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Working fluid selection for a small-scale organic Rankine cycle recovering engine waste heat

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Abstract

This paper reports the design and evaluation of a 1 kWe Organic Rankine cycle using different working fluids for engine coolant and exhaust recovery from a 6.5 kW small ICE. Six working fluids have been selected to evaluate and compare the performance of the ORC system. The net power output, thermal efficiency, rotational speed of the scroll expander and condenser load of the ORC system have been studied. Results indicated R134a and R125a have better overall performance than other candidates when the designed inlet temperature of the expander is higher than 150 °C. The highest net power and thermal efficiency are respectively 1.2 kW and 13% when R125a is used as the working fluid. R600 and R245fa are desirable to be used when the optimal rotational speed of the scroll expander is about 3000 RPM. The proposed ORC engine coolant and exhaust waste heat recovery system has the advantages of simple system layout, low dumped heat load of condenser, high power output.

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Keywords: Organic Rankine Cycle; scroll expander; coolant and exhaust recovery; Internal Combustion Engine

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1. Introduction

As one of the most promising heat recovery technologies to convert wasted energy from Internal Combustion Engine (ICE) into useful energy, Organic Rankine Cycle (ORC) attracts ever increasing attention from both academic and industry [1-3]. Velez et al. [4] pointed out the market available for ORC systems with the power ranges of 0.2 to 2 MWe under the cost of around 1 and 4×103 € /kWe. Most of the current research interest for engine waste heat recovery is mainly focusing on the recovery of engine exhaust energy because of the relatively high temperature from this energy source, which can potentially form a high thermal efficiency ORC system [2]. However, the engine coolant energy containing about 30% of the overall fuel energy, is difficult to recover and attracts ever increasing attention due to high demand for high energy efficiency and low emissions engines [5-7].

The working fluids in ORC are classified in three groups: dry, isentropic and wet types depending on the slope of the vapor saturation curve on the T-s diagram [8]. The selection of working fluid plays a key role in ORC performance [9-12]. Wang et al. [9] reported a study that compares the performance of 10 kW net power output ORC system using different working fluids for engine exhaust heat recovery. Results indicate R11, R141b, R113 and R123 manifest slightly higher thermodynamic performances than other working fluids [9].

A system performance study of a geothermal ORC system using 31 pure working fluids has been conducted by Saleh et al. [10]. The maximum thermal efficiency was found to be 0.13 with n-butane as the working fluid for 120 ºC heat source temperature [10]. Shu et al. [13] proposed a new dual-loop ORC for engine waste heat recovery and investigated the system performance using first and second law analyses. Six working fluids were selected for the evaluation and comparison of system performance. The results pointed to R1235yf as the optimal working fluid under engine high operating load [13]. However, dual-loop ORC requires relatively complex control strategies and more system components, which will increase the capital cost of the system and lead to high payback period.

In this study, we report the design and evaluation of a small scale ORC system using different working fluids for engine coolant and exhaust recovery. A scroll expander was selected as the expansion machine in the small scale ORC system because the scroll expander has the advantage of high reliability, relatively high isentropic efficiency and broad availability [14-16]. Six working fluids have been selected to compare the system performance including net power, thermal efficiency of the ORC, rotational speed of the scroll device and condenser loads. Moreover, the effects of using different working fluids on the overall engine performance have been conducted and discussed.

2. Description of the designed engine waste heat recovery ORC system

The ORC system designed to recovery the engine coolant and exhaust energy mainly includes a pump, two heat exchangers, a scroll expander, a condenser and a liquid receiver as shown in Fig. 1. The first heat exchanger (Heater 1) is used to recover the coolant energy from the engine. An exhaust heat exchanger has been located at the exhaust of the engine and an oil loop has been designed to transfer the exhaust energy to heat up the working fluid in the second heat exchanger (Heater 2). A liquid receiver has been located at the inlet of the pump in order to provide the pure liquid working fluid to the pump and prevent two phase working fluid entering the pump. A bypass line has been located between the inlet and outlet of the scroll expander, which will be used during the start-up of the system in order to provide full gas phase working fluid to the scroll device for power generation. The unused energy at the exit of the expander is dumped to the environment through the condenser, which cool down be the cooling tower. The working principles of the ORC system are defined as: isentropic compression process in the pump; isobaric process during the heating process of the working fluid recovering coolant energy; isobaric process for the recovery of exhaust energy; isentropic expansion process in the scroll expander; isobaric process in the condenser. Detailed calculation methods are introduced in the following section.