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Operation characteristic and performance comparison of organic Rankine cycle (ORC) for low-grade waste heat using R245fa, R123 and their mixtures

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ABSTRACT

The operation characteristic and performance comparison of low-grade organic Rankine cycle (ORC) using R245fa, R123 and their mixtures have been investigated. The heat source temperature is set to be 120 °C, while the mass flow rate is controlled by adjusting the pump frequency. The basic operation parameters are first examined, while the detailed operation characteristics of pure and mixture working fluids are addressed. The system overall performance, including thermal efficiency and system generating efficiency, for pure and mixture working fluids are explored. The experimental results show that the mixtures own a relatively higher pump power consumption and enhancing the pump performance is also significant for ORC application. Whether the mixtures exhibit better thermodynamic performance than the pure working fluids depend on the operation parameters and mass fraction of mixtures. 0.67R245fa/0.33R123 owns the highest maximum net electricity output of 1.67 kW, 4.38% higher than that of R245fa and 63.73% higher than that of R123. Compared to the pure working fluids, the mixture working fluids own a better thermodynamic performance and a moderate economic performance.

1. Introduction

U.S. Department of Energy (U.S. DOE) reported that approximately 60% of low-temperature waste heat from many manufacturing industries are exhausted directly to the environment. Meanwhile, the escalating global energy demands and rising energy cost remind us the significant of recover waster heat. Organic Rankine cycle (ORC) is considered to be a promising low grade thermal energy recovery technologies [1] due to its simple structure, high efficiency and environment friendly. ORC has been widely applied on all kinds of low-temperature heat sources [2], such as geothermal energy, solar energy, waste heat energy and biomass energy. Therefore, it is of primary importance to improve the system performance and increase the net power output.

Some researchers have shown their interest in ORC experimental studies to investigate the basic operation characteristics and improve the cycle performance. The operation characteristics of expander and pump have a significant on system overall performance, and thus numerous researchers devoted main efforts on expander development, as well as pump improvement. Various kinds of expanders have been used on small scale ORC prototype, such as open-drive scroll type expander [3,4,8,11–14], single stage axial flow turbine [5], radial turbine [6,7], single-screw expander [9] and rolling-piston expander [10]. The scroll type expander is common used for its low rotational speed and low requirements for bearing and shaft seal, while the radial turbine presents a better thermodynamic performance. Pump power consumption directly affects the net power output, and thus the improvement in pump behaviors is also important [15–20]. To boost the net power output and cycle performance, some researchers put their emphasis on regenerative ORC test rig [21–27]. For example, Wang et al. [26] conducted a primary test on a regenerative solar ORC using

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Nomenclature

A	heat transfer area, m^2
h	specific enthalpy, kJ/kg
m	mass flow rate, kg/s
M	torque, Nm
max	max
min	min
n	rotational speed, r/min
net	net
P	power output, kW; pressure, bar
Q	energy, kW
s	specific entropy, kJ/kg K
T	temperature, °C
U	overall heat transfer coefficient, W/m^2 °C
W	power, kW

Greek symbols

η	efficiency
ΔT_m	logarithmic mean temperature difference

Subscripts

1–4, i	state points
sh	shaft power
ele	electricity
is	isentropic
me	mechanical
th	thermal

Acronyms

BWR	Back Work Ratio
cond	condenser
eva	evaporator
exp	expander
gen	generator
GWP	global warming potential
ODP	ozone depletion potential
pump	pump
sup	supheating

R245fa. Kosmadakis et al. [27] investigated the engine performance off-design conditions of a 3 kW ORC setup from viewpoint of two different operation model: subcritical and supercritical condition.

Furthermore, great attention has been drawn to the experimental comparison using different working fluids, as well as the primarily dynamic test. Pu et al. [28] did an comparative analysis between R245fa and HFE7100 of a small-scale ORC, showing that R245fa obtained the maximum net power output of 1.98 kW, while HEF7100 yielded the net electric output of 1.03 kW. Molés et al. [29] conducted an experimental evaluation of an ORC test rig using HCFO-1233zd-E to replace HFC-245fa, indicating that the net electrical efficiency was ranging from 5% to 9.7%, and the maximum expander isentropic efficiency was 75%. Jung et al. [30] demonstrated the dynamic behavior of a kW ORC test rig coupled to a 30 kW Capstone™ Gas Turbine exhaust gas. A zeotropic mixture of R245fa/365mfc was used as working fluids and a scroll expander is employed. The thermal efficiency and expander efficiency were 3.9% and 28.4%, respectively. Li et al. [31] did an experimental comparison of an ORC using R245fa and R245fa/R601a from the viewpoint the optimum dimensionless volume ratio, demonstrating that the maximum thermal efficiency of R245fa/R601a was 4.45%, which is 0.07 higher than that of R245fa. Miao et al. [32] tested a 4 kW ORC prototype using R123 as working fluid and a scroll expander, concluding that the highest thermal efficiencies under 140 °C and 160 °C were 6.39% and 5.12%, respectively. Adopting the same type of working fluids and expander, Zhou et al. [33] constructed an small-scale ORC to recover industrial flue gas, and demonstrated that the net power output and calculated thermal efficiency were 645 W and 8.5%, respectively. Muhammad et al. [34] conducted an experimental study of a 1 kW ORC prototype with R245fa as working fluid and a scroll expander, mentioning that the maximum thermal efficiency of 5.75% and maximum expander isentropic efficiency of 77.74% were obtained, and more attention should be paid to improve the expander and pump performance. Quoilin et al. [35] developed an ORC model based on the experimental test of an ORC using R245fa. Galloni et al. [36] tested the system performance of a small ORC using R245fa, showing that the electrical power of 1.2 kW and cycle efficiency of slightly higher than 9% were achieved. Guillaume et al. [37] did a comparative test of an ORC prototype with a radial-inflow turbine using R245fa and R1233zd, reporting that R1233zd represented a better choice compared to R245fa for the current application. Usman et al. [38] implemented sliding pressure control strategy on an ORC test rig under off-grid model using a scroll expander, showing that the new scheme could better track expander rotational speed. Hu et al. [39] studied the effect of degree of superheat on a 500 W ORC prototype using R245fa, presenting that the system with a plate evaporator was instability because of liquid entrainment for degree of superheat of 1.8 °C. Ziviani et al. [40] analyzed the performance of an open-drive single-screw expander in a small-scale regenerative ORC test rig using R245fa and SES36, expressing that SES36 obtained a relatively higher pressure ratios and an expander overall isentropic efficiency of 64.7%. Sung et al. [41] conducted a real-time operating test on a 200 kW ORC prototype using R245fa to recover the waste heat from flue gas in a steel processing plant, demonstrating that the thermal efficiency of 9.6% and net power output of 177.4 kW were achieved. Yu et al. [42] proposed a novel cascaded system integrating the steam Rankine cycle as top cycle and ORC as bottom cycle using R123, and analyzed the impact of engine operations, indicating that the cascaded system output 5.6% more power than basic diesel engine.

A review of the previous literature reveals that several experimental investigations using pure working fluids (R123 and R245fa) of small-scale ORC test rig have been performed. However, few of them tried to fulfill the experimental comparison between pure and mixture working fluids. The mechanism on mixture working fluids having a better thermodynamic performance is not well reported. Furthermore, limited works attempted to take into account the heat transfer coefficients of evaporator and condenser for the pure and mixture working fluids. Therefore, the purpose of this work is to experimental comparison between pure and mixture working fluids. Practically should be pointed out that, R123 and R245fa fluids were frequently used for the experimental ORC systems. In order to ascertain the merits of pure and mixture working fluids, R245fa, R123 and their mixtures (0.67R245fa/0.33R123 and 0.33R245fa/0.67R123) are adopted as the working fluids. The basic operation parameters for pure and mixture working fluids are first illustrated in Section 4.1. The operation characteristics of pure and mixture working fluids, especially the behaviors of those four components (pump, evaporator, expander and condenser), are conducted in Section 4.2. A further comparison of system overall performance for the pure and mixture working fluids, including thermal efficiency and system generating efficiency, is addressed in Section 4.3, and the comparison with other studies is demonstrated in Section 4.4.