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Research on the thermodynamic performance of a novel power generation system for a natural gas pressure reduction station integrated with cold energy and geothermal energy utilization[#]

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ABSTRACT

In this paper, a novel multi-energy complementary power generation system used for natural gas city gate stations (NGCGS) is proposed, which aims at recovering considerable amount of energy (including NG pressure energy and cold energy after expansion) wasted at the pressure regulators in city gate stations (CGS). The proposed system consists of three major subsystems: geothermal water system (GWS), NG expansion power generation system (NGEPGS) and organic Rankine cycle power generation system (ORCGS). GWS works as a heat source to heat the organic working fluid in the ORC's evaporator and then to heat the NG before it enters the expander for power generation. NGEPGS uses an expander to recover the pressure energy for power generation which replaces the conventional process of NG pressure reduction in the CGS. The ORCGS takes the geothermal energy as heat source and uses the cryogenic NG from the outlet of the expander as ORC's heatsink for electricity generation. The thermodynamic model of the proposed system is established using EES (Engineering Equation Solver). 9 organic working fluids are selected and compared. Pentane has been chosen as the optimal working fluid in this study because it has the best performance. The proposed system is compared with another system established by previous researchers. The results show that the proposed system in this paper can generate more electricity under the same conditions.

Keywords: thermodynamic performance, multi-energy complementary power generation system, natural gas pressure energy, cold energy and geothermal energy, working fluid selection

NONMENCLATURE

Abbreviations	
NG	Natural gas
CGS	City gate stations
GWS	Geothermal water system
NGEPGS	NG expansion power generation system
ORCGS	Organic Rankine cycle generation system
HEX	Heat exchanger
ODP	Ozone depletion potential
GWP	Global warming potential

1. INTRODUCTION

Given the severe environmental challenges and problems today, it is imperative to prioritize energy conservation and emissions reduction. As one of the cleanest fossil fuels, natural gas (NG) plays an important role in promoting a low carbon energy transition. According to the Statistical Review of World Energy [1] released in 2024, the average annual growth rate of global NG consumption between 2013 and 2023 is 1.7%, while Chinese mainland is 8.9%. So in the future, NG will continue to serve as a key bridge for air pollution control and energy transition.

As low-density gas, NG has larger volume under normal temperature and pressure. As a result, it needs to be transported under higher pressure after extraction, which aims to improve transportation efficiency and reduce transportation costs. However, high-pressure NG must undergo pressure reduction treatment before it can be transported to the downstream pipeline networks. According to the pipeline pressure, pipeline networks can be divided into different grades. After thorough investigations, the current pressure of high-pressure pipeline networks is generally more than 4MPa,

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some even reach 10-20MPa, while low pressure pipeline networks are generally below 0.01MPa, so the pressure difference between different pipeline networks contains huge energy. However, at present, most NG city gate stations (CGS, undertake the task of reducing NG pressure between different grades of pipeline networks) waste this part of energy completely on the pressure regulators, and the pressure energy is not effectively utilized. Additionally, due to Joule-Thomson effect, the temperature of NG decreases after it passes through the pressure regulator. So extra energy is needed to heat NG in order to meet the temperature requirements of the downstream pipeline networks or users. If this part of the cold energy can be used, it is of great significance for energy conservation and emissions reduction.

Both domestic and foreign scholars have conducted many relevant studies. Yao et al. [2] chose a low-temperature geothermal well located in Tianjin for research. The study couples the NG cold energy and pressure energy from CGS with geothermal energy. Meanwhile, genetic algorithm is used to optimize the non-dimensional net profit and payback period. Hadidi [3] proposed a water tower energy storage system based on the NG pressure energy generation and designed water towers in different size to calculate their energy storage capacities and efficiencies. The results showed that the proposed system can recover 15.3 GWh of energy per year and reduce a large amount of carbon dioxide emissions at the same time, which has great significance for energy conservation and emissions reduction. Ermis et al. [4] proposed a system that contains NG pressure energy generation and hydrogen production. To avoid the formation of gas hydrate at low temperature, NG is preheated at preheating unit, and the electricity generated can be used for hydrogen production in PEM electrolyzer. The thermodynamic performance and technical-economic performance of the system are evaluated comprehensively. Wang et al. [5] proposed a CGS pressure energy recovery system based on Allam cycle, in which low-temperature NG is used as the heatsink of Allam cycle. The paper compared the proposed system with gas turbine preheating system. The results showed that when the combustor outlet temperature is 900℃, the energy efficiency and incremental efficiency of the proposed system are 99.31% and 103.55%, respectively. When compared with the preheating system, energy efficiency and incremental efficiency have increased by 9.84 percentage points and 19.32 percentage points respectively. Li et al. [6] proposed a system for recovering NG cold energy based on low-temperature heat source, which consists of two subsystems: the ORC part and the pressure energy generation part. A mathematical model of the system was established and multi-objective optimization was carried out. The simulation results showed that after optimization, the net power output and exergy efficiency are improved by 17.15% and 22.37% respectively and the cost of electricity is reduced by 42.23%. In order to save the energy consumed by NG in the preheating stage, Arabkoohsar et al. [7] used a solar heating set to preheat NG and the preheated NG enters the turbine for power generation. The researchers took Birjand CGS as an example to carry out thermodynamic and technical-economic calculations. The results showed that the pay back ratio is only 3.5 years. Xu et al. [8] conducted a coupling study of NG pressure power generation and CO2 Rankine cycle. The performance of the system under design and off-design conditions are analyzed.

As a promising renewable energy, geothermal energy has the advantages like stability, large reserves and wide distribution. [9] So based on the literature reviews above, this paper proposes a novel power generation system based on CGS, which combines geothermal energy with NG pressure energy and cold energy. In this paper, Engineering Equation Solver (EES) is used to build a mathematical model for the proposed system, and 9 different organic working fluids were selected according to their thermodynamic properties under the design working conditions. Finally, in order to verify that the proposed system has better performance, the system in this paper is compared with the system of Yao et al.[2].

2. SYSTEM DESCRIPTION AND MODELLING

2.1 System description

The proposed system consists of geothermal water system (GWS), NG expansion power generation system (NGEPGS) and ORC generation system (ORCGS), the detailed schematic diagram of the multi-energy complementary power system is shown in Fig.1.

For GWS: geofluid (90℃, state 1) extracted from the production well enters the ORC evaporator and exchange heat with organic working fluid. Then it (state 2) enters the HEX1 and preheat the upstream NG (10℃ /6MPa, state 5) entering the CGS so that the initial parameters of NG increase. After that, according to whether NG at state point 8 (the outlet of the ORC condenser) meets the temperature requirement of downstream pipeline, the geofluid at state 3 has two choices: the first is that the NG at state 8 does not meet

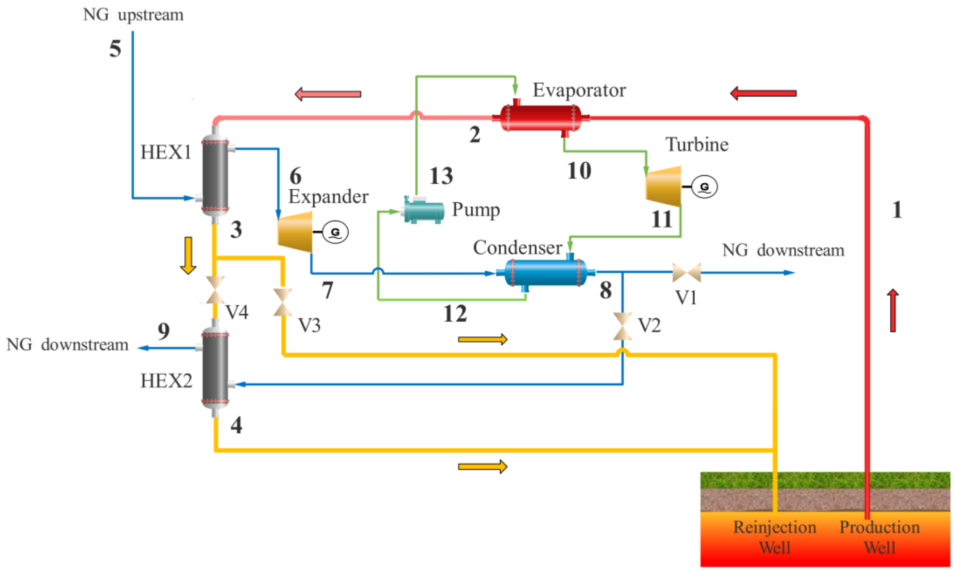


Fig. 1 Diagram of the proposed novel power generation system

the temperature requirement, then the valves V2 and V4 are open, V1 and V3 are closed, the geofluid at state 3 enters the HEX2 and heat the NG at state 8 to meet the requirement and finally the geothermal water is pumped underground through the reinjection well. If the requirement it met, then valves V1 and V3 are open, V2 and V4 are closed, geofluid at state 3 directly pumped underground through the reinjection well.

For NGEPGS, the preheated high pressure NG enters expander and the pressure energy is converted into electricity power. The cryogenic NG (state 7) then flows into ORC condenser and absorbs heat of ORC working fluid (state 11). As mentioned above, NG temperature at state 8 determines whether NG will be heated in HEX2. Finally, NG meets the requirement transported to the downstream pipeline networks.

For ORCGS, the working fluid at state 10 heated by geofluid and then expands in turbine for power generation, after expansion (state 11), it enters the ORC condenser and condensed by cryogenic NG at state 12. Finally, the condensed working fluid (state 12) is pressurized by the pump to complete the cycle.

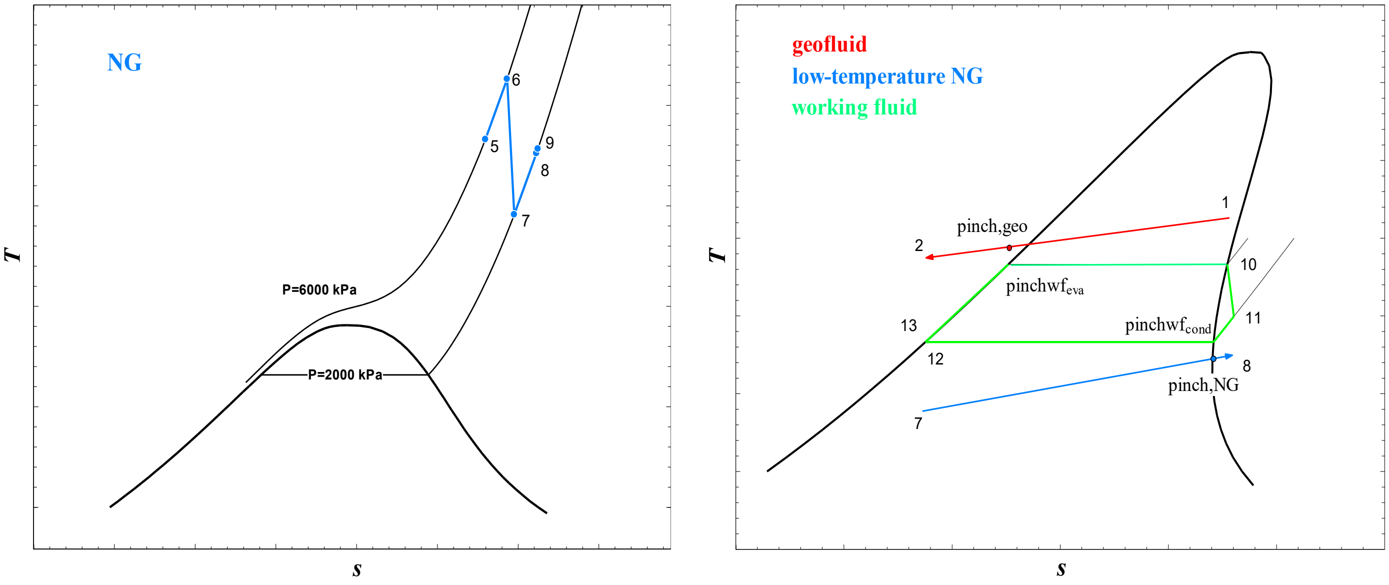


Fig.2 T-s diagrams of the two power generation systems: (a) NGEPGS (b) ORCGS

2.2 Mathematical model

2.2.1 Assumptions

In this paper, EES is used to build the mathematical model of the proposed system, and the fluid properties are referenced from NIST REFPROP 9.0. In order to simplify the model, the following assumptions and conventions are made in this paper:

(1) The system operates under steady-state conditions;

(2) For ORC, this paper only considers the sub-critical conditions;

(3) NG is modeled as pure methane;

(4) The heat exchange and pressure drop at the pipes and valves is ignored;

(5) Due to higher investment, superheater will not be considered in this paper;

(6) Assuming that the upstream NG has been dehydrated in advance, so no NG hydrate formed later.

2.2.2 Mathematical model

The mass and energy conservation equations are:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \tag{1}$$

$$\sum \dot{Q}_{\text{in}} + \sum \dot{W}_{\text{in}} + \sum \dot{m}_{\text{in}} h_{\text{in}} = \sum \dot{Q}_{\text{out}} + \sum \dot{W}_{\text{out}} + \sum \dot{m}_{\text{out}} h_{\text{out}} \tag{2}$$

NG pressure energy generation

The NGEPGS mainly includes a preheater and an expander. According to the thermodynamics laws:

$$m_{\text{ng}}(h_6 - h_5) = c_{\text{P,w}} m_{\text{geo}}(T_3 - T_2) \tag{3}$$

Considering the isentropic efficiency $\eta_{\text{iso,exp}}$, the work output of pressure energy generation can be calculated as below:

$$\frac{h_6 - h_7}{h_6 - h_{7\text{t}}} = \eta_{\text{iso,exp}} \tag{4}$$

$$W_{\text{pressure}} = m_{\text{ng}}(h_6 - h_7) \tag{5}$$

ORC condenser & evaporator

CGS mainly undertakes the task of decompressing a certain amount of upstream NG and NG is then heated by organic working fluid in the ORC condenser, so the mass flow rate of the working fluid is calculated by heat balance equations in condenser. Therefore, unlike most ORC studies, this paper first analyzes the heat balance in ORC condenser and calculate the mass flow rate of the working fluid. The equations are:

$$T_{\text{pinch,ng}} = T_{\text{pinchwf\_cond}} - \Delta T_{\text{pinch}} \tag{6}$$

$$m_{\text{ng}}(h_{\text{pinch,ng}} - h_7) = m_{\text{wf}}(h_{12} - h_{\text{pinchwf\_cond}}) \tag{7}$$

$$m_{\text{ng}}(h_8 - h_7) = m_{\text{wf}}(h_{12} - h_{11}) \tag{8}$$

The heat balance equations in evaporator are:

$$T_{\text{pinch,geo}} = T_{10} + \Delta T_{\text{pinch}} \tag{9}$$

$$c_{\text{P,w}} m_{\text{geo}}(T_1 - T_{\text{pinch,geo}}) = m_{\text{wf}}(h_{10} - h_{\text{pinchwf\_eva}}) \tag{10}$$

$$c_{\text{P,w}} m_{\text{geo}}(T_1 - T_2) = m_{\text{wf}}(h_{10} - h_{13}) \tag{11}$$

Where ΔTpinch represents the pinch point temperature difference in heat exchanger, the subscripts pinch,ng and pinchwf_cond represent the pinch point of NG and working fluid in condenser respectively and pinch,geo and pinchwf_eva represent the pinch point of geofluid and working fluid in evaporator respectively.

ORC pump & turbine

Considering the isentropic efficiency of pump $\eta_{\text{iso,pump}}$, the power consumed by ORC pump is:

$$\frac{h_{13\text{t}} - h_{12}}{h_{13} - h_{12}} = \eta_{\text{iso,pump}} \tag{12}$$

$$W_{\text{pump}} = m_{\text{wf}}(h_{13} - h_{12}) \tag{13}$$

The net power generated by ORC is calculated by:

$$\frac{h_{11} - h_{10}}{h_{11\text{t}} - h_{10}} = \eta_{\text{iso,turb}} \tag{14}$$

$$W_{\text{ORC}} = m_{\text{wf}}(h_{11} - h_{10}) - W_{\text{pump}} \tag{15}$$

HEX1 & HEX2

The heat transferred in HEX1 and HEX2 is calculated by:

$$Q_{\text{HEX1}} = m_{\text{ng}}(h_6 - h_5) = m_{\text{geo}}(h_2 - h_3) \tag{16}$$

$$Q_{\text{HEX2}} = m_{\text{ng}}(h_9 - h_8) = m_{\text{geo}}(h_3 - h_4) \tag{17}$$

Net power output and efficiency of the system

The power generation of the whole system is:

$$W_{\text{net}} = W_{\text{pressure}} + W_{\text{ORC}} \tag{18}$$

Both ORC efficiency and the whole system efficiency are considered in this paper:

$$\eta_{\text{en,ORC}} = {}^{W_{\text{ORC}}}\!\Big/_{m(h_{10} - h_{13})} \tag{19}$$

$$\eta_{\text{en,system}} = {}^{W_{\text{net}}}\!\Big/_{m(h_{10} - h_{13})} \tag{20}$$

Power output per kilogram of geothermal fluid (specific net power output) is:

$$\varphi = \frac{W_{\text{net}}}{m_{\text{geo}}} \tag{21}$$

2.3 Working fluid selection

Different working fluids affect the thermodynamic performance of the system directly, so selecting the appropriate working fluid is important in this research. According to the slope of saturated vapor curve in *T-s* diagram, the organic fluids can be divided into dry fluids (slope>0), wet fluids (slope<0) and isentropic fluids (slope=0). If no superheater installed before ORC turbine, the fluid at the outlet of the turbine may enter the two-phase region when using wet fluids, which may cause damage to the turbine. Therefore, only the dry and isentropic working fluids will be considered in this paper. In addition to thermodynamic properties, there are several other aspects need to be considered when selecting fluids: critical point, safety data, whether eco-friendly and so on. Based on previous literature, this paper selects 9 types of fluids, with their properties listed in Table1.

Table 1. Physical, safety and environmental data of the fluids

Working Fluid	**Type**	**Formula**	**T_{cr} (K)**	**P_{cr} (MPa)**	**ODP**	**GWP 100yr**	**Safety Data**
isobutene	isentropic	C4H8	418.09	4.01	0	<10	A3
R1234ze(z)	isentropic	C3H2F4	423.25	3.53	0	<10	A2L
R1234ze(e)	isentropic	C3H2F4	382.51	3.64	0	6	A2L
R1234yf	isentropic	C3H2F4	367.85	3.38	0	4	A2L
R245fa	dry	C3H3F5	427.16	3.65	0	1030	B1
isobutane	dry	C4H10	407.81	3.63	0	20	A3
pentane	dry	C5H12	469.80	3.37	0	11	-
R227ea	dry	C3HF7	374.90	2.93	0	3350	A1
R236ea	dry	C3H2F6	412.44	3.42	0	1370	A1

Before calculation, NG mass flow rate, upstream pressure and downstream pressure are firstly set as constant because they have no impact on fluid selection. The initial parameters of the system for calculation are listed in Table 2. As shown in Fig.3, the net power output and efficiency of ORC at different condensing temperatures of each fluid are calculated respectively.

Table 2. initial parameters of the system for calculation

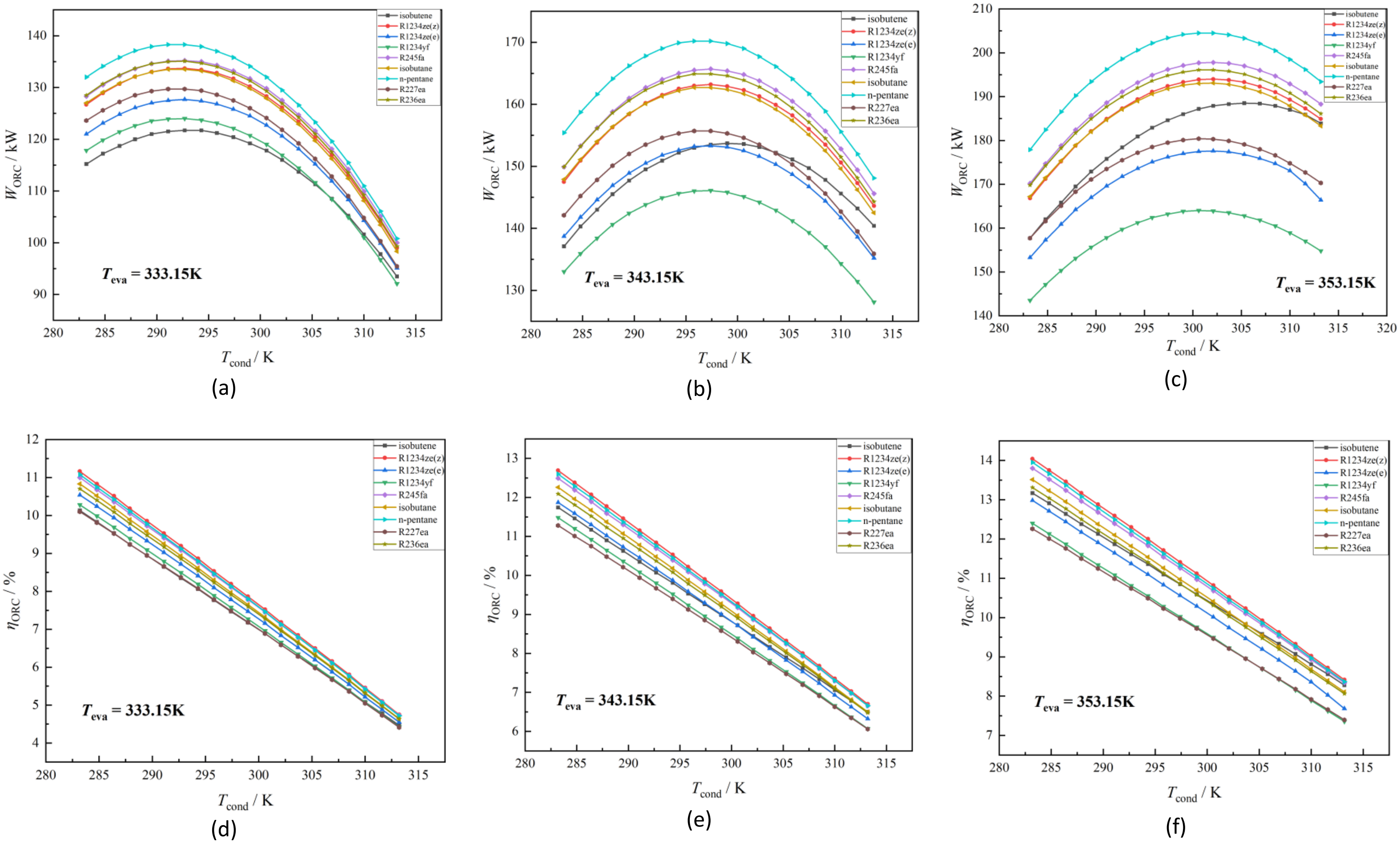
Parameters	Data
Geofluid temperature	90℃
NG mass flow rate	50000000Nm^3/month
NG upstream pressure	6Mpa
NG downstream pressure	2Mpa
NG downstream temperature requirement	>10℃
pinch point temperature difference	7℃
Isentropic efficiency of pump	80%
Isentropic efficiency of expander & turbine	85%

It can be noticed from the Fig.3 that with the increase of condensing temperature, the net power output of different fluids increases first and then decreases. So there is an optimal condensing temperature for each evaporation temperature. This is because on the one hand, the increase of condensing temperature reduces the latent heat during condensation. So the mass flow rate of the fluid increases to meet the equation in condenser; on the other hand, if the evaporation temperature is fixed, when the condensing temperature increases, the specific enthalpy drop in turbine reduces.

In addition, with the increase of evaporation temperature, the power generation of different fluids increases, and pentane has higher ORC net power output under different evaporation temperatures. The ORC efficiency decreases with the increase of condensing temperature, and it increases with the increase of evaporation temperature. The ORC efficiency of R1234ze(z) and pentane are better than that of other fluids under different evaporation temperatures, and the difference between them is little. Though R1234ze(z) performs better than pentane in ORC efficiency, pentane is chosen as the optimal working fluids considering the power generation comprehensively, and the thermodynamic performance of the system using pentane with optimal condensing temperature under evaporation temperature at 353.15K are shown in Table 3.

Table 3. Thermodynamic performance of the proposed system at the optimal condensing temperature with pentane as the working fluid (T_{eva}=353.15K)

Working Fluid	T_{eva}/ K	**T_{cond}/K**	$W_{pressure}$/ kW	W_{ORC}/ kW	W_{net}/ kW	η_{ORC}/%	η_{system}/%
Pentane	353.15	**301.4**	1682	204.6	1886.6	10.6	62.16



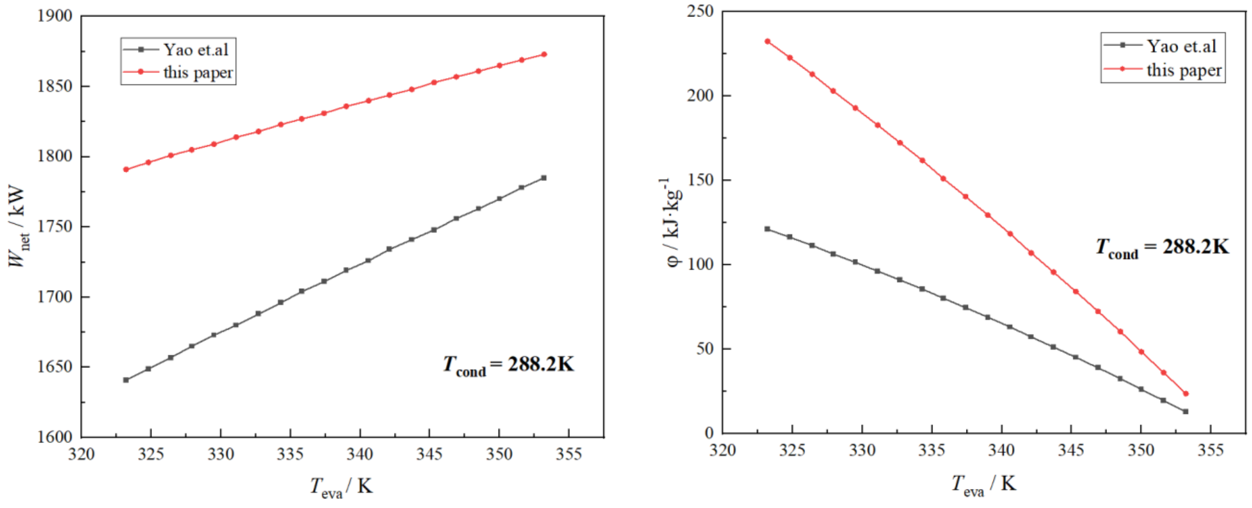
(a) (b) (c)

(d) (e) (f)

Fig.3 ORC power outputs (a-c) and efficiencies (d-f) under different evaporation temperatures

3. COMPARISON

In order to verify that the system has better thermodynamic performance, it is compared with the system proposed by Yao et al. (2018) [2], as shown in Fig.5. The systems have the following differences that need to be emphasized here: (1) Geofluid does not directly flows into the reinjection well after leaving ORC evaporator but into the HEX1 to preheat NG in this paper while the geofluid directly flows into reinjection well in the system of Yao et al. (2) As mentioned in Chapter 2, NG at the outlet of HEX1 (state 8) may enter HEX2 and exchange heat with geofluid according to the NG temperature at state 8. Firstly, the system model proposed by Yao et.al is rebuilt and verified in this paper, then the thermodynamic performances of the two systems are compared with each other under the same conditions. The results are shown in Fig.4. It can be found from the figures that both the net power output and specific net power output of the system proposed in this paper better than the system proposed by Yao et al. This is because the initial parameters of NG after preheating increase so more electricity is generated from NGEPGS.



(a) (b)

Fig.4 Thermodynamic performance of two systems under the same conditions：
(a) net power outputs (b) specific net power outputs

Although the cold energy of preheated NG at the expander outlet decreases, resulting in a decrease of ORC mass flow rate and thus a decrease in ORC power output, the final results in Fig.4 (a) show that the total power output increases because the ORC power output only accounts for a small proportion of total power output. Moreover, the decrease of ORC mass flow rate also leads to the decrease of geofluid mass flow rate so the specific power output increases as shown in Fig.4 (b).

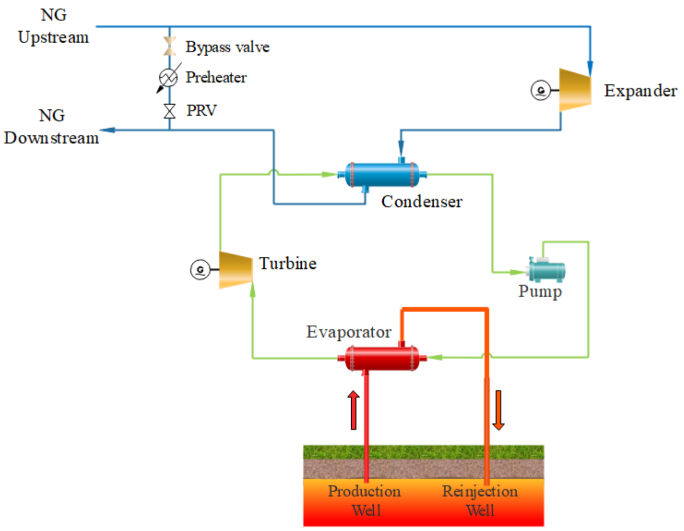


Fig.5 Schematic diagram of the system proposed
by Yao et al. (2018) [2]

In addition, it can also be found from the figures that when the evaporation temperature increases, the net power output of both systems increases. This is because the increase of evaporation temperature leads to increase the specific enthalpy drop of ORC turbine, and the ORC mass flow rate is constant because the condensation temperature is set to be constant in this part. Therefore, the net power output of the total system increases. Meanwhile, considering the heat balance equations in evaporator, the increase of evaporation temperature leads to the increase of geothermal water mass flow rate. Although the net power generation increases at this time, its growth rate is smaller than that of the geothermal water, so it is found that there is a decrease in specific power output.

4. CONCLUSIONS

In this paper, a multi-energy complementary power generation system integrated with cold energy and geothermal energy for a natural gas pressure reduction station is established and analyzed. The proposed system can recover a large amount of pressure energy wasted on the pressure regulators; the cryogenic natural gas at the outlet of the expander has been used as the heatsink of the ORC. Pentane is found to be the best working fluid for the ORC due to its good thermodynamic performances. The power output and system efficiency are 1886.6 kW and 62.16% respectively. In order to verify the proposed system has a better performance, it is compared with the system established by Yao et al. (2018). The results show that the proposed system can generate more power under the same operation conditions, and the specific net power output is also higher than that of the system of Yao et al. (2018). This research provides new solution and guidance for energy recovery and emission reduction at natural gas city gate stations.

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