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Investigation on the coupling mechanism of serial Organic Rankine Cycle based on the utilization of hot dry rock

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ABSTRACT

In the utilization of hot dry rock, the temperature of hot dry rock production well will vary with running time. A thermodynamic model of serial Organic Rankine Cycle (ORC) is established in present work. According to specific selection criteria, six kinds of organic working mediums are selected for calculation. The parameters such as thermal efficiency, net output power, exergy efficiency and working medium flow are obtained. The results indicate that when dry hot rock injection well temperature is constant, dry hot rock production well temperature decreases with the increase of running time, which causes descend of thermal efficiency, net output power, exergy efficiency and working medium flow of serial ORC system. As value of k (ratio of temperature difference (inlet and outlet of heat source) in HT-stage ORC evaporator to temperature difference (inlet and outlet of heat source) in serial ORC system) rises, thermal efficiency, net output power, and exergy efficiency of serial ORC system firstly rise and then decrease, but working medium flow firstly descends and then rises. Maximum thermal efficiency, net output power, exergy efficiency and minimum working medium flow are obtained under the same k. By comparing the 6 selected organic working mediums, R600 presents the better thermodynamic performance.

Keywords: Serial ORC, Variable temperature heat source, Coupling mechanism, Thermodynamic properties

NONMENCLATURE

Abbreviations	
GWP	Global warming potential
HT	High temperature
LT	Low temperature
ODP	Ozone Depletion Potential
ORC	Organic Rankine Cycle
Symbols	
E	Exergy
h	Enthalpy
I	Exergy loss
mf	Organic working medium flow
Q	Heat
T	Temperature
W	Power
x	Year
Greek symbols	
η_{ORC}	Exergy efficiency
η_{exe}	Thermal efficiency
Subscript	
1	HT-stage ORC
2	LT-stage ORC
c	Condenser
e	Evaporator
h	Heat source
in	Inlet
mid	HT-stage evaporator outlet
out	Outlet
p	Pump
t	Turbine

1. INTRODUCTION

In the past few years, global energy consumption has gradually increased and will increase further in the future. In addition, the consumption of traditional energy has brought a lot of greenhouse gases and pollutants. Therefore, it is urgently needed that develop low-carbon energy and renewable energy [1]. Although hot dry rock is a low and medium grade (< 350℃) energy source, it has attracted much attention due to its abundant reserves, stability and cleanliness [2]. Exploiting heat energy in hot dry rock have great advantages in mitigating the greenhouse effect and reducing pollution [3].

ORC power generation is regarded as a technology that utilizes low and medium grade energy effectively [4]. ORC with advantages of stability simplicity and flexibility compared to other low and medium grade energy conversion technologies [5]. The double-pressure ORC system is a concept that has just recently emerged in application of ORC [6]. Wang M has conducted in depth research on thermodynamics properties of isobutane in double-pressure ORC and single-pressure ORC. The research results show that net output power of DORC is greater than that of SORC when heat source temperature is between 100-177.2℃. This advantage is more obvious when heat source temperature at a low level. The results of thermal economic evaluation showed that optimized electricity cost decreased with increase of heat source temperature [7].

Manente, G et al. found double-pressure ORC can output more net output power than a single-pressure ORC system [8]. Li J et al. designed two turbine layouts and conducted a thermal economic analysis. The effect of double-stage evaporation pressure on thermal economy of two turbine arrangements was considered as well. The results show that compared with a single turbine layout, the induction turbine layout can raise net output power of system by 0.3% ~ 5.4%. In addition, low investment costs under most operating conditions, with largest drop of 34.2% [9].

Stijepovic MZ et al. believed that more parameters can be optimized in a multi-stage ORC (such as the evaporation temperature of different evaporation sections, the degree of superheat and working medium flow, etc.), which can better adapt to the heat source [10]. Wang J et al carried out a research on double-stage ORC, results indicate that double-stage evaporation increased evaporation temperature of high-pressure section and reduced irreversible losses [11]. According to research results conducted by Li et al, TSORC has advantages over ORC in terms of recovering heat from heat sources, and can reduce irreversible losses and output more net output power [12]. Li Jian et al investigated double-pressure ORC with R1234ze and optimized double-pressure ORC with heat source of 100-200℃ [13].

Xinyu Li et al put forward double-stage ORC with a regenerator. The results showed that regenerator can improve thermal efficiency while increasing the net output power of double-stage ORC [14]. Surendran A et al put forward a transcritical regenerative double-stage ORC (TR-STORC), which improved the efficiency of the double-stage ORC by combining partial evaporation with regeneration in LP stage and supercritical heating in HP stage. TR-STORC had a more efficient performance under a variety of heat ratios and temperature ranges [15].

In summary, serial ORC is a way to effectively develop and utilize low and medium grade energy, which has certain advantage compared to other ORCs. A lot of investigations on serial ORC layout and choices of organic working mediums have been conducted. In previous studies, the heat source temperature at outlet of ORC system was hardly considered. Such heat sources were called open heat sources [16]. However, according to work by Ma Y and Zhang, C, it was found that different injection temperatures had an impact on the temperature of the production well [17].

Based on previous work, the heat source temperature at outlet of ORC system is assumed to be a constant. The objective of present research is to probe variation of thermodynamic properties of serial ORC with variable temperature heat sources. In addition, the matching relationship between stages of high-temperature and low-temperature in serial ORC is investigated as well.

2. MODEL

2.1 *Composition of the serial ORC system*

Fig 1 is serial ORC system diagram, Fig 2 is endothermic process and Fig 3 T-S diagram of serial ORC system. The serial ORC system contains high-temperature (HT) stage ORC and low-temperature (LT) stage. Hot water pumped from the dry hot rock production wells flows through the HT-stage ORC and LT-stage ORC successively, and then returns to the underground through the recharge wells to exchange heat with the dry hot rock. The organic working medium absorbs heat and evaporates in evaporator, which are processes 5-1 and 11-7 in the T-S diagram. In T-S diagram, processes 1-2 and 7-8 represent the turbine expansion in HT-stage ORC and LT-stage ORC, respectively. Organic working medium condenses in condenser after leaving turbine, as shown in processes of 2-4 and 8-10 in T-S diagram. Processes of 4-5 and 10-11 represent the compression process of organic working medium in HT-stage and LT-stage.

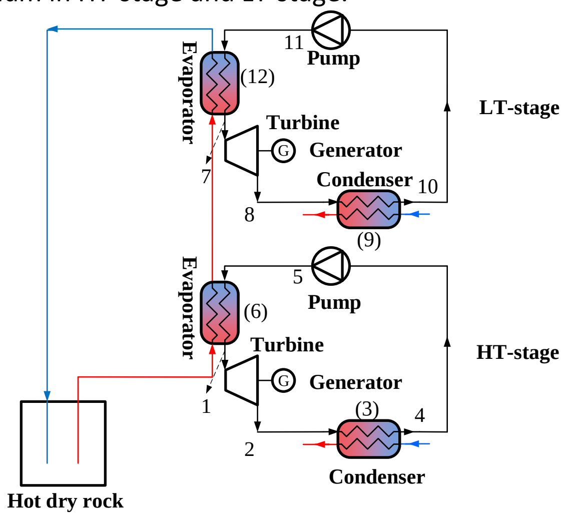

Fig 1 Serial ORC system diagram.

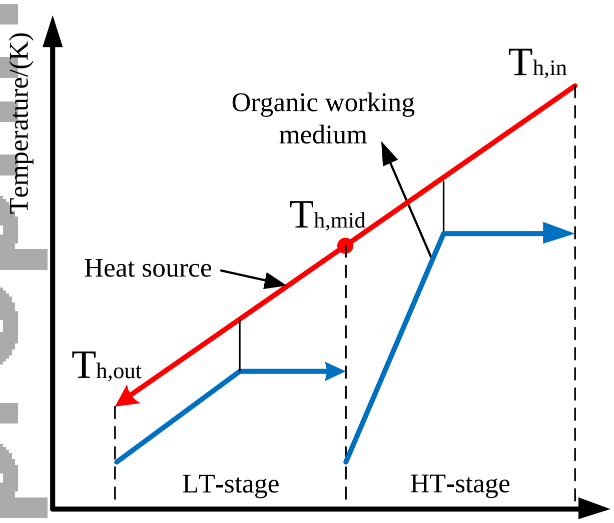

Fig 2 Endothermic process

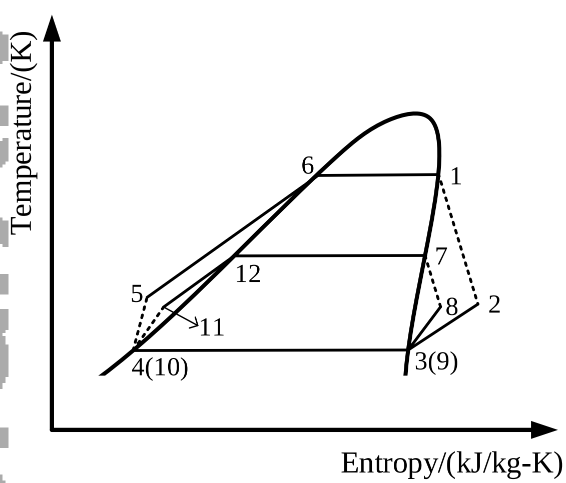

Fig 3 T-s diagram of serial ORC

2.2 *Thermodynamic model of serial ORC system*

The net output power in HT-stage ORC can be obtained as:

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

The work done by organic working medium expanding in turbine of HT-stage can be expressed as:

$$W_{t,1} = mf_1 \cdot (h_1 - h_2) \quad (2)$$

The consumed work by pump of HT-stage is expressed as:

$$W_{p,1} = mf_1 \cdot (h_5 - h_4) \quad (3)$$

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 serial ORC is expressed as

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

The exergy efficiency of serial ORC is expressed as

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

The ratio of temperature difference (inlet and outlet of heat source in HT-stage ORC evaporator) to temperature difference (inlet and outlet of heat source in serial ORC system) is defined as:

$$k = \frac{T_{h,in} - T_{h,mid}}{T_{h,in} - T_{h,out}} \quad (7)$$

3. ORGANIC WORKING MEDIUMS AND SYSTEM PARAMETERS

3.1 *Organic working mediums*

In general, organic working mediums can be segmented into isentropic mediums, dry mediums and wet mediums according to gradient of saturated vapor line of organic working mediums [18]. In subcritical ORC, isentropic or dry mediums are the preferred working mediums. For dry mediums and isentropic mediums that we need to further screen, following are detailed criteria:

a. Ozone Depletion Potential (ODP) represents the ability of a substance to destroy stratospheric ozone. Therefore, organic working mediums with high ODP(ODP>0.5) must be eliminated.

b. Global Warming Potential (GWP) is used for expressing and comparing the ability of ozone-depleting substances to contribute to global warming, which should be considered.

c. Other conditions that should meet the requirements of system, such as critical temperature and critical pressure.

According to the above criteria, 6 kinds of organic working mediums are selected as working mediums. The relevant parameters of working mediums used in present work is listed in Table 1.

Table 1 Physical properties of mediums.

mediums	T_{cr} (℃)	P_{cr} (MPa)	ODP	GWP (100yr)
R601	196.55	3.37	0	0.1
R601a	187.2	3.378	0	0.1
R365mfc	186.85	3.266	0	794
R123	183.68	3.662	0.02	79
R245fa	154.05	3.651	0	1030
R600	152	3.796	0	4

3.2 Selection of heat source temperature

The temperature of hot dry rock production well is related to mass flow rate, temperature and other factors of reinjection medium. As operating time increases, temperature of production well will drop with the decrease of temperature of hot dry rock. In present work, the relevant data by C. Zhang et al [19] are adopted, which are listed in Table 2.

Table 2 Related parameters of heat source.

Injection temperature (℃)	Injection flow rate (Kg/s)	Running time (x, year)	Production well temperature (℃)
60	50	40	$T_{h,in}$

The results [28] are fitted to derive the relationship between production well temperature and running time.

$$T_{h,in} = y_0 + A/(w\cdot\sqrt{\pi/2})\cdot e^{(-2\cdot((x-x_c)/w)^2)};$$
$$(y_0 = 162.6024\pm0.2161; x_c = 0.6835\pm0.7521; \quad (8)$$
$$w = 32.3203\pm1.5247; A = 437.2102\pm31.3415)$$

The variation of production well temperature with running time is shown in Fig 4.

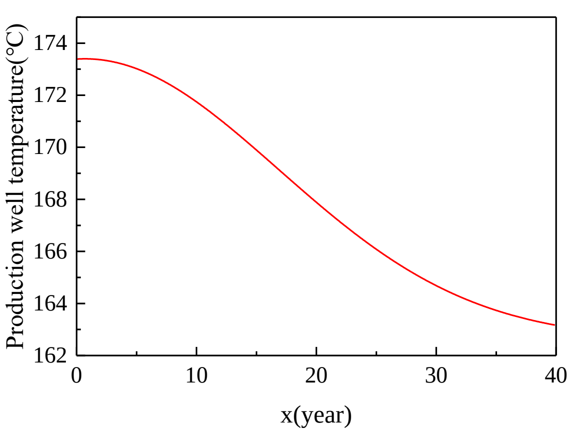

Fig 4 The variation of production well temperature with running time.

3.3 Setting of other system parameters

In reality, the ORC system has a certain pressure drop and heat loss, but due to its complexity, these factors are usually ignored in the process of theoretical analysis [20]. Refer to available literatures, some assumptions about the parameters of the system are made. The detailed parameters are shown in Table 3.

Table 3 Serial ORC system parameters.

Parameters	Values	Unit
Environment temperature	20	℃
The cooling water temperature	20	℃
Condensation temperature	30	℃
Pinch point temperature of evaporator and condenser	5	℃
Isentropic efficiency of turbine	0.85	
Isentropic efficiency of pump	0.80	

4. RESULTS AND DISCUSSION

In demonstration of present system, R123 is used as working medium. The change of net output power of serial ORC with running time and k is shown in Fig 4. W_{net} of serial ORC gradually decreases as running time becomes longer, and value range of k increases as the running time becomes longer. As the value of k increases, W_{net} of serial ORC system increases first and then decreases. With increase of running time, temperature of hot dry rock production well gradually lower. The injection temperature is constant, and available heat source temperature difference gradually decreases, which is main reason of the decrease in W_{net}. Because pinch point temperature exits in evaporator, k value will have a certain range.

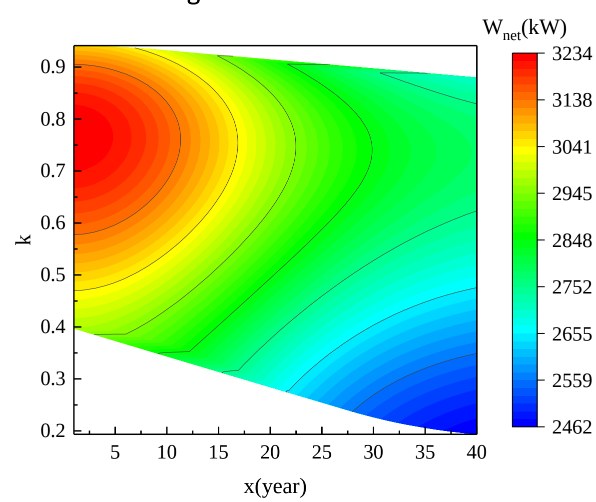

Fig 5 The net output power with running time and k.

Thermal efficiency of serial ORC system varies with running time and k as shown in Fig 5. η_{ORC} of serial ORC system decreases as running time gets longer, and as k increases, it increases first and then decreases. When outlet temperature of the serial ORC system is determined, as heat source temperature decreases, W_{net} of serial ORC system decreases, but reduction of heat loss in condenser is not significant. Therefore, η_{ORC} of serial ORC system is gradually decreasing.

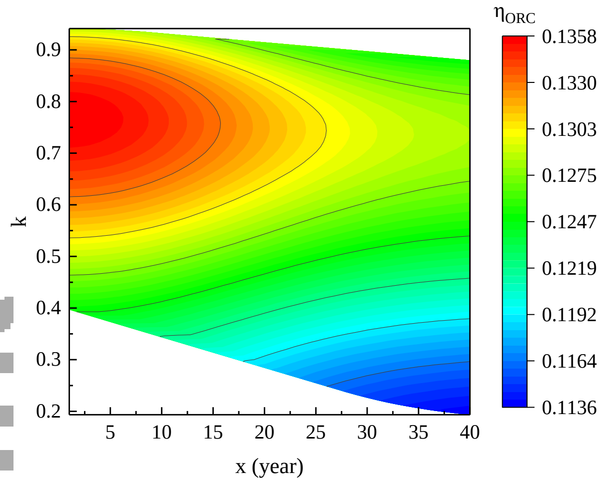

Fig 6 The thermal efficiency with running time and k.

The exergy efficiency of serial ORC system varies with running time and k as shown in Fig 6. As the running time increases, exergy efficiency of serial ORC system gradually decreases, but change is not obvious. As the value of k increases, exergy efficiency of serial ORC system increases first and then decreases. When outlet temperature of serial ORC system is determined, W_{net} of serial ORC system decreases, but reduction of exergy loss in serial ORC system is not significant. Therefore, exergy efficiency of serial ORC system is gradually decreasing.

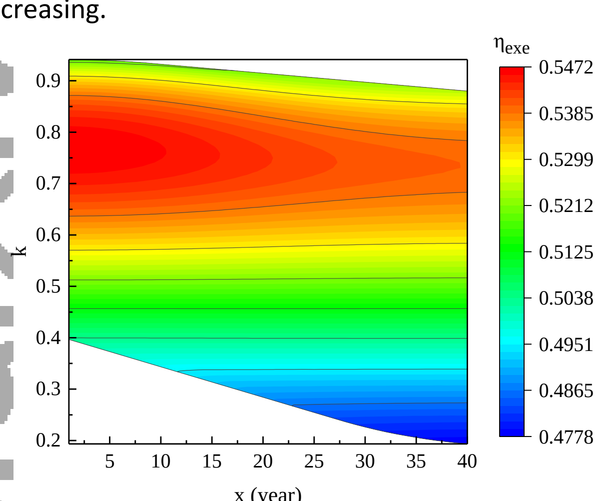

Fig 7 The exergy efficiency with running time and k.

The organic working medium flow of serial ORC varies with running time and k as shown in Fig 7. As running time gets longer, organic working medium flow in serial ORC system decreases. With increase of k value, organic working medium flow in HT-stage increases, but that of LT-stage reduces, so organic working medium flow in serial system increases first and then decreases. In same running time, net output power and organic working medium flow in serial ORC system have opposite changes with k value. When organic working medium flow is the smallest, the W_{net} is the largest.

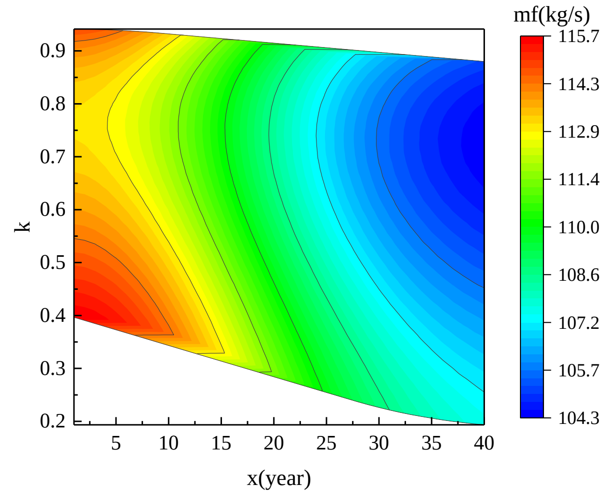

Fig 8 The organic working medium flow with running time and k.

5. *CONCLUSIONS*

Considering temperature change of hot dry rock production well with running time and the requirement of injection well temperature, a thermodynamic model of serial ORC is established. According to selection criterions, six kinds of organic working mediums are selected for thermal calculation, and net output power, exergy efficiency, thermal efficiency and mass flow rate of serial ORC system with different organic working medium are compared. The conclusions are drawn as following:

1) When the dry hot rock injection well temperature is constant, the dry hot rock production well temperature decreases as the running time increases, which results in a decrease in exergy efficiency, thermal efficiency, net output power and organic working medium flow in serial ORC system. Among them, decrease in net output power varies from 13.8% to 16.8%.

2) As the value of k increases, thermal efficiency, net output power and exergy efficiency of serial ORC system firstly increase and then decrease, but mass flow rate of the organic working medium firstly decreases and then increases. Maximum value of thermal efficiency, net

output power and exergy efficiency of serial ORC system and minimum value of mass flow rate of organic working medium are obtained at same k value.

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