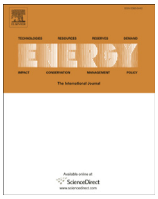
Energy 165 (2018) 769–775

Contents lists available at ScienceDirect

Energy

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



Experimental study on the net efficiency of an Organic Rankine Cycle with single screw expander in different seasons

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ARTICLE INFO

Article history:
Received 17 May 2018
Received in revised form
1 August 2018
Accepted 4 September 2018
Available online 4 October 2018

Keywords:
Organic Rankine cycle
Net efficiency
Single screw expander
Cooling system

ABSTRACT

The present paper experimentally investigates the thermal performances of an Organic Rankine Cycle (ORC) using a self-developed single screw expander. Experiments were conducted to study the net efficiency of the ORC under different cooling water flows in different seasons. Taking the power consumed by the circulation pump, cooling water pump, cooling tower fan and lubricant oil pump into account, the experimental results showed that the maximum value of produced net power and net efficiency achieved 3.27 kW and 3.04%, respectively, obtained at a cooling water flow of 12 $m^3 h^{-1}$ in winter. The experimental results also reported that the shaft power and shaft efficiency of the expander increased gradually with growth of cooling water flow. Under the same evaporating temperature, the performances of the ORC system deteriorated with the increase of ambient temperature, and the net efficiency of the system in summer was decreased by more than 16.45% than that in winter. In addition, the power consumption by the cooling system was the largest factor restricting the net efficiency than the power consumption by other auxiliary machines. Therefore, reducing the power consumption by the cooling system can effectively enhance the net efficiency of the ORC system.

1. Introduction

At present, in order to recover low temperature waste heat, the thermoelectric microgeneratorshe [1], thermochemical recuperations [2] and ORCs (Organic Rankine Cycle) are three important technologies. Among them, ORC is a promising technology because it can effectively convert low temperature heat into power with relatively high efficiency, simple configurations and suitable working pressures.

The purpose of an ORC system is producing power. However, the cooling system (condenser fans or water pump and cooling tower fan), lubricant oil system (lubricant oil pump) and the circulation pump always consume a portion of the expander power. Meanwhile, due to the low evaporation temperature and the resulting low thermodynamic efficiency, the heat released by the working fluids in the condenser for per unit of expander power is several times larger than that in traditional steam Rankine cycles. Therefore, the power consumption by the cooling system is also much larger, and it should be given much attention in the study of ORC system. In addition to the cooling system, the circulation pump and the lubricant oil pump, which is widely used for lubricating positive-displacement expander, also consume the expander power. Obviously, the net power produced by an ORC should be defined as the expander power minus the power consumed by all auxiliary machines, and the system net efficiency should be also defined as the ratio of the net power to the evaporator load. Recently, scholars have done a lot of works on ORC in which the main concentration is the selection of working fluids [3–5], key components [6–8] or thermal analyses [9–11]. There is very few work concentrating the net efficiency of ORC system.

Lots of theoretical works have been carried out to study the ORC. Song et al. [12] built a one–dimensional analysis method of the ORC for industrial waste heat recovery. In their work, only the power consumption by the circulation pump was considered, and the maximum net power and thermodynamic efficiency of the ORC system were 534 kW and 13.5% respectively. Dong et al. [13] analyzed the effects of the heat sink temperature on the performances of an ORC system which uses low-grade heat below 80 °C. They also only took the power consumption by the circulation pump into account and they reported that the produced net power and net efficiency of the ORC system were observed to decrease with increasing heat sink temperature. Li et al. [14] also neglected the power consumption by auxiliary machines except the

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https://doi.org/10.1016/j.energy.2018.09.013
0360-5442/

Nomenclature

P	power [W, kW]
h	enthalpy [$\mathrm{kJ\cdot kg^{-1}}$]
p	pressure [MPa]
q	flow rate [$\mathrm{m^3\cdot h^{-1}}$, $\mathrm{kg\cdot h^{-1}}$]
N	torque [$\mathrm{N\cdot m}$]
n	rotational speed [$\mathrm{r\cdot min^{-1}}$]
Q	heat [kJ]
η	efficiency[%]
ε	expansion ratio
k	power consumption index

Subscripts

1	inlet state of expander
2	outlet state of expander
3	outlet state of condenser
4	outlet state of circulating pump
is	isentropic
sh	shaft
P	circulating pump
W	water pump
C	cooling system
oil	lubricant oil pump
fan	cooling tower fan
evap	evaporator
cond	condenser
V	volume
m	Mass

circulation pump and they had come to the similar conclusion with Dong et al. In general, most of the theoretical works noticed the power consumption by the circulation pump, while neglected that consumed by other auxiliary machines.

As for experimental investigations, the power consumption by the auxiliary machines did not draw enough attention. Table 1 summarizes recent experimental results which focus on the efficiency of ORC. The table reported that only some of the investigators took the power consumption by the circulation pump into account, and the power consumption by other machines in cooling system was not considered in all the literatures.

It is worth mentioning that a few investigators have noticed that the cooling system has large influences on the performances of ORC system and paid special attention to the cooling system. He et al. [31] theoretically examined the effects of ambient temperatures on operational conditions of an air-cooled ORC, and they reported that in order to maintain a turbine back pressure, the heat transfer area of condenser should be increased by 42% when the ambient temperature changes from 304 K to 308 K. Shao et al. [18] presented some experimental results about a water-cooled ORC with different cooling water flows. They reported that the produced power increased from 889.47 W to 1242.67 W with the growth of cooling water flow, and the power consumption by the cooling system was also neglected. Usman et al. [32] made a thermo-economic comparison of air-cooled and cooling tower based ORC for different geographical climate conditions. In general, although a few investigators noticed the importance of cooling system for ORC, there is still lack of experimental results about the cooling system in ORC, especially those results which took the power consumptions by the cooling system into account. It is even rarer that the power consumptions by auxiliary machines were all considered.

In the present work, an experiment on the net efficiency of ORC with varied cooling water flow has been carried out in winter and summer respectively, and the power consumed by the working fluid system (circulation pump), cooling system (water pump and cooling tower fan) and lubricant oil system (lubricant oil pump) were all taken into account. Therefore, the real values of ORC net efficiency were experimentally obtained.

2. Descriptions of the ORC system

Fig. 1 gives a schematic diagram of the ORC system which mainly includes four circuits: working fluid circuit (indicated by solid lines), heat source circuit (indicated by dash lines), cold source circuit (indicated by center lines) and lubricant oil circuit (indicated by dash dot lines). A picture of the experimental facilities is presented in Fig. 2, which includes single screw expander, oil separator, evaporator, condenser, circulation pump, conductive oil boiler, water pump and cooling tower.

The main parameters of the single screw expander, oil separator, evaporator, circulation pump, conductive oil boiler were provided in Reference [10]. The parameters of the condenser, water pump and cooling tower are presented in Tables 2–4, respectively. R123 was used as the working fluid. The lubricant oil system and

Table 1
List of the experimental study on Net efficiency of ORC in literatures.

Authors	Working fluids	Cooling mediums	Expander power	cycle efficiency	Comments
Zheng et al. [15]	R245fa	Water	0.35 kW	5%	Not considering any auxiliary power consumption
Twomey et al. [16]	R134a	Water	0.676 kW	3.47%	Not considering any auxiliary power consumption
Hsieh et al. [17]	R218	Water	–	5.7%	Only the circulation pump consumption considered
Shao et al. [18]	R123	water	–	5.2%	Only the circulation pump consumption considered
Li et al. [19]	R245fa/R601a	water	0.55 kW	4.45%	Not considering any auxiliary power consumption
Yamamoto et al. [20]	R123	Water	0.15 kW	1.25%	Only the circulation pump consumption considered
MIAO et al. [21]	R123	Water	2.645 kW	5.64%	Only the circulation pump consumption considered
Landelle et al. [22]	R134a	Water	6 kW	1%	Only the circulation pump consumption considered
Pang et al. [23]	R245fa/R123	Water	–	4.4%	Only the circulation pump consumption considered
Pu et al. [24]	R245fa	Water	1.979 kW	4.01%	Not considering any auxiliary power consumption
Yang et al. [25]	R245fa	Water	2.64 kW	5.92%	Only the circulation pump consumption considered
Sun et al. [26]	R245fa	Water	1.9 kW	3.01%	Only the circulation pump consumption considered
Suankramdee et al. [27]	R141b	Water	0.185 kW	1.57%	Not considering any auxiliary power consumption
Unamba et al. [28]	R245fa	Water	0.6 kW	6%	Only the circulation pump consumption considered
Liu et al. [29]	R123	Water	0.76 kW	2.9%	–
Peris et al. [30]	R245fa	Air	15.93 kW	10.88%	Only the circulation pump consumption considered