A COMPREHENSIVE GEOTHERMAL SYSTEM IN THE USAGE OF OILFIELD ASSOCIATED WATER FROM ABANDONED OIL WELLS

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ABSTRACT

High water-cut oil wells are weak in exploitation of crude oil but cost a lot for maintenance, an appropriate way to deal with this problem is making full use of the waste heat from the oilfield associated water. A comprehensive geothermal system was proposed to the cascade utilization of the geothermal water from the oil well, and it consisted of a power generation system based on organic Rankine cycle (ORC), a gathering heat tracing system, an absorption refrigeration system for house cooling, and a house heating system. Exergy and sensitivity analysis about the ambient temperature were conducted to evaluate the thermal performance of the comprehensive system, and heat consumption equivalent was applied to assess its economic performance. Results showed that the best evaporating pressure of ORC subsystem was 650kPa, and the overall system could work with a exergy efficiency higher than 42.5% the whole year. Moreover, nearly 8916 tons of kgce could be saved every year. The work done may provide some guidance for researchers in the usage of the geothermal water based on high water-cut oil wells.

1. INTRODUCTION

In recent years, the rapid development of the society and economy demands the increasing consumption of energy sources all over the world. According to British Petroleum's report (BP Energy Outlook 2019 edition), primary energy is still dominant in energy consumption structure, and no obvious change will occur in a short time although the share of renewable energy consumption has increased considerably. However, the environmental issues caused by fossil fuel's burning become more serious, and the rapid growth of economy has exacerbated the results by accelerating the energy consumption. Consequently, it is recommended that almost 60% of all new power generation capacity should be supplied by renewable energy by 2040 without any subsides (World exergy outlook 2018).

As one of the potential and competitive renewable energy resources, the geothermal energy shows the advantages of long-term stability, zero-pollution emissions and favorable cost (Hammons et al,.2004; Cheng et al., 2016), which has attracted researchers and manufacturers' attentions in recent decades. As a result, more and more geothermal power plants, which convert the geothermal energy to electric energy, have been set up for power generation in many countries (Hammons et al,.2004).However, several obstacles slow down the development of geothermal power generation, including the drilling cost of the geothermal wells, injection of water and corrosion (Stáhl et al., 2000; Bu et al., 2012). Specially, about half of the total cost of a geothermal project is used to drill geothermal wells, which restricts the generalization and marketing of the geothermal power generation significantly (Enrico, 2002). Meanwhile, after years of exploitation, the water cut in many mature oil and gas wells is very high and many of these wells have been abandoned. The oil and gas wells have become "water" wells, storing large amount of heat energy (Hu et al., 2017). Thus, transforming these abandoned wells into geothermal wells for electric power generation not only takes full advantage of the huge heat reservoir, but also saves plenty of drilling cost, which is regarded as a potential and promising geothermal technology, called coproduction (Bennett 2012).

A number of researchers have published relevant studies about the power generation from coproduced geothermal resources. Davis et al. (2009) performed a simulation for geothermal power production from abandoned oil wells with consideration of local geothermal gradient, pipe diameters and well depth. Bu et al. (2012) discussed the feasibility of the geothermal energy production from existing abandoned oil and gas wells based on the developed heat exchange equations between fluid and rocks. Cheng et al. (2013; 2014) established a geothermal power generation model based on transient formation heat conduction of abandoned oil wells and investigated the influences of working fluid, well depth and geothermal gradients on the system performances. Yang Yi et al. (2017) established an organic Rankine cycle power generation with intermediate heat exchanging system based on the geothermal water from abandoned oilfield, and provided some experimental results.

Apart from the single use of geothermal water to generate electricity, some scholars put forward multi-system model to maximize the utilization of waste heat from abandoned oilfield. Li Tailu et al. (2012) proposed a cascade utilization of geothermal water by adding a gathering heat tracing subsystem on an organic Rankine cycle power generation system, then they (2014) established a novel system through supplementing cooling, heating and domestic hot water systems, and they studied the performance of the novel system with different working fluids (R600, R601a, R601, R245fa, R123, R141b). Besides, Li Tailu et al. (2018) designed a poly-generation energy system by replacing the top and bottom cycles between ORC and absorption chiller systems. Imran et al. (2016) investigated different ORC configurations for geothermal power plants including simple ORC, regenerative ORC, recuperated ORC and ORC with internal heat exchanger, and assessed these ORC configurations with different objective functions. Zhai et al. (2014) concerned the effects of various working fluids on the system performances, to choose the most suitable working fluid for the specified geothermal resource.

The review of previous work above shows that there have been many investigations about geothermal ORC system. However, most of the studies are focused on the power generation or multi-system in series while the flexibility is ignored. Besides, no one has taken the reinjection temperature of geothermal water into consideration and neglects the sediment in the original geothermal water, which could cause jam and lower the efficiency of heat exchanging. Therefore, a comprehensive geothermal system consisting of four parallel subsystems (ORC, House heating, Absorption Chiller, Heat gathering tracing) is established in this paper. Intermediate heat exchangers are designed to deal with the jam caused by sediment, and R245fa is select to be the working fluid of ORC system due to its availability although R601a was proved better (Li et al. 2014). Further, exergy analysis and sensitivity study about ambient temperature are conducted. In addition, heat consumption equivalent is proposed to assess the economic performance of the comprehensive system based on high water-cut oil from abandoned oilfield.

2. MODEL

2.1 system model

Figure 1 shows the schematic diagram of the comprehensive utilization system about the geothermal water from high water-cut oil well, four subsystems were established to make full use of the thermal energy, they are organic Rankine cycle system used for power generation (marked blue in Figure 1), heat gathering tracing subsystem (HGT) used for oil pipeline's heating (marked purple in Figure 1), house heating subsystem (HH, marked yellow in Figure 1) and house cooling subsystem (HC, marked brown in Figure 1). Each line in different color refers to different circuits, and the red line represents the high water-cut oil. After pumping from the production well, the mixture will first enter the separator, and gas will be separated, then the high water-cut oil will flow in the subsystems according to demand. Four valves were placed to divide the flow into four parts, the specific mass flow will be adjusted by the opening of the valves. The HGT system and ORC system were designed to work all the time while the HC system and the HH system only operated in the summer or winter. Giving that the water-oil mixture contains silt, long-term operation of the heat exchangers will cause jam, which will weak the efficiency of heat transfer. So an intermediate system was established for the cleaning or replacement of the heat exchanger, and two intermediate heat exchangers were placed in the HGT and ORC subsystems, one was for operation, the other was for emergency, only one heat exchanger will work during HE1 and HE2, IHE1 and IHE2 normally. Besides, valve group will match the intermediate heat exchangers, that means Valve1 (V1) and V2 will open if HE1 works, while the V3 and V4 should be closed meanwhile, the same applies to V6-V8 and V7-V9. Considering that the HH and HC subsystems will not work all the year, only two valves (V13-V14, V15-V16), marked but not painted in Figure 1) rather than two heat exchangers were set to deal with the emergency. After releasing heat in those subsystems, the high water-cut oil will gather and enter the oil removal tank, then oil will be extracted and gathered in the oil tank, leaving the tail water to be injected in the reinjection well.

ORC subsystem was marked blue in Figure 1, it contains an evaporator, a turbine, a generator, a condenser, a working fluid pump, a cooling tower, and a regenerator. R245fa was selected as working fluids due to its availability. The saturated working fluid (6) was first pumped into the regenerator to recover the heat from exhaust steam, then it (8) will enter the evaporator to absorb heat. The superheated steam (9) from the evaporator will come into the turbine and drive the generator to generate power. After cooling in the regenerator, the exhaust steam (11) will be cooled to saturated liquid in condenser. The regenerator was set to improve the thermal efficiency of the ORC system and the dropping valve 12 was set to guarantee the normal operation of the whole system if the turbine break down, generally, V12 should be closed.

The HGT subsystem was designed to heat the oil pipeline buried underground, that the temperature of the oil can be maintained constant, which can help the oil flow at a lower viscosity and reduce the risk of blocking. Similar to the ORC subsystem, the mass flow of the geothermal water can be controlled by the opening of V1 or V3 according to demand.

Different from the ORC and HGT subsystems mentioned above, HC and HH systems only worked several months, thus no spare intermediate heat exchangers were prepared to handle the emergency. The water-lithium bromide absorption refrigeration was applied in the house cooling system, for it can use the low-temperature thermal energy, and the schematic diagram of HC was showed in Figure 2. After absorbing heat in the generator, a portion of superheated steam escaped from the weak water-lithium bromide solution, leaving the strong solution to flow back to the absorber. The steam (32) will first be cooled in the condenser, then it went through the throttle valve to release pressure and heat, after that, the two-phase liquid (34) will acquire heat from the chilled water (30-31) in the evaporator, and the chilled water can be provided for residents. In the absorber, the strong solution (36) from generator will be transferred into weak solution (41) after absorbing the steam (35) from evaporator, besides, the heat generated in the absorption will be taken away by the cooling water (27-28). In order to make full use of the source, the cooling water will enter the condenser before exiting. In view of the application, only single stage absorption chiller was adopted.

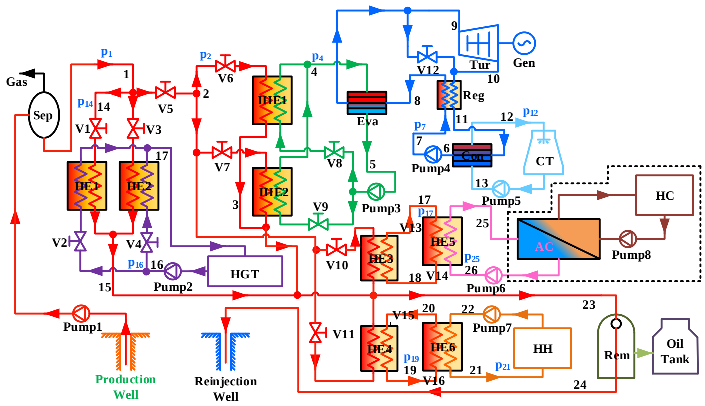


Figure 1 Schematic diagram of the comprehensive utilization system about the geothermal water

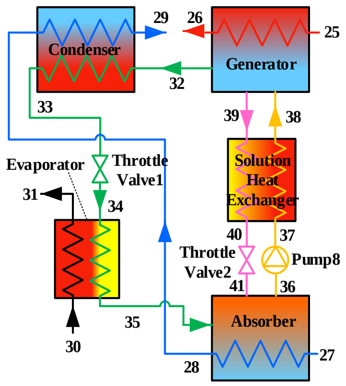


Figure 2 Schematic diagram of the water-lithium bromide absorption refrigeration subsystem

2.2 thermodynamic model

A comprehensive thermodynamic analysis is conducted on the basis of mass and energy conservation principles and exergy balance to each device of the comprehensive geothermal system. To simplify the mathematical model, both kinetic and potential energies were neglected in the energy and exergy analysis, thus the energy conservation and specific exergy can be expressed as:

$$\sum_{in} mh + \sum_{i} Q + \sum_{j} W = \sum_{out} mh + \sum_{k} Q + \sum_{l} W \qquad (1)$$

$$e = h - h_0 + T_0(s - s_0) \qquad (2)$$

where 0 refers to the state at ambient temperature, when the temperature is lower than the ambient temperature, specific exergy should be written as:

$$e = h_0 - h + T_0(s_0 - s) \qquad (3)$$

Mass conservation in the absorber and generator of absorption chilling subsystem can be written as:

$$m_{41} = m_{35} + m_{36} \tag{4}$$

$$m_{41}\mathrm{x}_w = m_{36}\mathrm{x}_s \tag{5}$$

where x refers to the lithium bromide concentration, defined as:

$$\mathrm{x} = \frac{m_{LiBr}}{m_{solution}} \tag{6}$$

Besides, thermal efficiency and exergy efficiency as well as *COP* were performed to evaluate the performance of the subsystems, and they can be expressed as:

$$\eta_{ORC} = \frac{W_{net}}{m_2(h_2 - h_3)} \tag{7}$$

$$\eta_{ex} = \frac{\sum_{in} me}{\sum_{out} me} \tag{8}$$

$$COP = \frac{m_{32}(h_{34} - h_{35})}{m_{25}(h_{25} - h_{26}) + m_{41}(h_{37} - h_{36})} \tag{9}$$

Heat consumption equivalent of the total system is defined as:

$$HC_e = \sum(\frac{W_{net,ORC}}{\eta_{tpg}} + \frac{W_{AC}}{\eta_{tpg} \cdot COP_{hac}} + W_{HH}) \tag{10}$$

where η_{tpg} refers to the thermal efficiency of thermal power generation, and COP_{hac} represents the COP of normal household air conditioner.

In addition, energy and exergy balance equations for the primary devices of the whole system are listed in Table 1, and Table 2 shows the initial conditions of the whole system.

2.3 appropriate assumptions

In order to simplify the calculation, appropriate assumptions are performed during the analysis about the thermodynamic performance of the comprehensive system:

(1) The whole system works at steady state;
(2) Energy losses and pressure drop in the pipes and heat exchangers are neglected in the thermodynamic analysis;
(3) Chemical reaction is not considered and all the energy exist in the form of internal energy;
(4) Solutions at the exits of generator (39) and absorber (36) are saturated, while the water at the exits of condenser (33) and evaporator (35) is saturated too;
(5) Leakages of working fluids are negligible and the high water-cut oil is regarded as pure water at calculation;
(6) The temperature at the exit of geothermal water keeps constant at 110.9 ℃, and the temperature of tail water maintains 75 ℃ all the year.

Besides, all the physical properties refer to NIST REFPROP 9.1 and ASHRAE Handbook.

Table 1 Energy and exergy balance equations for primary devices of the geothermal system

Components	Energy balance	Exergy loss
Evaporator(ORC)	$m_6(h_9 - h_8) = m_4(h_4 - h_5)$	$E_{eva,ORC} = m_4(e_4 - e_5) - m_6(e_9 - e_8)$
Pump4	$W_{p,ORC} = m_6(h_7 - h_6)$	$E_{p,ORC} = W_{p,ORC} - m_6(e_7 - e_6)$
Regenerator	$m_6(h_8 - h_7) = m_{11}(h_{10} - h_{11})$	$E_{re} = m_{11}(e_{10} - e_{11}) - m_6(e_8 - e_7)$
Turbine	$W_{tur} = m_9(h_9 - h_{10})$	$E_{tur} = m_9(e_9 - e_{10}) - W_{tur}$
Condenser(ORC)	$m_6(h_6 - h_{11}) = m_{12}(h_{13} - h_{12})$	$E_{con,ORC} = m_6(e_6 - e_{11})$
HGT	$m_{16}(h_{16} - h_{17}) = m_{14}(h_{14} - h_{15})$	$E_{HGT} = m_{14}(e_{14} - e_{15}) - m_{16}(e_{16} - e_{17})$
HH	$m_{21}(h_{21} - h_{22}) = (m_2 - m_3)(h_2 - h_{23})$	$E_{HH} = (m_2 - m_3)(e_2 - e_{23}) - m_{21}(e_{21} - e_{22})$
Absorber	$m_{27}(h_{28} - h_{27}) = m_{32}h_{35} + m_{41}h_{41} - m_{36}h_{36}$	$E_{abs} = m_{32}e_{35} + m_{41}e_{41} - m_{36}e_{36} - m_{27}(e_{28} - e_{27})$

Evaporator(AC)	$m_{30}(h_{30}-h_{31})=m_{32}(h_{35}-h_{34})$	$E_{eva,AC}=m_{32}(e_{34}-e_{35})-m_{30}(e_{31}-e_{30})$
Throttle valve1	$h_{33}=h_{34}$	$E_{TV1}=m_{32}(e_{33}-e_{34})$
Condenser(AC)	$m_{27}(h_{29}-h_{28})=m_{32}(h_{32}-h_{33})$	$E_{con,AC}=m_{32}(e_{32}-e_{33})-m_{27}(e_{29}-e_{28})$
Generator	$m_{25}(h_{25}-h_{26})=m_{32}h_{32}+m_{41}h_{39}-m_{36}h_{38}$	$E_{ge}=m_{25}(e_{25}-e_{26})+m_{36}e_{38}-m_{32}e_{32}-m_{41}e_{39}$
Solution Heat Exchanger	$m_{41}(h_{39}-h_{40})=m_{36}(h_{38}-h_{37})$	$E_{HE}=m_{41}(e_{39}-e_{40})-m_{36}(e_{38}-e_{37})$
Throttle valve2		$E_{TV2}=m_{41}(e_{40}-e_{41})$
Pump8	$W_{P,AC}=m_{36}(h_{37}-h_{36})$	$E_{P,AC}=W_{P,AC}-m_{36}(e_{37}-e_{36})$

Table 2 Initial conditions of the comprehensive geothermal system

parameters	Unit	value	parameters	Unit	value
m_1	kg/s	600	t_1	℃	110.9
m_2	kg/s	450	t_{23}	℃	75
m_3	kg/s	150-450	t_2-t_4	℃	10
p_2	kPa	190	Pinch point temperature of Evaporator (ORC)	℃	5
p_4	kPa	250	Average ambient temperature	℃	22
p_7	kPa	650	Average cooling water inlet temperature	℃	15
$\eta_{\text{generator,ORC}}$	/	0.92	$\eta_{\text{pump,AC}}$	/	0.75
η_{turbine}	/	0.6	$\eta_{\text{pump,ORC}}$	/	0.7

3. RESULTS AND DISCUSSIONS

It can be revealed from Figure 3 that the net power and exergy efficiency of the ORC subsystem increase with the growth of evaporating pressure, while the lower terminal temperature difference of evaporator decrease at the same time. Although the exergy efficiency grows with p_7, the increment speed slow down gradually. Given that the terminal difference should be larger than the minimum value, the evaporating pressure is designed as 650kPa, while the terminal difference is nearly 5℃ (marked red in Figure 3).

Besides, the impact of evaporating pressure (p7) on the exergy loss and exergy efficiency of the ORC devices are separately demonstrated in Figure 4(a) and Figure 4(b). As the evaporating pressure rises, exergy loss shrink in the evaporator and intermediate heat exchanger while it rises in the turbine, meanwhile, it nearly keeps constant in the condenser, regenerator and pump (4). When the evaporating pressure approaches 650kPa, the exergy loss in turbine and evaporator occupy the most of the ORC subsystem, among which turbine exceeds evaporator. That may due to the increase of exhaust temperature in turbine and the destruction of terminal temperature difference in evaporator. On the other hand, exergy efficiency rises in the IHE1 and evaporator but reduces in the regenerator, while it almost remains constant and is close to the thermal efficiency of pump 4 and turbine. Results show that a higher evaporating pressure will contribute to the improvement of ORC performance, but weakens the effect of regenerator on the thermal efficiency.

Figure 5(a) and Figure 5(b) depict the variation of exergy loss and exergy efficiency to ambient temperature in absorption devices respectively. As the ambient temperature rises, exergy loss increases in absorber but decreases in condenser, while it keeps constant in other components. However, variations of exergy efficiency are different in different components, and the cooling system seems to have a higher exergy efficiency under a higher ambient temperature, which mainly due to the increase of cooling exergy and the decrease of thermal exergy as ambient temperature rises. Actually, cooling system only works in summer and the ambient temperature is high that a relative higher exergy efficiency could be reached. Besides, the COP of the absorption cooling system is 0.914, which is basically the same as that of single absorption cooling. We can also learn from the figure that thermal insulation measures should be taken on the devices of the absorption cooling system if better performance is needed, because the system always works under higher temperature.

Meanwhile, sensitivity analysis was conducted on the exergy efficiency of the ORC devices to ambient temperature, results are displayed in Figure 6. Except for the regenerator, little variation is showed on the exergy efficiency of the rest components with different ambient temperature, which mainly results from the reduction of temperature different between the exhaust steam and ambient temperature, thus resulting in the exergy decline of exhaust steam. The result also indicates that regenerator is only suitable for the condition with large temperature difference between exhaust steam and environment.

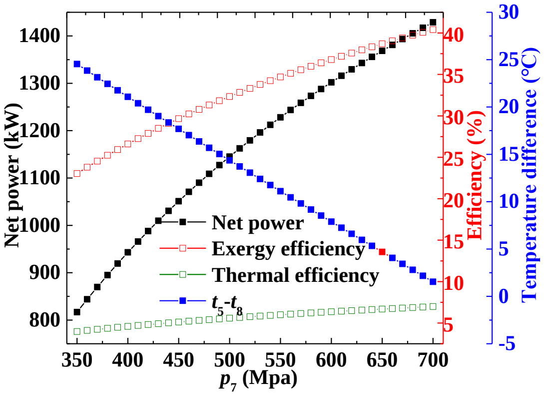
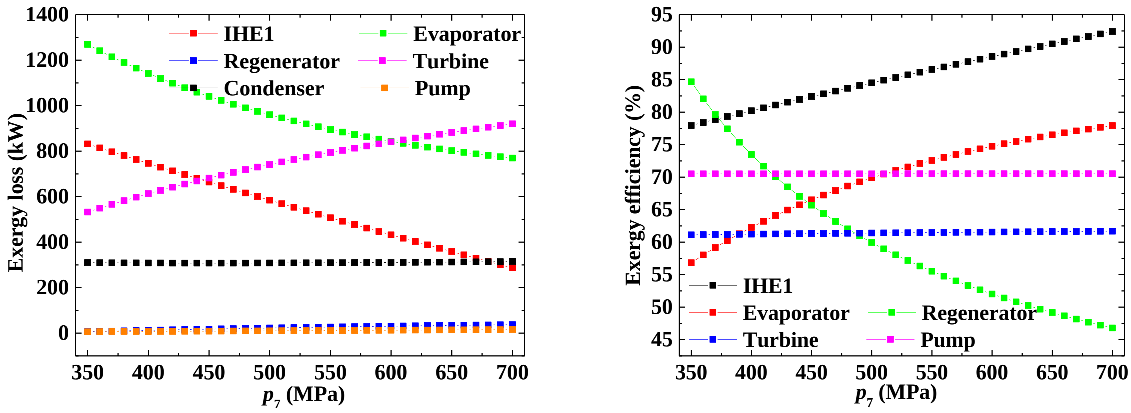


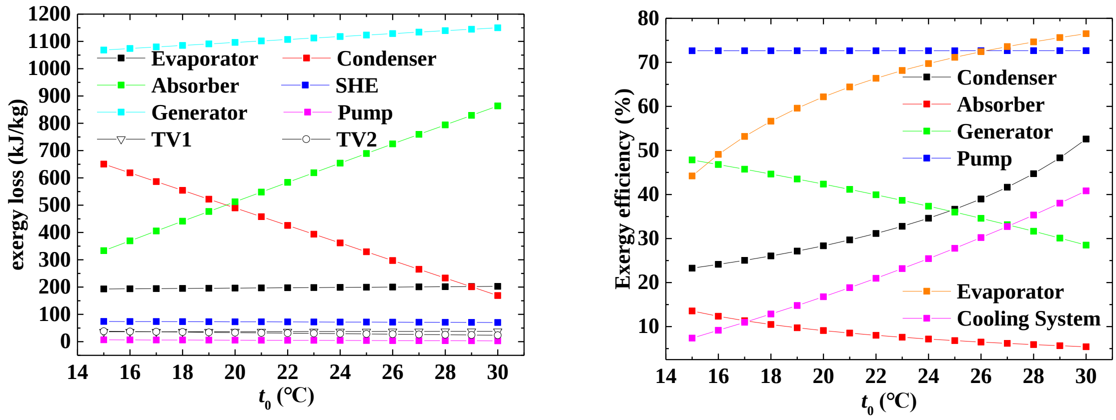
Figure 3 Effect of ORC evaporation pressure on net power, exergy and thermal efficiency, lower terminal temperature difference of the evaporator, at m_3=450 t·h^{-1}, t_0=22 °C



(a) Exergy loss

(b) Exergy efficiency

Figure 4 Effectiveness of evaporating pressure (p_7) on **(a)** exergy loss and **(b)** exergy efficiency of the ORC devices



(a) Exergy loss

(b) Exergy efficiency

Figure 5 Variation of **(a)** exergy loss and **(b)** exergy efficiency to the ambient temperature in the devices of absorption cooling system

In order to evaluate the economic performance of the whole geothermal system, heat consumption equivalent is proposed, which is the conversion of energy in different forms. Variations of heat consumption equivalent and exergy efficiency in the geothermal system as well as the ORC net power with time are presented in Figure 7, fluctuation exists in all the variables according to the figure, which mainly because of the temperature variation at different seasons. We can find that the comprehensive system performs better in summer and winner even though the power generation is sacrificed. Besides, the exergy efficiency of the comprehensive system is higher than 42.5% all the year, which validates the practicability of the system that more waste heat could be recovered with multiple outputs. When the system works in April and October, the net power output could reaches a peak but the economic performance arrives at trough, which reflects the performance of a single ORC system applied in the utilization of geothermal water. If all the heat consumption equivalent is converted into kgce, nearly 8916 tons of standard coal could be saved a year from the comprehensive system, much higher than 3387 tons in the single ORC system.

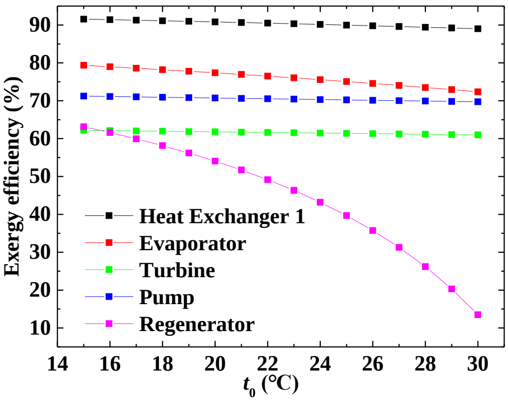


Figure 6 Exergy efficiency of the components in ORC with ambient temperature, at p7=650 kPa

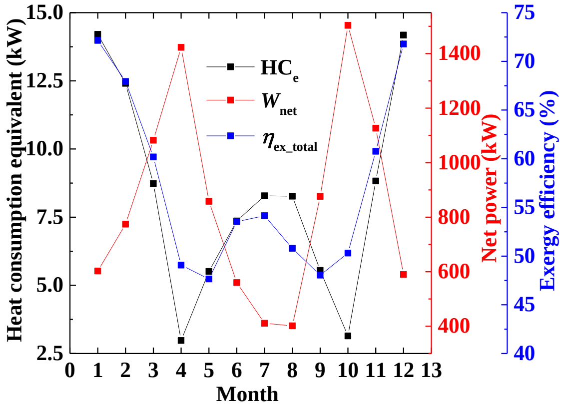


Figure 7 Variation of net power in ORC, total exergy efficiency and heat consumption equivalent in the geothermal system with time

4. CONCLUSION

Consisting of ORC, house heating, absorption cooling and HGT subsystems, a comprehensive parallel system was established to recover the heat from high water-cut oil in an abandoned oilfield. Exergy analysis as well as sensitivity study with ambient temperature was conducted to evaluate the performance of subsystems, and heat consumption equivalent was proposed to assess the economic performance of the whole system. Results show that more net power could be generated when the evaporating pressure reaches 650kPa considering the minimum terminal temperature difference of evaporator. According to the sensitivity analysis, most components of the system are sensitive to the ambient temperature fluctuation for the variation of exergy loss and exergy efficiency are obvious but linear. Appropriate heat insulation measures should be taken to guarantee high exergy efficiency of the system under different ambient temperature, especially in summer and winter. If assessed through kgce, the comprehensive system could save nearly 8916 tons of standard coal a year, higher than 3387 tons in the single ORC system. Besides, the comprehensive system could always operates with a exergy efficiency higher than 42.5%, better than the situation that only power generation system works to recover the heat, which illustrates the fact that the comprehensive system may be more appropriate for the heat recovery from geothermal water on the basis of the exergy efficiency and revenue economy.

NOMENCLATURE

COP	coefficient of power	(–)
E	specific exergy loss	(kJ/kg)
Q	heat	(kJ/kg)
T	Kelvin temperature	(K)
W	power	(kW)
e	specific exergy	(kJ/kg)

h	specific enthalpy	(kJ/kg)
m	mass flow rate	(kg/s)
p	pressure	(kPa)
s	specific entropy	(kJ/(kg·K))
t	Celsius temperature	(°C)
x	mass fraction	(–)

Subscript

AC	absorption chiller
HH	house heating
ORC	organic Rankine cycle
ex	exergy
hac	household air conditioner
tpg	thermal power generation

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