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Research Paper

Experimental study and performance analysis of a hydraulic diaphragm metering pump used in organic Rankine cycle system

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HIGHLIGHTS

- The operating performance of the metering pump for different strokes was analyzed.
- The influence of the metering pump on the ORC system was conducted.
- The maximum value of the specific speed was determined.
- The effect of pump efficiency on net output power was discussed.

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ABSTRACT

In this paper, a performance test of a hydraulic diaphragm metering pump using R123 is conducted. The interaction relationships of key parameters of the pump and its influence on the performance of the ORC system are analyzed. The application feasibility of the pump has been proved by comparison to previous studies. The results indicate that the mass flow rate of the pump varies from 0.23 t/h to 2.06 t/h and is mostly independent of outlet pressure. Both power input and actual efficiency of the pump increase with stroke; the actual efficiency reaches up to a maximum of 88.27%. The specific speed decreases with the increase of outlet pressure. Moreover, the actual net power output and thermal efficiency of the ORC system increase with evaporating temperature. Actual net power output is more sensitive than thermal efficiency to stroke. The thermal efficiency presents a nonlinearly rapid decline trend with the increase of specific speed. Back work ratio (BWR) can reach up to a maximum of 0.93. Thus, the power input of working fluid pump is not negligible in the ORC system and the assumptions of actual efficiency of pump should be dependent on experimental results according to various operating conditions.

1. Introduction

With energy being the driving force of socioeconomic development, the increasing number of vehicles has caused serious problems such as pollution and energy crisis. As observed from the energy balance of internal combustion engine (ICE), only 20–30% (gasoline engine) or 30–45% (diesel engine) of total fuel combustion energy is used for power output, the remaining is mainly discharged into the atmosphere through the cooling medium or exhaust [1,2]. The waste heat recovery (WHR) of ICE can improve the total energy conversion efficiency and reduce fuel consumption. Moreover, several methods have already been introduced for ICE waste heat recovery including turbocompounding [3], absorption refrigeration cycle [4], and thermoelectric generators [5]. However, the energy utilization rate of these methods is low. Organic Rankine cycle (ORC) system can convert low-grade energy into useful power, which has been widely applied to geothermal energy [6,7], solar energy [8,9], biomass energy [10,11], industrial waste heat [12,13] and many other areas.

ORC system is also considered as a promising approach to recover waste heat energy of ICE because of its simple structure, flexible adjustment and low driving temperature, etc. Uusitalo et al. [14] discussed the working fluid selection and experimental results of a small-scale ORC unit utilizing exhaust heat of a diesel engine. Glover et al. [15] focused on multiple series heat sources from vehicles and presented the analysis of a supercritical WHR

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Nomenclature

q	flow rate (t h^{-1})
p	pressure (MPa)
W	power (W)
Q	heat absorption rate (W)
h	enthalpy (J kg^{-1})
Greek symbol	
η	efficiency (%)
ρ	density (kg m^{-3})
Subscripts	
m	mass
P	pump
exp	expansion process
net	net
th	thermodynamics
eva	evaporate
1	inlet state of expander
2	outlet state of expander
3	inlet state of pump
4	outlet state of pump
Acronyms	
ORC	organic Rankine cycle
BWR	back work ratio
ICE	internal combustion engine
WHR	waste heat recovery
HDMP	hydraulic diaphragm metering pump
MCP	multistage centrifugal pump

ORC modelling study. Katsanos et al. [16] investigated the potential improvement of the overall efficiency of a heavy-duty truck diesel engine equipped with ORC system for recovering heat from the exhaust gases. Galindo et al. [17] presented a multi-objective optimization method to design an ORC system for vehicle WHR. In order to improve the overall performance of the ORC system, current research is devoted to selection of working fluid [18], parametric optimization of the ORC system [19], expander [20] and heat exchanger [21]. However, few scholars have focused on the working fluid pump, which provides mass flow rate and evaporating pressure to satisfy the requirements of the ORC system. Moreover, evaporating pressure has significant effects on improving the overall performance and component properties of the ORC system, such as net power output, thermal efficiency and expander efficiency [22]. Bianchi et al. [23] presented that pumping work in energy recovery units based on organic Rankine cycles can severely affect the net power output recovered. Quoilin et al. [24] presented that the power consumption of the pump should be considered in the calculations of the thermal efficiency and net power of the ORC system. Yang et al. [25] explored the effect of pump performance on the ORC system, showing that the piston pump had a wide range of flow rates and the practical flow rate was difficult to reach the rated value. Meng et al. [26] constructed a test bench of a multistage centrifugal pump in simulative organic Rankine cycle (ORC) conditions, indicating the pump efficiency is between 15% and 65.7% in an ORC system environment.

Positive displacement pumps were suitable for the system of high pressure, medium and small mass flow rate, which was widely used in the ORC system due to good airtightness, small volume, light weight and convenient maintenance [27–29]. Nevertheless, many studies are restricted to obtain the actual efficiency and power input of the positive displacement pump at various operating conditions because of the ORC experiment limitations. Very few studies have specially concentrated on the effect of different operating conditions of the positive displacement pump on variation tendency and interaction relationships of key parameters. Furthermore, the strategy to improve the efficiency and reduce power input of the positive displacement pump has yet to be further investigated.

The ORC system for ICE waste heat recovery runs under various operating conditions. In addition, the control strategy of the ORC system is complex due to the transient regime of the heat source. Thus, it is necessary to control the positive displacement pump to maintain required conditions to maximize the utilization of waste heat energy. Hydraulic diaphragm metering pump is a typical positive displacement pump. We conducted a performance test of the hydraulic diaphragm metering pump using R123 under simulative ORC conditions with certain condensing conditions (T_c = 313.65 ± 1 K, p_c = 0.19 ± 0.01 MPa). The performance of the hydraulic diaphragm metering pump in the ORC system for WHR of ICE was explored, characteristic curves of the hydraulic diaphragm metering pump under various operating conditions were obtained. The interaction relationships of key parameters of the hydraulic diaphragm metering pump and its influences on the ORC performance under various operating conditions were analyzed. Subsequently, the application feasibility of the hydraulic diaphragm metering pump in the ORC system was justified according to the analysis of experimental data.

2. Experiment statement

The working principle of the hydraulic diaphragm metering pump is to deliver working fluid and increase its pressure relying on periodic changes of working volume [30]. The hydraulic diaphragm metering pump has many characteristics: small noise, simple maintenance, strong sealing, simple maintenance, safe discharge device and so on. The technical parameters are shown in Table 1.

2.1. Performance-testing platform

Figs. 1 and 2 exhibits experimental setup and schematic diagram of the performance test platform of the hydraulic diaphragm metering pump, respectively. Main components in the platform are as follows: storage tank, globe valve, hydraulic diaphragm metering pump, pulse damper, back pressure valve, filter, power meter, temperature or pressure sensors, mass flow meter, data acquisition instruments and so on.

Before experimentation, pipeline and components were ensured to be connected hermetically, the whole system was vacuumed and R123 was poured into the storage tank. During the experiment process, the working fluid was extracted and

Table 1
Parameters of the hydraulic diaphragm metering pump.

Parameters	Value	Unit
Type	JYSR700/1.6	–
Pressure	1.6	MPa
Power	1500	W
Plunger diameter	60	mm
Plunger stroke	30	mm