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Analysis of Residual Pressure Power Generation in Natural Gas Pressure Regulating Station

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Abstract: Turboexpander, placed parallel to the regulator in natural gas pressure regulating station (PRS), was proposed to utilize the residual pressure by engineers and researchers. However, the relationship between the power generated by the turboexpander and the energy used to preheat the natural gas (NG) needs to be carefully analysed. This article estimated the electric power that could be generated using residual pressure based on an actual PRS in China. An analysis model was established to study the relationship between electric power generated by the turboexpander and energy used to preheat the NG. Pressures both inlet and outlet and inlet temperature of the established power generation model were carefully analysed as well as the natural gas hydrate formation temperature. The results indicate that the electric power generated by the turbine expander and the energy used to preheat natural gas decrease as the pressure difference decreases. Most of the energy needed to preheat NG in the procedure of PRS can be obtained through the established turboexpander. What's more, residual electric power can be obtained when the difference pressure is less than the critical point in which the energy used to preheat NG is equal to the energy generated by the turboexpander.

Keywords: Natural gas, Residual pressure recovery, Power generation, Preheat amount, Turboexpander.

1. Introduction

As a clean and efficient energy source, natural gas (NG) is of great significance in reducing air pollution, reducing carbon emissions, and optimizing resource structure.[1] In inland areas, natural gas is mainly transported through high-pressure pipelines.[2] The natural gas transported by the pipeline needs to be regulated by the PRS before providing to the users. Throttle valves are widely used in PRS to regulate the pressure of natural gas. The heating devices are usually added before the throttle valve to prevent ice blocking and hydrate formation. This method can cause significant energy loss.[3] Theoretically, the natural gas pressure energy wasted by utilizing a throttle valve can be recovered. The recovered energy can also be used to preheat natural gas. It can not only reduce the waste of resources, but also produce considerable economic benefits.

Nomenclature			
s	Specific entropy before expansion, *J/(kg·K)*	M	The molar mass, *kg/mol*
s_0	Specific entropy after expansion, *J/(kg·K)*	L	Flow rate, *Nm³/h*
h	Specific enthalpy value of inlet, *kJ/kg*	W	Electric power, *KW*
h_0	Specific enthalpy value of outlet, *kJ/kg*	a, b	State equation parameters
c_p	Isobaric specific heat capacity, *kJ/(kg·K)*	P	Pressure, *MPa*
Q_e	The generated electric power, *KW*	T	Temperature, *K*
Q_p	The energy used to preheat, *KW*	V	Molar volume, *L/mol*
$e_{x,h}$	Specific enthalpy exergy, *kJ/kg*	P_c	The critical pressure, *MPa*
$e_{x,t}$	Specific temperature exergy, *kJ/kg*	T_c	The critical temperature, *K*
$e_{x,p}$	Specific pressure exergy, *kJ/kg*	T_r	Temperature ratio
η_t	Expansion efficiency of expander, take 0.75	ω	acentric factor
η_g	The power generation efficiency, take 0.95	Subscripts	
ρ	Natural gas density, *kg/m³*	1,2,3	State points of the system
T_0	Ambient temperature, *K*	*in*	inlet
R	Molar gas constant, 8.314*J/(mol·K)*	*out*	outlet

Natural gas pressure recovery can be used for power generation,[4] ice making,[5] cold storages,[6] rubber crushing,[7] dry ice making,[8] liquefied natural gas,[9] and so on. It is a common and efficient way to use a turboexpander instead of a pressure throttle valve to generate electricity.[10]

In 1969, the Soviet Union tried to use natural gas residual pressure for power generation.[11] Wang et al.[12] proposed a gas-steam combined cycle system for recovering the pressure energy of the natural gas pipeline network. Shen et al.[13] proposed the idea of using a turboexpander instead of throttle valve to recover natural gas pressure energy for power generation. Peng proposed a scheme to recover the pressure energy of PRS by paralleling a turboexpander at the original throttle valve. The power generation potential and its economic benefits are estimated.[14] Mahdi Deymi-Dashtebayaz et al.[15] proposed a scheme to produce electricity and freshwater using the pressure energy of natural gas PRS. Based on the "three-box" exergy analysis model, Zhi Dong Li et al.[16] proposed a black-gray-box hierarchical exergy analysis and evaluation method for evaluating natural gas differential pressure expansion power generation technology. Jaroslav Poživil et al.[17] simulated the natural gas residual pressure recovery process. The influence of the isentropic efficiency of the turboexpander on the output power and inlet temperature of the expander is studied. Dragan Ristanovic et al.[18] discussed the influencing factor of mechanical and electrical aspect of the turbo-expander power generation process. Paweł Bielka et al.[19] verified the feasibility of using a turboexpander to generate electricity in a Polish natural gas decompression station. It is found that the expansion process is more economic when the inlet pressure and temperature are high. Sepehr Sanaye et al.[20] proposed a cogeneration system to replace the pressure regulating valve to recover pressure. A new method for selecting the number of gas engines and boilers and determining their rated power is proposed. Mehmet Alparslan Neseli et al.[21] studied a case of a natural gas PRS in Izmir using a turboexpander to generate electricity. The exergy efficiency of the system and its components are determined. A.V. Klimenko et al.[22] found that after replacing the throttling device with an expander generator unit at PRS, the efficiency was increased by more than half. To improve the utilization of natural gas pressure energy, Hooman Golchoobian et al.[23] proposed a novel integrated system for the trigeneration of power, refrigeration, and freshwater using pressure recovery. Zheng bin et al.[24] analysed how the exergy is reduced during natural gas expansion. The calculation methods of temperature exergy, pressure exergy and chemical exergy and the evaluation factors of turbine expansion output shaft power limit capacity are obtained. Clifford Robert Howard [25] proposed a hybrid turboexpander and fuel cell system for pressure energy recovery in natural gas PRS. Molten carbonate fuel cells are used to preheat natural gas in the system. Many actual cases also prove that it is feasible to use the natural gas pressure energy to generate electricity.[26-28]

Recovering natural gas pressure to power generation by using turboexpander is a common way, and a lot of research has been done in this area. In previous research, there is a lack of research on further study on relationship between the electric power generated by the turboexpander and the energy used to preheat NG. This article established an analysis model to study the influence of different parameters on the generated electric power and the energy preheat amount.

2. Residual Pressure in Reducing Station

2.1. Exergy analysis

The exergy analysis method is an effective method for evaluating energy performance. The exergy analysis method can be used to analyse the available pressure energy of natural gas PRS. Equation (1) can be used to calculate the specific enthalpy exergy at PRS.[29]

$$e_{x,h} = h - h_0 - T_0\left(s - s_0\right) \tag{1}$$

$$s - s_0 = c_p \ln\frac{T_{in}}{T_{out}} - \frac{R}{M}\ln\frac{P_{in}}{P_{out}} \tag{2}$$

$$e_{x,h} = h - h_0 - c_p T_0 \ln\frac{T_{in}}{T_{out}} + T_0\frac{R}{M}\ln\frac{P_{in}}{P_{out}}$$

$$= e_{x,t} + e_{x,p} \tag{3}$$

$$e_{x,p} = T_0\frac{R}{M}\ln\frac{P_{in}}{P_{out}} \tag{4}$$

In this article, the pressure energy was used to power generation. The specific pressure exergy of the natural gas can be calculated by Eq. (4).

2.2. Calculation result

Taking a pressure regulating station as an example, the annual recoverable natural gas pressure energy is calculated.30 The inlet pressure of this PRS is 4MPa, and the PRS needs to supply 0.4MPa natural gas for downstream. The specific parameters are shown in Table 1. The component and the corresponding molar fraction of natural gas are shown in Table 2.

Table 1. Data of natural gas PRS

Items	Values
Natural gas flow rate, Nm^3/h	2.08×10^4
Inlet pressure, MPa	4
Outlet pressure, MPa	0.4
Temperature, K	298.15

The molar mass of it is calculated to be 0.01648kg/mol based on the molar fraction of each component of NG. The natural gas density of this component under standard conditions is calculated to be 0.68628kg/m3. By bringing these parameters into equation (4), the specific pressure exergy of natural gas is 346.34kJ/kg. The annual available electric power of this PRS is 4.33×1010kJ. It is equivalent to the electric power generated by a power station with an installed capacity of 1373KW for one year. The results show that the pressure energy recovery potential of natural gas PRS is huge.

Table 2. Component and molar fraction of natural gas

Component	Molecular formula	Molar fraction
Methane	CH_4	0.9778
Ethane	C_2H_6	0.0088
Propane	C_3H_8	0.0021
i-Butane	C_4H_{10}-2	0.0007
n-Butane	C_4H_{10}-1	0.0005
i-Pentane	C_5H_{12}-2	0.0005
n-Pentane	C_5H_{12}-1	0.0005
n-Hexane	C_6H_{14}-1	0.0005
Nitrogen	N_2	0.008
Water	H_2O	0.0001
Carbon Dioxide	CO_2	0.0005

3. Key Technology

The temperature decreases with the decrease of pressure when the throttle valve is used to adjust the pressure of natural gas in the PRS.[31] It is usually necessary to add heating equipment before throttling to prevent ice blockage and the formation of natural gas hydrates.[32] This not only wastes natural gas pressure energy but also requires additional energy to heat natural gas. The advantage of using a turboexpander is that the electricity generated by it can be used to preheat natural gas. Using it can not only offset part of the energy required for preheating but also produce economic benefits under certain circumstances.

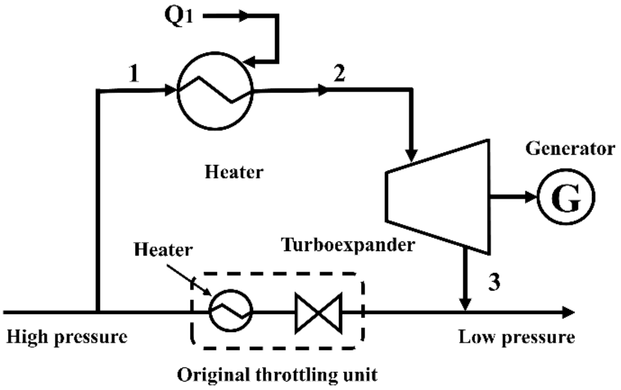

Figure 1. Analysis model of power generation using residual pressure in pressure regulating station.

The method of preheating before expansion ensures that the natural gas temperature of the whole system remains at a high state. It can effectively prevent hydrate formation and ice blocking.in the whole power generation process. Therefore, this article established an analysis model as shown in Fig. 1 to study the relationship between electric power and preheat amount. Q1 is the energy required to preheat natural gas.

3.1. Fundamental assumption

The Peng-Robinson equation is suitable for calculating the thermodynamic properties of light hydrocarbons.[33] In this article, the Peng-Robinson equation is used to analyse the natural gas residual pressure power generation process in PRS. Peng-Robinson equation is given by:

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)+b(V-b)} \tag{5}$$

$$b = 0.07780\frac{RT_c}{P_c} \tag{6}$$

$$a = 0.45724\frac{(RT_c)^2}{P_c} \times \alpha \tag{7}$$

$$\alpha = \left[1 + m\left(1 - T_r^{0.5}\right)\right]^2 \tag{8}$$

$$T_r = T/T_c \tag{9}$$

$$m = 0.37464 + 1.54226\omega - 0.26992\omega^2 \tag{10}$$

Due to the limitations of software simulation and theoretical calculation, it cannot fully simulate the real situation. Therefore, some assumptions need to be made to simplify the expansion power generation process.

(1) The kinetic and potential energy of the system are neglected.

(2) The natural gas flow rate throughout the entire process were assumed a steady state.

(3) Assuming the system does not exchange heat with the external environment.

(4) The pressure loss in heat exchangers and pipes is neglected.

3.2. Determine the least outlet temperature

Different natural gas compositions have different hydrate formation temperatures. In this article, the formation temperature of hydrate under the natural gas components in Table II was analysed. The prediction curve of natural gas hydrate is shown in Fig. 2.

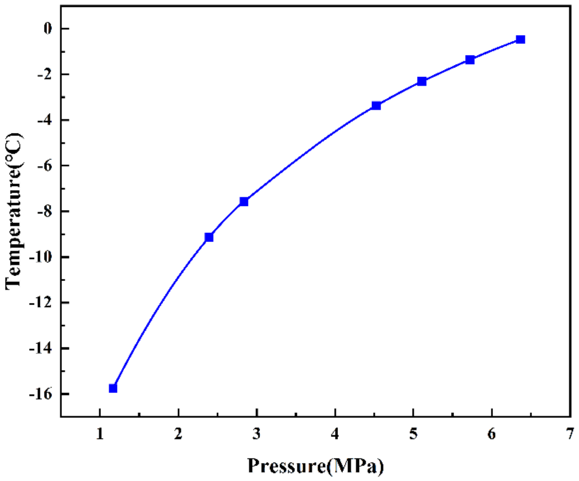

Figure 2. Hydrate prediction curve

As shown in Fig. 2, the hydrate formation temperature under different pressure conditions is all below 0°C, and the highest formation temperature is -0.468°C. Ensuring that the outlet temperature is greater than the maximum temperature of hydrate formation can effectively prevent ice blockage and hydrate formation. In the case of this natural gas composition, it is at least necessary to ensure that the minimum outlet temperature is greater than − 0.468. The natural gas outlet temperature is set to 5 °C after minimizing the energy required for preheating while considering avoiding hydrate formation.

4. Analysis of the Inlet and Outlet Pressure

Different end users have different pressure needs. The inlet temperature and pressure of different pressure regulating stations also vary. Therefore, the pressures regulating the range of natural gas PRS are very wide. In the process of natural gas expansion power generation, the pressure difference is one of the parameters that directly affect the generated electric power and preheat amount. The pressure of long-distance pipelines in China is about 10 MPa.

In this article, the maximum inlet pressure is set to 10 MPa. The control variable method and is used to study the relationship between the generated electric power and preheat amount under different inlet and outlet pressures. Keeping other parameters unchanged and only changing the inlet and outlet pressure of natural gas. When the inlet pressure remains constant, the outlet pressure is gradually changed at intervals of 1MPa, and the above analysis model is used to research. The specific parameters are shown in Table 3.

Table 3. Simulation parameters

Items	Values
natural gas flow rate, *Nm^3/h*	10000
inlet temperature, *℃*	20
outlet temperature, *℃*	5
Inlet pressure variation range, *MPa*	10~2
Inlet pressure variation range, *MPa*	10~2

4.1. Results

The preheat amount under different pressure combinations and the pressure and temperature of natural gas at different state points are obtained by analysis. Based on the temperature and pressure of each point, the specific enthalpy of each point is obtained by querying the standard database. Based on the law of conservation of conservation of conservation of energy, the enthalpy difference Δh before and after expansion can be regarded as the work done by natural gas pressure energy. Considering the expansion efficiency of the expander and the power generation efficiency of the generator, the generated electric power of the turboexpander can be calculated by Equation (11).

$$W=\frac{L}{3600}\times\rho\times\Delta h\times\eta_t\times\eta_g \tag{11}$$

The relationship between the electric power generated by the turboexpander and the energy used to preheat NG under different inlet and outlet pressure changes is shown in Fig. 3 and Table 4.

Table 4. Results after inlet pressure is less than 5MPa

P_1-P_3 (*MPa*)	h_2 (*kJ/kg*)	h_3 (*kJ/kg*)	Δh (*kJ/kg*)	Q_e (*KW*)	Q_p (*KW*)	Differences (*KW*)
4-3	842.91	813.83	29.08	52.66	8.08	44.58
4-2	898.69	825.57	73.12	132.42	123.12	9.30
4-1	991.33	837.04	154.29	279.42	314.21	-34.79
3-2	867.64	825.57	42.07	76.19	37.07	39.12
3-1	957.45	837.04	120.41	218.06	222.25	-4.19
2-1	911.33	837.04	74.29	134.54	105.42	29.12

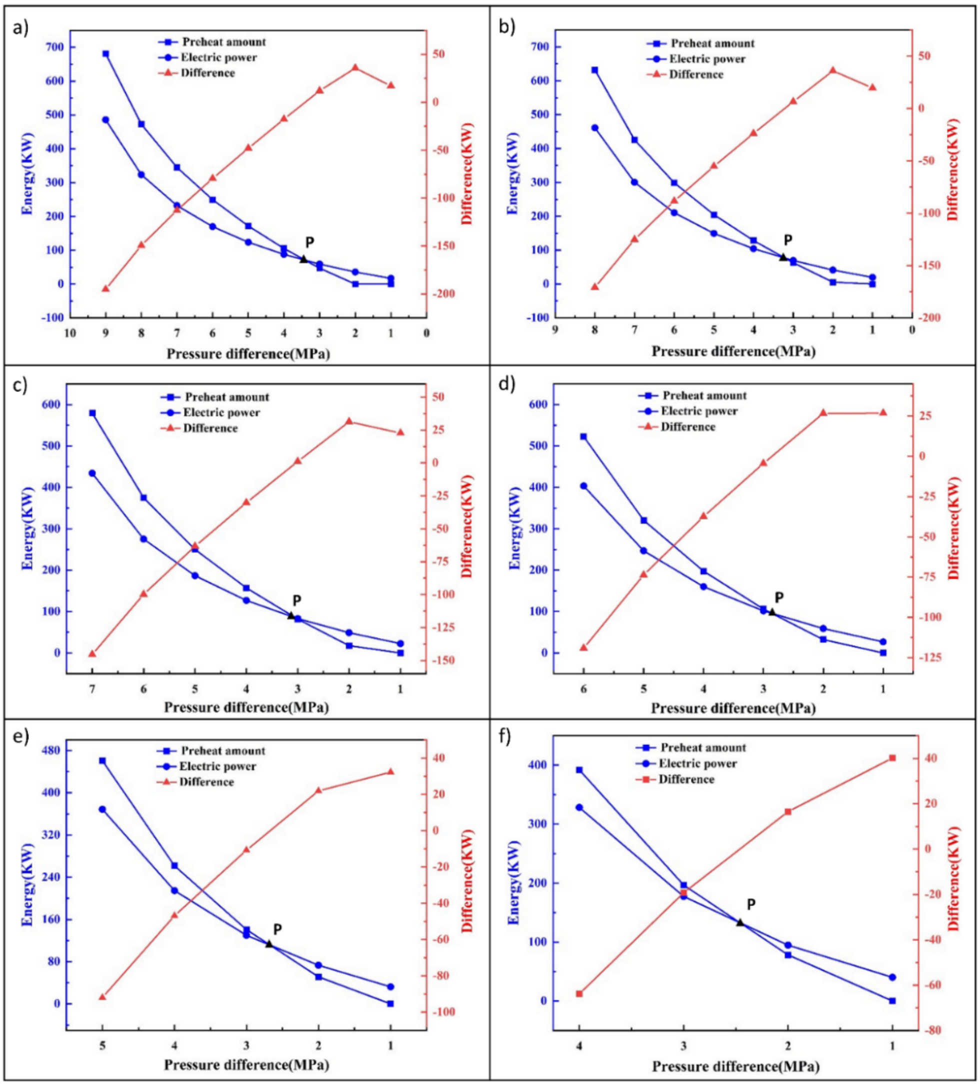

Figure 3. The influence of pressure changes on the generated electric power and preheat amount: (a) The inlet pressure is 10MPa. (b) The inlet pressure is 9MPa. (c) The inlet pressure is 8MPa. (d) The inlet pressure is 7MPa. (e) The inlet pressure is 6MPa. (f) The inlet pressure is 5MPa.

The critical point P is the point where the numerical value of the electric power generated by the turboexpander is equal to the numerical value of the energy used to preheat NG. As shown in Fig. 3, natural gas does not need to be preheated and the energy used to preheat is 0KW when the inlet and outlet pressure difference is small. The generated electric power and preheat amount gradually decrease with the increase of outlet pressure when the inlet pressure remains unchanged. The energy used to preheat NG is greater than the electric power generated by the turboexpander when the outlet pressure is less than the P point. When the outlet pressure is greater than the P point, the result is opposite.

The difference in Fig.3 and Table IV is obtained by subtracting the value of energy used for preheating NG from the value of electric power generated by the turboexpander. The greater the value, the more energy used to preheat natural gas can be offset. The difference greater than 0KW indicates that there is residual electric power after offsetting the energy used to preheat NG. The residual electric power can be provided to the PRS or merged into the power grid to obtain economic benefits. The difference increases first and then decrease with the decrease of pressure difference when the inlet pressure is greater than 8MPa. The difference increases with the decrease of pressure difference when the inlet pressure is less than 8 MPa.

The critical point P is the turning point of the relationship between the electric power generated by the turboexpander and the energy used to preheat NG. The changing trend of critical point pressure difference has important reference significance for the selection of inlet and outlet pressure of expansion power generation system. The changing trend is shown in Fig. 4 The results show that the pressure difference of critical point P increases with the increase of inlet pressure. The pressure difference of all critical points in this study is less than 4 MPa.

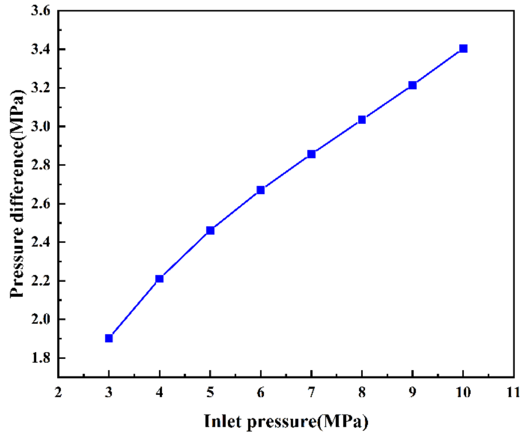

Figure 4. Variation of pressure difference at critical point P.

5. Analysis of the Inlet Temperature

The inlet temperature is also an important factor affecting the generated electric power and preheat amount. The change of inlet temperature directly affects the outlet temperature and preheat amount. This article used the maximum difference points obtained above to analyse the impact of inlet temperature changes on the generated electric power and preheat amount. The detailed simulation parameters are shown in Table 5.

Table 5. Simulation parameters

Items	Values
natural gas flow rate, *Nm³/h*	10000
inlet pressure, *MPa*	4
outlet pressure, *MPa*	3
Minimum outlet temperature, *℃*	5
The variation range of inlet temperature, *℃*	0~22

This article kept other conditions unchanged, the inlet temperature is increased from 0°C to 30°C at an interval of 2°C. The generated electric power, preheat amount, and the difference between them at different inlet temperatures were obtained through analysis. The final result is shown in Fig. 5.

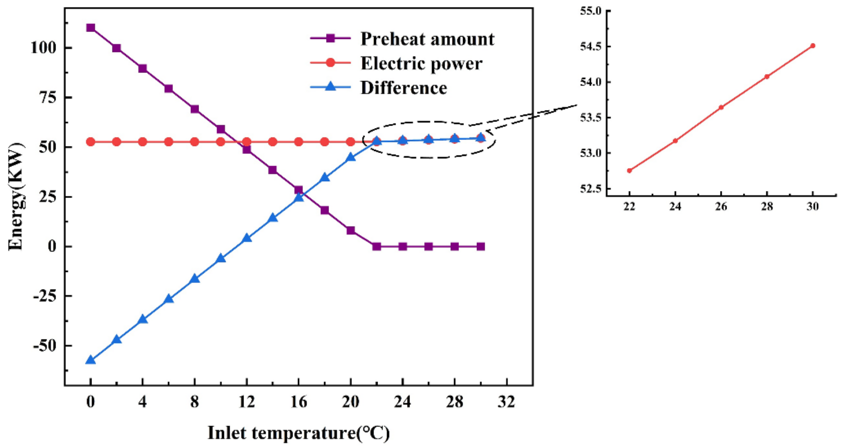

Figure 5. The influence of inlet changes on the generated electrical power and preheat amount.

From Fig. 5, it can be obtained that with the increase of the inlet temperature, the preheat amount is significantly reduced and the generated electric power remains unchanged when the inlet temperature is lower than 22°C. The preheat amount is less than the generated electric power when the inlet temperature is higher than 12.24°C. It can produce considerable economic benefits while offsetting the energy required for preheating. Natural gas does not need to preheat when the inlet temperature is higher than 22°C. Therefore, the difference is equal to the value of the generated electric power. At this time, the electric power generated by the turboexpander and the difference increases slowly with the increase of inlet temperature.

6. Conclusion

This article established an analysis model to study the effects of natural gas inlet pressure, outlet pressure, and inlet temperature on the electric power generated by the turboexpander and energy used to preheat NG. The results indicate that the electric power energy generated by turboexpander can be used to heat natural gas to offset the energy consumption during the preheating process. Under certain circumstances, it can also generate economic benefits. The pressure exergy of an actual PRS in China was calculated to be 346.34kJ/kg and about 4.33×1010kJ electrical power can be obtained each year. The electric power generated by the turboexpander and the energy used to preheat the natural gas decrease with the decrease of the pressure difference. The value of the preheat amount is greater than the value of the generated electric power when the pressure difference is greater than the critical point P. After it is less than the critical point P, the results are opposite. The difference between generated electric power and preheat amount increases first and then decrease with the decrease of pressure difference when the inlet pressure is greater than 8MPa. The difference increases with the decrease of pressure difference when the inlet pressure is less than 8MPa. The pressure difference at the critical point increases with the increase of natural gas inlet pressure. The higher the inlet temperature, the less the preheat amount required. The electric power generated by the turboexpander increases slightly with the increase of the inlet temperature when the natural gas does not need to be preheated.

7. Conflicts of Interest

There are no conflicts to declare.

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