typical working conditions are shown in Table 1. The exhaust component can be figured out based on the actual volume ratio of air and natural gas with the assumption of complete combustion: $N_2 = 73.4\%$, $CO_2 = 7.11\%$, $H_2O = 14.22\%$ (gas), $O_2 = 5.27\%$. Then the thermophysical property like specific heat capacity, enthalpy and so on can be obtained by REFPORP.

The basic fundamental principle of the ORC is simple as described in the *T-s* diagram of Fig. 2: the liquid working fluid is heated into vapor of high temperature and pressure by the exhaust in the exhaust heat exchanger. Then the vapor expands in the turbine and generates power at the same time, lowing its temperature and pressure. After that, the vapor is cooled into liquid in the condenser. At last, the liquid working fluid is pumped to the

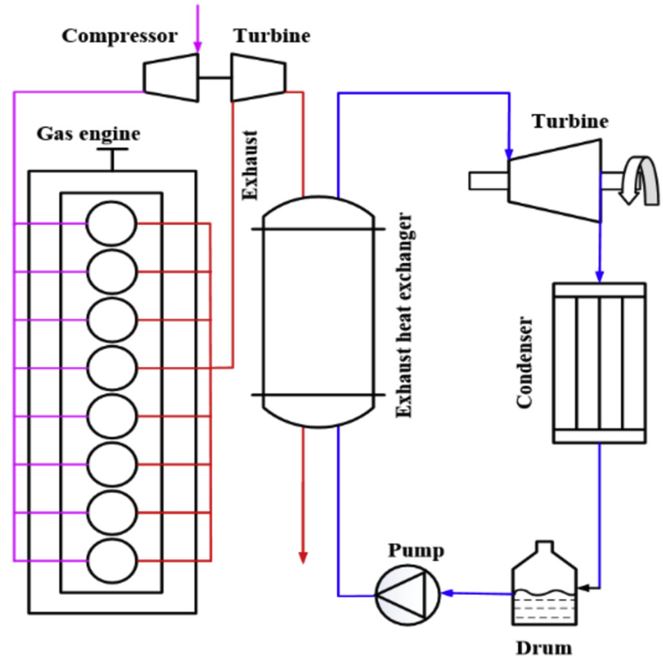

Fig. 1. The schematic diagram of the ORC WHRS.

exhaust heat exchanger again, restarting a new cycle. Most of the organic working fluids are dry fluid, which have positive slope in the *T-s* diagram [13], so just a little superheating degree needs to be kept during the whole running process [14].

3. Math model

The dynamic models are established by Simulink to study the dynamic behavior of the ORC as the engine WHRS. Firs of all, the dynamic models of each main component of the ORC are established and then all of them are connected together, forming the whole system model, based on their interrelationships. The models of the pump and expander are usually replaced by static models, because they respond much faster than heat exchangers [15–17].

3.1. The dynamic models of the components

3.1.1. The heat exchangers

The exhaust heat exchanger is the tubular heat exchanger. The number of the tube pass is more than 4, so it can be regarded as countercurrent [18]. All the heat exchangers in this work are represented as typical counter flow straight pipes for sake of simplicity, although it is well known that complex flow patterns are usually adopted to enhance heat transfer and decrease the size. This assumption reduces the calculation of the dynamic math model to a great extent, but still has enough accuracy, so it is widely applied when establishing the dynamic model of the heat exchanger [19].

Since there is phase change in the exhaust heat exchanger and the heat transfer coefficients of various phase regions are quite different, the dynamic model of the exhaust heat exchanger is established by the MB (moving boundary) method. The MB method has been considered as the most effective and popular way to establish the dynamic modeling of heat exchangers with phase change and proven to be accurate enough by experimental data [20]. Dynamically tracking the length of each region is the main principle of this method. Fig. 3 illustrates the schematic of the three-region MB-model. The lumped parameter method is applied