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Research paper

Performance analysis of exhaust waste heat recovery system for stationary CNG engine based on organic Rankine cycle

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HIGHLIGHTS

- The characteristics of exhaust energy for the stationary CNG engine are investigated.
- The ORC system with IHE is designed to recover the exhaust energy from engine.
- Zeotropic mixture R416A is used as the working fluid of the ORC system.
- The electric efficiency of combined system is defined and investigated.
- BSFC of combined system is studied under various operating conditions of engine.

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ABSTRACT

In order to improve the electric efficiency of a stationary compressed natural gas (CNG) engine, a set of organic Rankine cycle (ORC) system with internal heat exchanger (IHE) is designed to recover exhaust energy that is used to generate electricity. R416A is selected as the working fluid for the waste heat recovery system. According to the first and second laws of thermodynamics, the performances of the ORC system for waste heat recovery are discussed based on the analysis of engine exhaust waste heat characteristics. Subsequently, the stationary CNG engine-ORC with IHE combined system is presented. The electric efficiency and the brake specific fuel consumption (BSFC) are introduced to evaluate the operating performances of the combined system. The results show that, when the evaporation pressure is 3.5 MPa and the engine is operating at the rated condition, the net power output and the thermal efficiency of the ORC system with IHE can reach up to 62.7 kW and 12.5%, respectively. Compared with the stationary CNG engine, the electric efficiency of the combined system can be increased by a maximum 6.0%, while the BSFC can be reduced by a maximum 5.0%.

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1. Introduction

At present, most of stationary compressed natural gas (CNG) engines are developed based on gasoline or diesel engines, which can be widely applied in the power generation industry. Due to the restraints of working principle and structure of internal combustion engine (ICE), it is difficult to fully convert the fuel combustion energy of ICE into the effective power output, and the waste heat from ICE is released into the air via exhaust gas and coolant. The thermal efficiency of most CNG engines is about 30%, which is lower than that of diesel engines. Therefore, recovering the waste heat from stationary CNG engine is an effective way to improve thermal efficiency and save fuel.

At present, many researchers have introduced and discussed some kinds of waste heat recovery systems for the stationary ICE. Therein, the combined heating and power (CHP) as well as the combined cooling, heating and power (CCHP) has been widely applied in the field of stationary ICE waste heat recovery.

Klaassen et al. used the district heat from CHP by means of NGCC (natural gas-fired combined cycle) plants to reduce primary energy consumption for heating. They found that CO_2 mitigation costs were acceptable from a social perspective (at discount rates up to 4%, excluding fuel taxes) and negative from a private perspective (at discount rates up to 10%, including fuel taxes) [1]. Mago et al.

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designed the CHP system to capture the waste heat for space heating or hot water. Results indicated that the use of a CHP system always reduced the emissions of CO_2, NOx and CH_4, as well as the carbon equivalent for all buildings [2]. Wu et al. proposed and investigated a micro-CCHP (micro combined cooling, heating and power) system. The waste heat of ICE was collected and managed by a thermal management controller. So the waste heat could be automatically assigned to different water cycles for heating, cooling, or to be released. Results showed that the system could realize 17.7 kW heating output, 6.5 kW cooling output and 16 kW electric output simultaneously [3]. Li et al. presented the distributed energy system/combined cold, heat and power (DES/CCHP) could not only increase the current energy efficiency from 33% to 50.3% (the world's average), but also reduce the cost of terminal supplies of power, cold, steam and hot water [4].

As one of the promising technologies of converting low-grade waste heat into electricity or useful work, the Organic Rankine Cycle (ORC) system has been studied from different aspects [5–11].

More recently, the waste heat recovery technology with ORC system for stationary ICE has been actively studied by many scholars. Vaja et al. designed a power cycle equipment to match a stationary internal combustion engine, and accordingly chose three pure working fluids to examine three different ORC schemes separately. The analysis demonstrated that a 12% increase in the total efficiency could be achieved with respect to the engine with no ORC cycle [12]. Jacek Kalina investigated the performance of a distributed generation plant made up of gasifier, ICE and ORC machine as a bottoming unit, and applied R123 and R245fa to recover the waste heat. The results obtained were compared in terms of electric energy generation efficiency of the system. The lowest obtained value of the efficiency was 23.6% while the highest one was 28.3% [13]. Lecompte et al. developed a design strategy for an ORC based on thermo-economic considerations, and detected R152a was the optimal working fluid. Through a year simulation, they found that the net power output varied strongly over a year, which in turn affected the specific investment cost [14].

The match of organic working fluids with heat source and ORC system heavily affects the system performance. Zeotropic mixtures have a property called “temperature slip” in evaporation and condensation process and this can reduce exergy destruction rate due to the heat transfer temperature difference.

Garg et al. investigated the properties of isopentane, R245fa and their mixtures used as possible ORC working fluids and found that their mixtures in 0.7/0.3 mol fraction were shown to obviate these disadvantages and yet retained dominant merits of each fluid [15]. Heberle et al. analyzed the influences of working fluids isobutane/isopentane and R227ea/R245fa on the running performances of ORC system, the results showed that the use of mixtures as working fluids leaded to a higher efficiency than pure fluids [16]. Chen et al. performed a comparative study between an organic Rankine cycle and a proposed supercritical Rankine cycle. Through analysis, they concluded that the proposed cycles using zeotropic mixture working fluids could achieve thermal efficiency of 10.8%–13.4% with the cycle high temperature of 393 K–473 K as compared to 9.7%–10.1% for the organic Rankine cycle using pure working fluids [17]. Li et al. compared the cycle efficiency of R141b/RC318 mixtures with that of three pure fluids. It was found that the use of mixtures allowed a wider selection of working fluids. The increase in thermal and exergy efficiencies by adding a recuperator was higher for the mixture R141b/RC318 than for R141b [18]. Wang et al. compared three different mixture compositions of dry R245fa and wet R152a to pure R245fa, in a range from 25 °C (condensation temperature) to 85 °C (vaporization temperature), the main benefits of the mixtures were that the cost of the cycle could be reduced as smaller expanders were suited and that the range of usable fluids increased [19].

Through investigation, CHP, CCHP and ORC systems are all effective ways to recover the waste heat from stationary ICE. Therein, CHP and CCHP that established the concept of energy cascade utilization is a polygeneration total energy system integrating generating electricity, cooling and heating. The thermal efficiency of ICE can reach up to 80% by using CHP and CCHP. In the view of recovering waste heat from stationary ICE, compared with ORC system, CHP and CCHP are adopted for utilizing the waste heat from exhaust gas and coolant to drive refrigeration unit and supply heat through heat exchanger, but there is no conversion of waste heat into mechanical power which can be used to drive electricity generator. In order to produce more electricity and then improve the electric efficiency of stationary ICE, ORC waste heat recovery system is more suitable for stationary ICE. For the stationary CNG engine-ORC combined system, few scholars study the system performances of ORC under various operating conditions of a stationary ICE for the purpose of waste heat recovery and high electric efficiency. Furthermore, under various operating conditions of a stationary ICE, zeotropic mixtures have significant potential in optimizing the ORC system performances than pure working fluids. For now, however, few scholars use the zeotropic mixtures for ORC system in recovering the exhaust energy from a stationary ICE.

2. Exhaust waste heat recovery system based on ORC with IHE

2.1. System description

In order to take full advantage of the exhaust waste heat from a stationary CNG engine, the ORC system with IHE is designed as shown in Fig. 1. The system consists of an evaporator, a condenser, an expander, a recuperator (namely IHE), a pump, a reservoir and two generators. At the beginning, the exhaust gas exchanges heat with the high-pressure liquid state organic working fluid in the evaporator, then the exhaust gas is released through the evaporator into the atmosphere. At the same time the working fluid turns into high-temperature and high-pressure gas and soon enters the expander to produce useful work which is used to generate electricity. Later, the temperature and pressure of the working fluid drop, the working fluid exhausted from the expander goes into the recuperator to exchange heat with the liquid working fluid exported from the pump. Subsequently, the cooled working fluid that is exhausted from the recuperator condenses into a saturated liquid state in the condenser and flows into the reservoir. The working fluid is pressurized into a high-pressure liquid state using the pump and then absorbs heat in the recuperator. Finally, the working fluid flows into the evaporator to absorb the heat from engine exhaust. So far, the whole process is completed.

2.2. Thermodynamic model

Fig. 2 is the T–s diagram of the ORC system with IHE. Process 1–2 is the actual pressurization process in the pump. Process 1–2s is the isentropic pressurization process corresponding to Process 1–2. Process 2–3 is the isobaric endothermic process of the working fluids in the recuperator. Process 3–4 is the isobaric endothermic process, in which the working fluid absorbs the heat from engine exhaust in the evaporator and soon turns into high-temperature and high-pressure gas. Process 4–5s is the isentropic expansion process, while Process 4–5 is the actual expansion process. Process 5–6 is the isobaric exothermic process of the working fluid in the recuperator. Process 6–1 is the isobaric condensation process. Process $T_{\text{exh\_in}} - T_{\text{exh\_out}}$ is the heat rejection process of the engine exhaust in the evaporator, $T_{\text{exh\_in}}$ is the exhaust gas temperature at the inlet of the evaporator, $T_{\text{exh\_out}}$ is the exhaust gas temperature at the outlet of the evaporator.

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