Applied Thermal Engineering 126 (2017) 9–16

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Experimental study on multi-stage gas-liquid booster pump for working fluid pressurization

Tengma Wu [a], Jianhua Liu [a,b,*], Liang Zhang [a], Xiaojin Xu [c]

[a] School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
[b] Shanghai Key Laboratory of Multiphase Flow and Heat Transfer in Power Engineering, Shanghai 200093, China
[c] No. 704 Research Institute, CSIC, Shanghai 200031, China

ARTICLE INFO

Article history:
Received 14 March 2017
Revised 16 May 2017
Accepted 18 July 2017
Available online 21 July 2017

Keywords:
Organic Rankine cycle
Pump power
Multi-stage gas-liquid booster pump
Conversion efficiency

ABSTRACT

To improve the performance of organic Rankine cycle (ORC) system, this paper proposes to replace the electric working fluid pump with multi-stage gas-liquid booster pump which is driven by high pressure gas generated in evaporator of ORC system. This pump consists of four gas-liquid booster pumps. The working principle of gas-liquid booster pump and multi-stage gas-liquid booster pump are introduced respectively. By using high pressure air as driving force and water as pressurized working fluid, the performance of multi-stage gas-liquid booster pump is tested experimentally. The experimental results of this study mainly consist of two parts: the first part focuses on the pump performance with various pressure at pump inlet and outlet while valve at pump inlet is completely open; the second part focuses on various valve open ratio at pump inlet which is operated at fixed inlet and outlet pressure of 1.8 MPa and 0.15 MPa. The results show that the pump conversion efficiency decreases with the increase of inlet pressure and the decrease of outlet pressure. The maximum conversion efficiency, volume flow rate of water and volume flow rate of high pressure air are 0.72, 0.55 L/s and 0.42 L/s respectively. When the pump is operated at different valve open ratio, the volume flow rate of water and high pressure air decreases with the decrement of valve open ratio. In addition, the conversion efficiency almost maintains identical under different valve open ratio.

1. Introduction

With increasingly world-wide environmental concerns about global warming due to carbon emission associated with fossil fuel consumptions, the utilization of low temperature heat sources (such as solar, biomass, geothermal and waste heat) becomes more and more important [1]. One method enjoying a resurgence of interest in this area is the organic Rankine cycle (ORC), which is understood as the most realized one among several proposed technologies for generating electricity via the utilization of low-grade heat sources [2–6]. Among the components of the conventional ORC for low-grade heat recovery, the working fluid pump tends to cause a critical decline in the net cycle efficiency. This drawback is pronounced in small ORC systems in which the power output is less than 10 kW and the heat source temperature level is less than 200 °C [7]. In the worst case, the net cycle efficiency can be zero or negative depending on the pumping power consumption.

The working fluid is pressurized from the condensing pressure to the evaporating pressure by the working fluid pump in the ORC system. The efficiency of pump decreases sharply due to off-design conditions. For example, mass flow rates are greater or less than the designed value while electricity is used as the driving force [8]. The efficiency of ORC pump is assumed at various levels: 0.65 [9], 0.75 [10], 0.8 [11], up to 0.85 [12]. Unfortunately, theses assumptions have simplified the analysis of ORC pump and lead to overestimation of the performance of ORC. According to the results presented by Chang et al. [13], the maximum pump efficiency tested in the experiment is only 0.33 at power consumption of 0.204 kW by the motor and power production of 1.56 kW from the generator respectively. The average pump efficiency of the system ranges from 0.22 to 0.30, which is much lower than the assumed levels in early studies. In addition, the net cycle efficiency of the ORC decreases significantly while the pump efficiency is below 20% due to off-design operation [14,15].

Furthermore, the power consumed by ORC pump is much more appreciable [16]. In the conventional steam Rankine cycle, the power for water pressurization is negligible as the water pump consumes 1–2% of the power produced by expander [17]. However,

* Corresponding author at: School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China.
E-mail address: usst135@126.com (J. Liu).

http://dx.doi.org/10.1016/j.applthermaleng.2017.07.159
1359-4311/

Nomenclature

P	pressure (MPa)
S	area (m^2)
V	volume flow rate (L/s)
p	pump
m	mass flow rate (kg/s)
v	specific volume (m^3/kg)
W	power (kW)
Greek symbols	
η	efficiency
Subscript	
H	high
L	low
g	gas
s	process
l	liquid
1	pump 1
2	pump 2
3	pump 3
4	pump 4

the ORC pump will consume a large portion of the power produced by expander, and this statement is proved by existing researches. A small-scale ORC using R123 as working fluid is tested by Miao et al. and the results show that the portion of power consumed by ORC pump is 11.5% and 29.9% of the total power output at the heat source temperature of 140 °C and 160 °C respectively [18]. A study conducted by Usman et al. shows that the portion of power consumed by ORC pump is 18.9% when power generated by expander is 1 kW and R245fa is used as working fluid [19]. There are also some other studies in which the portion of power consumed by ORC pump can be indirectly derived from the measured data provided in the published papers, such as 16.7% [20], 21.9% [21], and 22.2% [22]. From the discussions above, it is obvious that the portion of power consumed by ORC pump has a significant influence on the performance of ORC system.

To solve the problems caused by ORC pump, Li et al. [23] develops a novel gravity driving ORC for small-scale cogeneration applications, but the lowest required height for working fluid pressurization is about 18.7 m while PF5060 is selected as the working fluid. Although the ORC pump is replaced, enough room is needed for the novel gravity driving ORC. Another study presented by Yamada et al. [24–26] is a new PRC (pumpless organic Rankine-type cycle), which has the characteristics of low cost and relatively high net power. However, the maximum net power generated in this system is on small scale, and the output of the power is unstable, which will influence the usage of energy.

To overcome the drawbacks mentioned above, a working fluid pump (gas-liquid booster pump) driven by high pressure gas generated in the evaporator of ORC is proposed in this paper. As there is no electric power consumed by working fluid pump, the conversion losses associated with electrical motor is eliminated and the net power by ORC increases. As multi-stage gas-liquid booster pump is used, the conversion losses between high pressure gas and pressurized liquid are reduced largely. In order to investigate the possibility and performance of the multi-stage gas-liquid booster pump, a test rig is established in this study. With water as pressurized working fluid and high pressure air as driving force, the work capacity and efficiency are examined at different work conditions. This pump is expected to be further used in ORC system.

2. Working fluid pump driven by high pressure gas

2.1. Working principle of gas-liquid booster pump

Fig. 1 shows the schematic diagram of the gas-liquid booster pump, which consists of a cylinder block, a piston, a reversing valve, four one-way valves and two valves at the internal face of the cylinder. High pressure gas acts on large area of the piston and pressurized liquid is acted on small area of the piston. By adjusting the location of high pressure gas acting on the large area of the piston, the moving direction of the piston is controlled, and the moving direction of the pressurized liquid in the cylinder E and

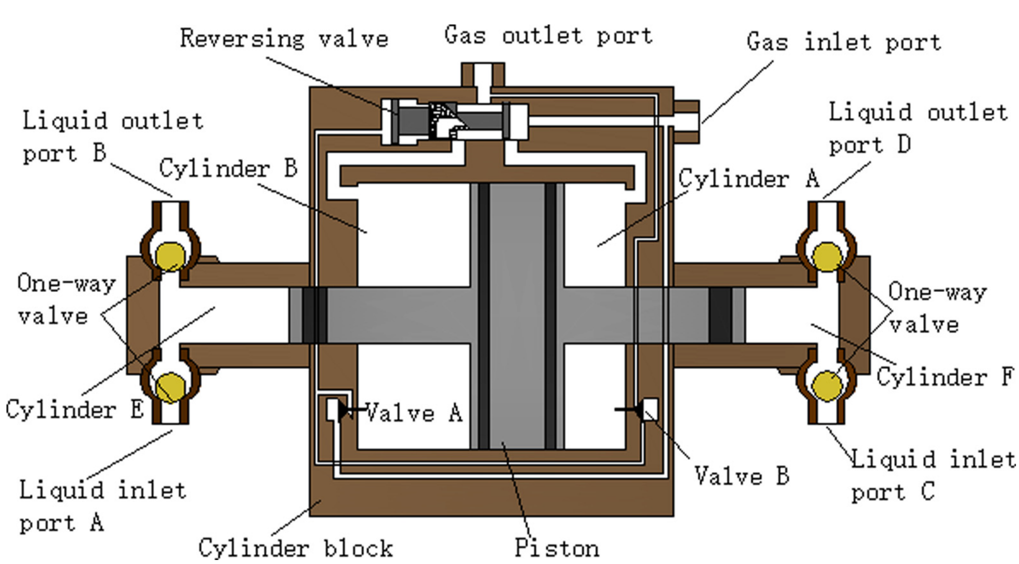

Fig. 1. Schematic diagram of gas-liquid booster pump.