Applied Thermal Engineering 110 (2017) 779–786

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Study of efficiency of a multistage centrifugal pump used in engine waste heat recovery application

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HIGHLIGHTS

- The performances of the pump under various operating conditions were studied.
- The interactive relations of key parameters of the pump were investigated.
- The influence of the pump on the ORC system was conducted.
- The optimal control strategy of the pump was presented.

ARTICLE INFO

Article history:
Received 25 July 2016
Accepted 31 August 2016
Available online 1 September 2016

Keywords:
Organic Rankine cycle
Waste heat recovery
Multistage centrifugal pump
Various operating conditions
Running performance

ABSTRACT

A test bench of a multistage centrifugal pump was constructed using R123 as working fluid in simulative organic Rankine cycle (ORC) conditions. Experimental results of the pump under various operating conditions were obtained based on controlled working frequency and mass flow rate. The effect of the key pump parameters on the ORC performance was analyzed in this study. In addition, the control strategy of the pump was presented. Results show that the overall pump efficiency was between 15% and 65.7%. The outlet pressure, pump efficiency, and ORC thermal efficiency increased with the working frequency of the pump. The mass flow rate needed to be regulated as the frequency became increasingly high. The maximum thermal efficiencies of the ORC system corresponding to various working frequencies of the pump were observed. Furthermore, back work ratio (BWR) can reach up to 0.45 with the increase of the evaporating temperature of the ORC system. Pumping power should not be neglected for small-scale ORC applications, and pump efficiency assumptions should be dependent on experiments. Low pump efficiency affected the increase of the thermal efficiency and net power of the ORC system. The superheat degree was also discussed.

1. Introduction

The energy currently generated by fuel combustion in internal combustion (IC) engines is not entirely converted into useful work. The thermal efficiency of IC engines is often below 30% (gasoline engine) or 45% (diesel engine). Most of the combustion energy is released into the atmosphere in the form of waste heat through the coolant system and exhaust [1–3]. The recovery of low-grade thermal energy can effectively improve the overall energy conversion efficiency and substantially reduce fuel consumption. Organic Rankine cycle (ORC) is a promising approach to recover the energy of waste heat and has been extensively used in low-grade waste heat [4]. The large-scale ORC system technology has matured [5], whereas the IC engine exhaust [6–8], geothermal energy [9,10], solar energy [11,12], biomass energy [13], and the ORC technology for low temperature heat source have yet to undergo mass production. Therefore, scholars have performed numerous theoretical and experimental studies on small-scale ORC systems. However, most of these scholars have focused considerable attention to the expander and heat exchangers [14–17]. Moreover, the working fluid pump, which is a key component, also limits the further development of small-scale ORC systems.

In general, an ORC system runs under various operating conditions when the waste heat of IC engines is recovered. Thus, the

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.226

Nomenclature

p	pressure (MPa)
q_v	volume flow rate (m^3/s)
q	the absorbed heat (kJ/kg)
w	specific pumping work (kJ/kg)
P	electrical power consumption (W)
Greek letters	
ρ	density (kg/m^3)
η	efficiency (%)
Subscripts	
1	inlet state of pump
2	outlet state of pump
p	pump
th	theoretical
ex	expander
ev	evaporator
ORC	organic Rankine cycle

working fluid pump should accurately provide the required mass flow rate and high evaporating pressure based on the varied operating conditions to satisfy the requirements of the ORC system. Therefore, particular attention should be focused on the working fluid pump at off-design pump conditions. Meanwhile, the working fluid pump is the main component of power consumption in an ORC system. Therefore, the power consumption of the pump should also be strictly controlled to ensure the maximization of the net power. In addition, the parameter values of the working fluid pump are often assumed constant in the present theoretical analysis. For example, the evaporating pressure of an ORC system is frequently assumed in the range of 3–10 MPa to match the variation of the mass flow rate [18–21]. However, these two parameters are mainly dependent on the working fluid pump itself in practical applications. Accordingly, pump work is equal to the product of the enthalpy differences at the pump inlet and outlet and mass flow rate [22,23], thereby possibly resulting in underestimation of the actual power consumption. By contrast, pump efficiency is often assumed to be 75–85% [24–28]. Consequently, the effect of the efficiency variation of the working fluid pump on the ORC running performance is also neglected. Thus, all the assumed parameter values of the pump should be verified through experiments, and cannot be constant under various operating conditions.

A few scholars conducted a series of theoretical and experimental investigations on the ORC system pump. Quoilin et al. [29] indicated that the power consumption of the pump should be considered in the calculations of the thermal efficiency and net power of ORC systems. Meanwhile, back work ratio (BWR) increases significantly when the evaporating temperature nears the critical temperature of the organic fluid. Aleksandra [30] analyzed 18 different organic fluids in ORC systems. The results showed that working fluids with low critical temperature had considerable pressure difference and pumping power. BWR ranges from 0.3% to 14%. Yang et al. [31] indicated that the efficiency of the piston pump ranged from 17% to 30% in the ORC system experiment. Meanwhile, the analysis showed that the low overall efficiency resulted from the low mechanical efficiency of the pump. Chang et al. [32] indicated that the efficiency of the plunger pump improved with the increase of the pressure drop of the ORC system. The maximum pressure drop of the ORC system and efficiency of the plunger pump were 0.8 MPa and 33.6%, respectively; the corresponding pumping power of the motor was 2040 W. Evidently, the efficiency of the plunger pump did not vary with the degree of superheat, and the pressure difference of the ORC system mainly affected the performance of the pump. Mathias et al. [33] indicated that the gear pump consumed 2200 W. The tests were performed again at similar conditions with the duplex, positive displacement, and piston pump, and merely consumed 560 W. The highest efficiency of the pump was 69% and the highest pressure was 2.57 MPa.

Most current studies are limited to obtaining the efficiency and power consumption of the working fluid pump at several operating conditions, as well as illustrates the poor performance of the pump in the ORC system, because of the ORC experiment limitations. However, the effect of poor pump performance on ORC systems has not been specifically investigated. Meanwhile, few studies have focused on the variation tendency and interactive relationships of the working parameters over various operating ranges of the pump. Furthermore, the method to improve the pumping efficiency and reduce the power consumption of the pump has yet to be further considered. The current study is to investigate the running performances of a multistage centrifugal pump under various operating conditions in a simulative ORC environment. A test bench of multistage centrifugal pump was built using R123 as working fluid. The match between the multistage centrifugal pump and ORC system for engine waste heat recovery were studied. Subsequently, the thermodynamic performances of the ORC system according to the pump experimental results were analyzed.

2. Pump experimental setup

Fig. 1 shows the schematic diagram of the experimental system. The experimental system mainly includes the reservoir, multistage centrifugal pump, mass flow meter, cut-off value and filter. Table 1 lists the main performance parameters of the multistage centrifugal pump. A multistage centrifugal pump is a typical vane pump that can satisfy the working demand of the ORC system. Each component and the pipes were connected hermetically before the experiment. The working fluid (i.e., R123) was poured into the reservoir after the entire system was vacuumed. The working fluid was extracted and pressurized by the multistage centrifugal pump during the experiment. The high pressure working fluid flowed through the cut-off valve, filter, and mass flow meter. Thereafter, the working fluid was sent back to the reservoir. The rotational speed of the multistage centrifugal pump was changed by the frequency converter, and the cut-off valve was used to regulate the mass flow rate of the organic fluid to change the operating conditions of the multistage centrifugal pump. Table 3 provides the rotational speeds of the pump at different frequencies. In order to avoid cavitation damages, a balance pipe was connected between the reservoir and inlet of the pump to ensure the same pressure. The power consumption of the electric machine was measured using a power meter. Pressure and temperature sensors were placed at the pump inlet and outlet to measure the pressure and temperature of the organic fluid. A mass flow meter was installed at the back of the cut-off valve to measure the mass flow rates. Experimental data were collected using an Agilent data acquisition instrument when the system operated under steady state conditions. Table 2 shows the main parameters of the sensors. Fig. 2 provides the photos of the experimental system.