Energy 116 (2016) 43–52

Contents lists available at ScienceDirect

Energy

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

Development and experimental study on a single screw expander integrated into an Organic Rankine Cycle

Biao Lei, Wei Wang*, Yu-Ting Wu, Chong-Fang Ma, Jing-Fu Wang, Lei Zhang, Chuang Li, Ying-Kun Zhao, Rui-Ping Zhi

Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education and Key Laboratory of Heat Transfer and Energy Conversion, Beijing Municipality, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Article history:
Received 13 February 2016
Received in revised form
13 July 2016
Accepted 14 September 2016

Keywords:
Organic Rankine Cycle
Single screw expander
R123
Circulation pump

ABSTRACT

Expander is a key components in Organic Rankine Cycle (ORC) system. In order to improve the performances of single screw expander in large expansion ratio conditions and give consideration to normal conditions, a new idea called 'increasing the built-in volume ratio appropriately and converting single screw expander into double-stage machine in large expansion conditions by utilizing the discharge velocity of screw grooves was proposed. By implementing this idea, a new prototype of single screw expander was designed and manufactured. Then the prototype was integrated into an experimental ORC system with R123. Experiments were carried out to analyze the characteristics of the developed single screw expander and the ORC system. The results show that the maximum expander shaft power, shaft efficiency, isentropic efficiency, volume efficiency and expansion ratio were 8.35 kW, 56%, 73%, 83% and 8.5, respectively. In addition, under expansion losses seem to be eliminated by the new structure of the expander. It was also found that 12–17% of the expander power was consumed by the circulation pump, of which the measured efficiency was between 20% and 31%. A maximum ORC efficiency of 7.98% was achieved.

1. Introduction

Steam Rankine cycle is widely used in the field of heat-power conversion. However, when the temperature of heat source is below 250 °C, steam Rankine cycle is not favorable because the high specific volume of steam at low pressure requires large installation and mandatory air removal in condensing mode [1]. In order to address this issue, organic fluids with low boiling point, such as R123 and R245fa, were proposed to substitute water as the working fluids. The Rankine cycle using organic fluids instead of water turns into an Organic Rankine Cycle (ORC). ORC has attracted a lot of attention in recent years [2–4], and it is one of the most promising technologies in the field of converting low grade heat into power [5–7]. The low grade heat can be solar energy [8], geothermal energy [9,10] and industrial waste heat [11,12], which are all widely available.

Expander is a key component in ORC system. There are two types of expander. One is the turbo type, and the other is the positive-displacement type. Large scale ORC systems normally adopt turbo expanders [6,13]. However, for small scale ORC unit, turbo expander might not be favorable. Previous investigations have revealed that the rotational speed of turbo expanders increases with the decrease in turbine output power [14]. The rotational speed of small scale turbo expanders become very high, and the experimental data are normally between 17000 and 65000 $r \cdot min^{-1}$[6,15,16]. In this condition, positive-displacement expanders, such as rolling piston expander [17], scroll expander [18,19] and single screw expander [20,21], are good substitutes for turbo machines due to their relatively high efficiency, high pressure ratio, low rotational speed and tolerance of two-phase fluids [6]. Therefore a lot of experimental small scale ORC units employ positive-displacement expanders. Scroll expander is a research hotspot. Table 1 summarizes recently experimental results which focus on scroll expanders. From the table, it is known that:

(1) The expanders were reversely operated scroll compressors, and the expander power was normally smaller than 3.5 kW.

* Corresponding author.
E-mail address: wang_wei@bjut.edu.cn (W. Wang).

http://dx.doi.org/10.1016/j.energy.2016.09.089
0360-5442/

Nomenclature

$\dot{W}$	power [W, kW]
h	enthalpy [J kg^{-1}, kJ kg^{-1}]
p	pressure [Pa, kPa, MPa]
Δp	pressure drop [Pa, kPa, MPa]
v	specific volume [m^3 kg^{-1}]
N	torque [N m]
n	expander rotational speed [r min^{-1}]
q	flow rate [kg s^{-1}, kg h^{-1}, m^3 h^{-1}, m^3 s^{-1}]
m	mass

Greek symbol

η	efficiency [−]
ε_p	expansion ratio [−]

Subscripts

1	inlet state of expander
2	outlet state of expander
2′	outlet state of oil separator
3	inlet state of circulation pump
4	outlet state of circulating pump
is	isentropic
sh	shaft
t	expander
th	theoretical
P	circulating pump
V	volume
m	mass

Abbreviations

ORC	Organic Rankine Cycle
AC	Alternating Current
CP	Cylinder and Plane

Table 1
List of scroll expanders in literature.

Authors	Built-in volume ratios	Working fluids	Output power (kW)	Rotational speed (r min^{-1})	Expansion ratio	Efficiency	Expander specifications
Lemort et al. [23]	4.05	R123	0.4–1.8	1770–2660	2.7–5.4	42–68%	Reversely operated oil-free scroll air compressor
Declaye et al. [22]	3.95	R245fa	2.1	2000–3500	3–7.4	55–75.7%	Reversely operated oil-free scroll air compressor
Lemort et al. [24]	3.0	R245fa	0.45–2.2	2000–2850	2–6	71.03%[a]	Reversely operated Refrigeration scroll expander
Chan et al. [25]	2.12	R245fa	1.375	Unknown	Unknown	60.8–68.4%[a]	Reversely operated automotive air conditioning scroll compressor
Chang et al. [25]	2.95	R245fa	1.77	Unknown	Unknown	72–75%[a]	Reversely operated Refrigeration scroll expander
Chan et al. [19]	4.05	R245fa	2.3	1535–2970	About 6	73.1%[a]	Reversely operated oil-free scroll air compressor

[a] Note: The authors only provided isentropic efficiency.

(2) The built-in volume ratios of the expanders were between 2 and 4, and the expansion ratios were normally less than 6. Although Declaye et al. [22] increased the expansion ratio to 7.4, obvious under expansion ratio losses were observed.

When the output power is larger than 3.5 kW, single screw expander seems more promising. Compared to scroll expander and rolling piston expander, it has many advantages, such as balanced load of the screw, long service life, high volume efficiency, good performances in partial load, low leakage, low noise, low vibration and simple configuration [20,21,26]. A few investigators performed theoretical analyses on single screw expanders. Ziviani et al. [27] reported a comparison between single screw and scroll expander under part-load conditions for low-grade heat recovery ORC systems. It was found that the single screw expander presents higher power output and leads to higher ORC overall efficiency despite a lower maximum value of the isentropic efficiency due to limited expansion ratio. In another paper of Ziviani et al. [28], they reported a geometry-based modeling of single screw expander in ORC system for low-grade heat recovery. Some other investigators conducted experimental studies on single screw expanders. Wang et al. [21] and He et al. [26] performed experimental investigations on single screw expander with compressed air, and it was proved that the single screw structure can work well as expander. However, only very few investigators presented experimental results about single screw expander in ORC conditions. It is worthy to quote here the small scale experimental ORC system constructed by Zhang et al. [29] In their system, a developed single screw expander with rotor diameter of 155 mm was used, and R123 was adopted as the working fluid. The expander power achieved 10.38 kW. However, the maximum efficiency of the cycle was only 6.48%, mainly because the maximum expansion ratio was 4.6.

Both scroll expanders and single screw expanders have fixed built-in volume ratios after they are manufactured, and over or under expansion losses would be thus produced. For an ORC system using R123 with evaporating temperature of 120 °C and condensing temperature of 30 °C, the expansion ratio would reach up to 10 if the pressure losses are not taken into account. The reversely operated compressors might result in obvious under expansion losses in such conditions [30]. Therefore, it is necessary to develop expanders specifically.

Besides the expander, the circulation pump is another key component in ORC system. Several investigators have noticed its significance. For example, Quoilin et al. [30] summarized that the circulation pump should meet the cycle requirements in terms of controllability, efficiency, tightness and net positive suction head. They also reported that the experimental data of circulation pump efficiency in small scale ORC systems were between 7% and 25%