International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 0225

Research on Coupling of double-stage ORC System Based on Efficient Utilization of Hot Dry Rock Energy

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ABSTRACT

For the purpose of effective utilization of hot dry rock resource, a double-stage Organic Rankine Cycle (ORC) power generation system is established in present work. Six kinds of organic working fluids are selected for thermodynamic calculation. The results indicate that the evaporation temperature of double-stage ORC system affects performance parameters of system. Compared with single-stage ORC system, double-stage ORC system can improve net output power by 8.44% to 12.20%. The thermal efficiency of double-stage ORC system reduces maximally by 0.81%. The results also show that exergy efficiency is related to the type of organic working fluids. The organic working fluid flow in double-stage ORC is higher than that in single-stage ORC. When R601, R601a and R600 are used as working fluids, the required mass flow rate is small. The double-stage ORC system can effectively reduce the outlet temperature of heat source in the evaporator, ranging from 12.51 to 14.07℃.

Keywords: Evaporation temperature, Net output power, Thermal efficiency, Exergy efficiency

NONMENCLATURE

Abbreviations	
HT	High temperature
LT	Low temperature
ORC	Organic Rankine Cycle
Symbols	
E	Exergy(J)
h	Enthalpy(J)
I	Exergy loss(J)
m	Mass flow rate
Q	Heat
s	Entropy
T	Temperature
W	Power
Greek letters	
η_{exe}	Exergy efficiency
η_{ORC}	Thermal efficiency
Subscripts and superscripts	
c	Condenser
cw	Cooling water
e	Evaporator
h	Heat source
i	Inlet
o	Outlet
p	Pinch point temperature difference(K)/ Pump
t	Turbine
1	High temperature stage/point of T-S diagram
2	Low temperature stage/point of T-S diagram

1. INTRODUCTION

With the rapid development of society and economy, the reserves of traditional energy resources are constantly decreasing. And it has caused a large amount of carbon dioxide and pollutant emissions. The utilization of renewable energy is a good way to solve these problems[1]. The hot dry rock geothermal resource is a kind of clean and renewable resource, which have features of small pollution emission and good thermal energy continuity [2]. Using the heat stored in hot dry rock to generate electricity is the most common method. So far, more than ten countries have made substantial development of hot dry rock resource [3].

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

Organic Rankine Cycle (ORC) power generation technology is considered as an effective low grade energy utilization technology [4]. The ORC had the advantages of simplicity, flexibility, stability and safety compared with other low medium grade thermal energy conversion technologies [5]. Single-stage ORC systems use a single organic working fluid which vaporizes at specific pressure and temperature. The relevant of theoretical and experimental investigations have been widely conducted [6], and many methods have been proposed to improve the performance of single-stage ORC system.

Florian Heberle et al. [7] proposed a double-stage ORC power generation system for Enhanced Geothermal System (EGS) system. By analyzing the system exergy efficiency with different organic working fluids, it was found that the exergy efficiency of the double-stage ORC was generally higher than that of the single-stage ORC system, and the system exergy efficiency with mixture organic working fluids was higher than that with single organic working fluid.

Previous investigations have indicated that double pressure ORC (DPORC) system can significantly increase the output power of the system under the same heat source temperature level. The comparison of thermal performance between double pressure ORC and single pressure ORC (SPORC) was performed, which indicated that the output power of double pressure ORC increased by about 29% at lower geothermal fluid temperature (100-125℃), but the augment would decrease at higher heat source temperature (150-200℃) [8].

Li et al.[9,10] selected 9 kinds of organic working fluids, and probed the optimal circulation parameters under different heat source temperatures, and conducted a comparative analysis of the two turbine layouts. Yang et al. [11] compared the performance of ordinary ORC and that of parallel double pressure ORC (DPORC) at low geothermal water temperature level. Wang, X., et al [12] divided the organic working fluid into dry fluid, wet fluid and isentropic fluid, and further introduced the selection criteria of organic working fluid.

As mentioned above, many investigations have been conducted on the features of single-stage and double-stage ORC system. And more importantly, the exergy efficiency of the double-stage ORC was proved to be generally higher than that of the single-stage ORC system, which means that the double-stage ORC system will contribute to make more efficient and optimal use of various renewable energy, especially geothermal energy. But little research about the influence of coupling relationship between two stages on the performance of double-stage ORC system was performed. In fact, the coupling relationship between the first stage and second stage of double-stage ORC system pays a key role in the comprehensive performance of double-stage ORC system.

Based on the above mentioned purpose of present work, a double-stage ORC power generation system, which is used for hot dry rock efficient utilization is established. Different organic working fluids, including R123, R245fa, R601, R601a, R600, R365mfc are applied. In addition, for the purpose of evaluating the performance of proposed double-stage ORC power generation system, a single-stage ORC system is established as well.

2. MODEL OF THE DOUBLE-STAGE ORC SYSTEM

2.1 The basic composition of double-stage ORC system

As shown in Fig 1, the double-stage ORC system consists of a high temperature (HT) stage and a low temperature (LT) stage. Each stage contains a turbine, evaporator, generator, condenser and pump. The heat extracted from the hot dry rock by water is used to evaporate the low-boiling organic working fluid in the evaporator. Then, the water from the evaporator in first stage cycle flows into the evaporator of the second stage cycle. The organic working fluid in the evaporator turns into vapor with high-temperature and high-pressure. The vaporized organic working fluid is then used to drive the turbine and perform the output of work. The output work derived from the turbine can be used to drive the generator to generate electricity. Then, the vapor that expands in turbine enters the condenser and exchanges heat with cooling water and flows back to storage tank. Final, the organic working fluid flows back to the evaporator by pump.

2.2 Thermodynamic model of ORC system

In present ORC system, net output power, thermal efficiency and exergy efficiency are important parameters for evaluating the thermal performance of double-stage ORC system. According to the composition of present ORC system, the temperature entropy diagram is shown in Fig 2. As mentioned above, the double-stage ORC system is divided into HT-stage and LT-stage.

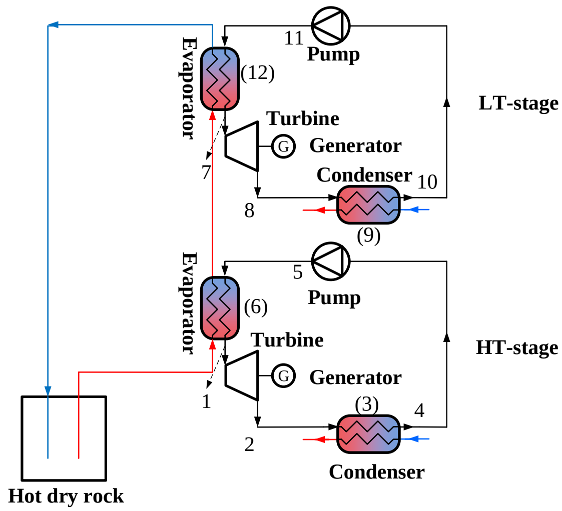

Fig 1 The schematic of double-stage ORC system

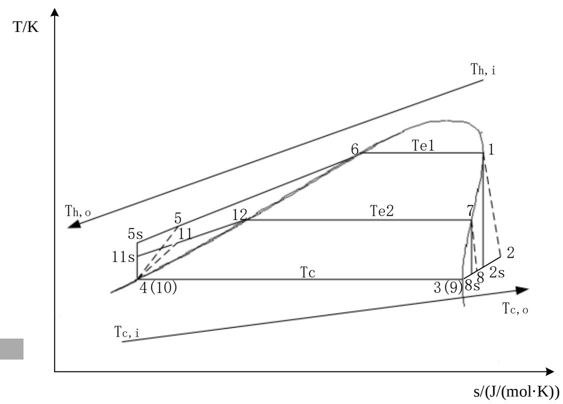

Fig 2 T-S diagram of double-stage ORC system

The turbine expansion work in HT-stage ORC is expressed as

$$W_{t,1} = m_{wf1}(h_1 - h_2) \quad (1)$$

The power consumption of pump in HT-stage ORC is expressed as

$$W_{p,1} = m_{wf1}(h_5 - h_4) \quad (2)$$

The net output power of the HT-stage ORC can be expressed as

$$W_{net,1} = W_{t,1} - W_{p,1} \quad (3)$$

Exergy loss of HT-stage ORC is expressed as:

$$I_1 = I_{e,1} + I_{t,1} + I_{c,1} + I_{p,1} \quad (4)$$

The calculation method of LT-stage ORC is the same. So net output work of double-stage ORC is expressed as:

$$W_{net} = W_{net,1} + W_{net,2}$$

The thermal efficiency of double-stage ORC is expressed as

$$\eta_{ORC} = W_{net} / Q_h \quad (5)$$

The exergy efficiency of double-stage ORC is expressed as

$$\eta_{exe} = W_{net} / E_h \quad (6)$$

3. THERMAL CALCULATION

In present work, the hot dry rock is the heat source of ORC system. To simplify the thermal calculation, the pressure drop and heat loss of the proposed ORC system are ignored. Meanwhile, it is assumed that the organic working fluid is saturated vapor at the turbine inlet and saturated liquid at the condenser outlet. The calculation parameters are listed in Table 1[13].

Table 1 ORC system parameters

Parameters	Values
Mass flow rate of heat source/(kg/s)	1
The heat source temperature/(K)	423.15
Environment temperature/(K)	293.15
The cooling water temperature/(K)	293.15
Tc/(K)	303.15
The pinch point temperature of evaporator and condenser /(K)	5
Isentropic efficiency of turbine	0.85
Isentropic efficiency of working fluids pump	0.80

The properties of organic working fluid have great influence on the system performance. In general, low boiling point organic working fluid is usually chosen in hot dry rock power generation. In addition, the critical temperature and the environmental protection of organic working fluid are considered as well. In hot dry rock power generation system, the organic working fluid is usually freon and alkane. In present work, 6 kinds of organic working fluids are selected. The main properties of these organic working fluids are listed in Table 2.

Table 2 Properties of organic working fluids

Organic working fluids	Critical temperature (℃)	ODP	GWP (100yr)
R123	183.68	0.02	79
R245fa	154.05	0	858
R601	196.55	0	0.1
R601a	187.20	0	0.1
R365mfc	186.85	0	794
R600	152.00	0	4

4. RESULTS AND DISCUSSION

Since the variation trend of three-dimensional diagram of 6 organic working fluids is similar, the three-dimensional diagram of R123 is selected here for display.

Fig 3 represents mass flow rate of organic working fluid of R123. The mass flow rate of organic working fluid of double-stage ORC system increases with increase of HT-stage evaporation temperature. With increase of LT-stage evaporation temperature, mass flow rate of organic working fluid of double-stage ORC system decreases. When evaporation temperature of LT-stage is constant, as the increase of evaporation temperature of the HT-stage, the mass flow rate of the organic working fluid of the HT-stage decreases, but the mass flow rate of organic working fluid of LT-stage increases, and increase is greater than decrease of HT-stage. Therefore, mass flow of organic working fluid increases as a whole. When HT-stage evaporation temperature is constant, HT-stage working fluid mass flow rate does not change, and organic working fluid mass flow rate in system decreases as LT-stage evaporation temperature increases.

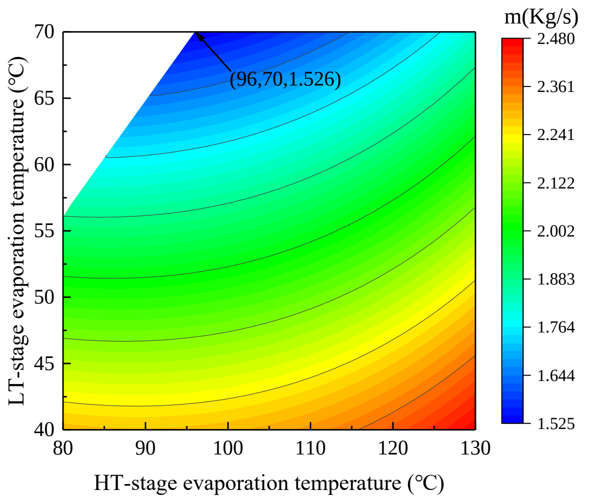

Fig 3 The mass flow rate of organic working fluid of R123 at different double-stage evaporation temperatures.

Fig 4 represents the net output power of R123. The net output power of double-stage ORC increases first and then decreases with increase of two stages evaporation temperature. Therefore, the matching relationship between the two evaporation temperatures determines the net output power of the double-stage ORC system. The maximum net output power obtained by the system is 45.26KW, and evaporation temperature of HT-stage is 104℃, and evaporation temperature of LT-stage is 55℃.

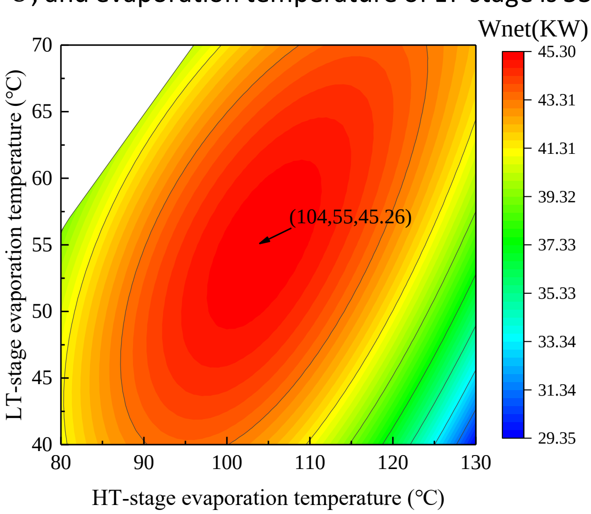

Fig 4 The net output power of R123 at different double-stage evaporation temperatures.

Fig 5 represents thermal efficiency of R123. The thermal efficiency of double-stage ORC system increases first and then decreases with increase of HT-stage evaporation temperature. With increase of LT-stage evaporation temperature, thermal efficiency of double-stage ORC increases. The maximum thermal efficiency obtained is 13.06%, and evaporation temperature of HT-stage and LT-stage are 106℃ and 70℃.

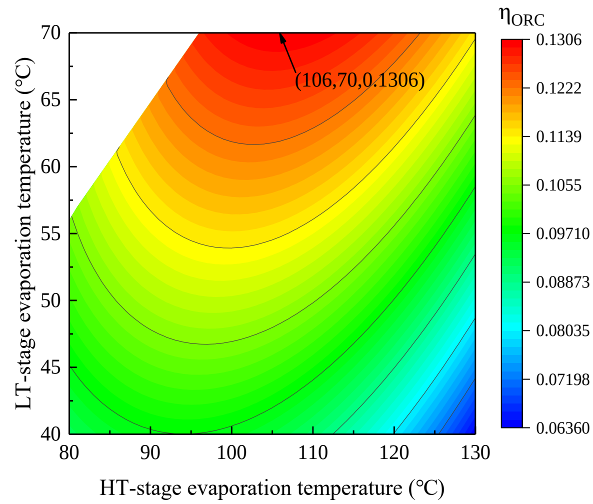

Fig 5 The thermal efficiency of R123 at different double-stage evaporation temperatures.

Fig 6 represents exergy efficiency of R123. The exergy efficiency of double-stage ORC increases first and then decreases with increase of HT-stage evaporation temperature. With increase of LT-stage evaporation temperature, exergy efficiency of double-stage ORC increases. The maximum exergy efficiency obtained is 59.58%, and evaporation temperature of HT-stage is 110℃, evaporation temperature of LT-stage is 70℃.

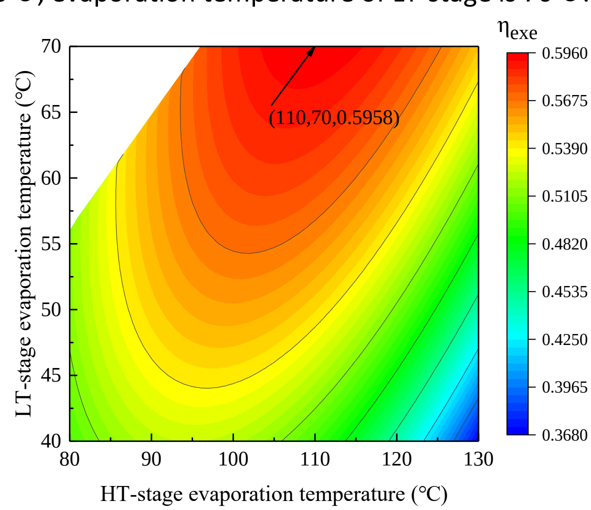

Fig 6 The exergy efficiency of R123 at different double-stage evaporation temperatures.

As shown in Fig 7, by comparing net output power in single-stage and double-stage ORC with different organic working fluids, it can be found that net output power of double-stage ORC is significantly greater than that in single-stage ORC system. Among the six organic working fluids selected, net output power increases by R123 is the highest (12.20%) and net output power increases by R245fa is the lowest (8.44%). R600 has the largest net output power in double-stage ORC, and R245fa has the largest net output power in single-stage ORC.

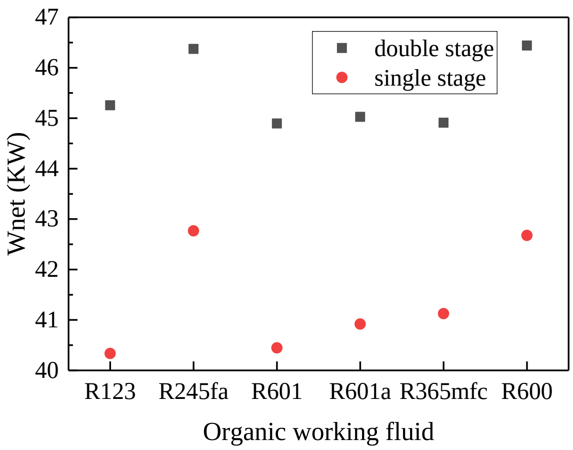

Fig 7 Comparison of net output power between single-stage and double-stage ORC system.

As shown in Fig 8, by comparing thermal efficiency in single-stage and double-stage ORC with different organic working fluids, it can be found that thermal efficiency in double-stage ORC are lower than that in single-stage ORC system. Among the 6 organic working fluids selected, thermal efficiency decreases by R600 is the highest (0.81%) and the thermal efficiency decreases by R123 is the lowest (0.52%).

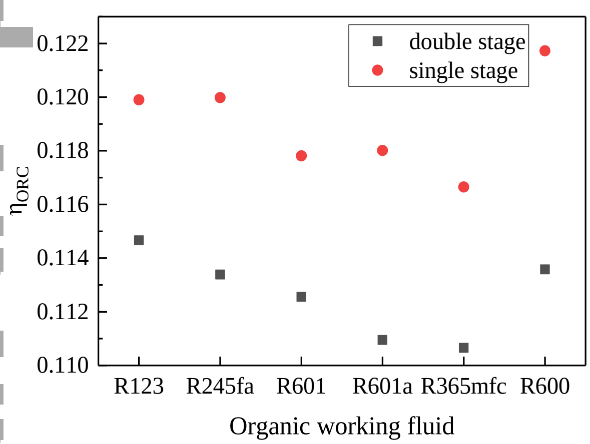

Fig 8 Comparison of thermal efficiency between single-stage and double-stage ORC system.

As shown in Fig 9, by comparing exergy efficiency in single-stage and double-stage ORC system with different organic working fluids, it can be found that exergy efficiency in double-stage ORC is lower than that in single-stage ORC with R600. In contrast, when R123, R601a, R365mfc and R601 are used as working fluids, exergy efficiency of double-stage ORC is higher than that of single-stage ORC. The special one is R245fa, which has little difference in exergy efficiency of single-stage and double-stage ORC. Exergy efficiency is related to the nature of organic working fluids.

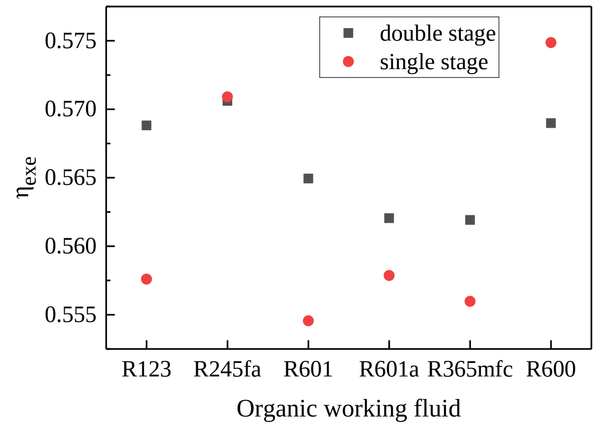

Fig 9 Comparison of exergy efficiency in single-stage and double-stage ORC system.

As shown in Fig 10, by comparing single-stage with double-stage ORC system, it can be found that the mass flow rate of organic working fluid in double-stage ORC system is higher than that in single-stage ORC. When R601, R601a and R600 are used as organic working fluids, mass flow rate required by the system is less than that of the heat source. When other organic working fluids are used as circulating fluids, the mass flow rate required by the system is greater than that of the heat source. When R601, R601a and R600 are used as circulating fluids, the mass flow rate required for double-stage ORC system is smaller than that of single-stage system.

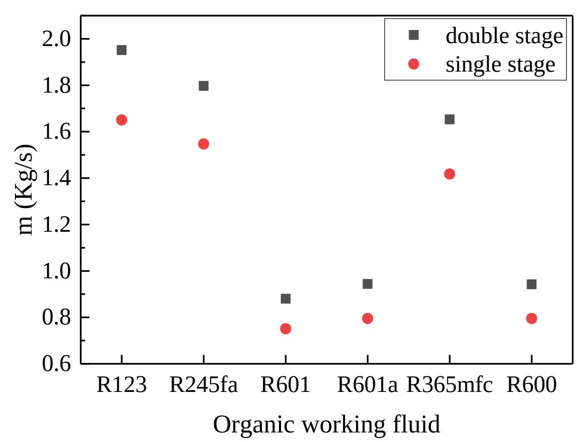

Fig 10 Comparison of mass flow rate of organic working fluid in single-stage and double-stage ORC system

As shown in Fig 11, by comparing the outlet temperature of the heat source in single-stage and double-stage ORC system, it can be found that the outlet temperature of the heat source in double-stage ORC system is lower than that in single-stage ORC system.

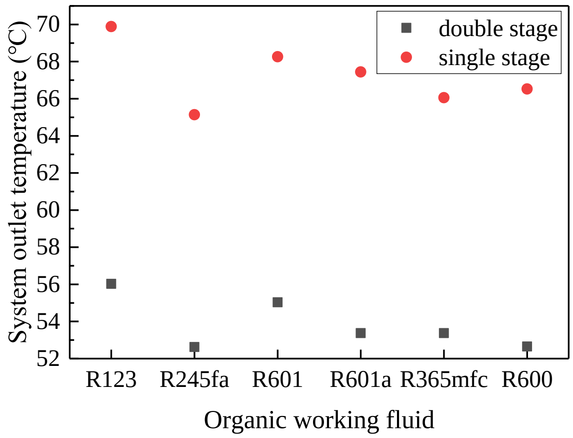

Fig 11 Comparison of outlet temperature of heat source in single-stage and double-stage ORC system.

5. CONCLUSIONS

This paper discusses the coupling mechanism of the double-stage ORC system. The thermodynamic properties of single-stage ORC and double-stage ORC are compared. The conclusions can be drawn as following:

1) The double-stage ORC system can effectively improve the net output power of the system by 8.44% to 12.20%. The net output power of the system can be adjusted according to the double-stage evaporation temperature coupling relationship.

2) Compared with single-stage ORC system, thermal efficiency of double-stage ORC system reduces by up to 0.81%. Exergy efficiency of double-stage is related to the type of organic working fluids, and the exergy efficiency of different types of organic working fluids will be different. R245fa has little difference in efficiency between single-stage ORC and double-stage ORC.

3) Compared with single-stage ORC system, the mass flow rate of organic working fluid of double-stage ORC system is higher than that of single-stage ORC system. The double-stage ORC system can effectively reduce the temperature of the evaporator outlet heat source, which ranges from 12.51 to 14.07℃.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support by the National Key R&D Program of China (No. 2018YFB1501805).

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