RESEARCH ON THE PROCESS FLOW OF NATURAL GAS DIFFERENTIAL PRESSURE POWER GENERATION SYSTEM

by

Ran ZHANG [a,b]***, Han-Bing WU*** [a*]***, Dong-Ming GAO*** [a]***, Kun YV*** [a] ***, and Kun LIAO*** [a]

[a] School of Mechanical Engineering, Xihua University, Chengdu, China
[b] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, China

Original scientific paper
https://doi.org/10.2298/TSCI2502115Z

During the transmission of natural gas in the pipe-line network, the high pressure natural gas needs to be depressurized by the regulator station and enter the low pressure pipe-line, and the depressurization process will release a lot of pressure energy. At present, some scholars and enterprises have begun to use turbine expanders to convert excess natural gas pressure energy into electricity. However, with the different working conditions of different regulator stations, there are differences in the use of pressure energy. In this paper, energy analysis of energy power generation process of a city gate station was applied to optimize the design of energy power generation process. This works provide a method for natural gas pressure power generation process design.

Key words: *city gate station, pressure difference power generation, multistage expansion, optimum process*

Introduction

China's natural gas consumption is increasing year by year, and the gas consumption of urban residents is growing rapidly [1]. In 2023, the total mileage of China's long distance natural gas pipe-lines will exceed 124000 kilometers [2]. In recent years, the design pressure of the west-east gas transmission pipe-line and the Shaanxi-Beijing gas transmission pipe-line has been increased to 10 MPa, while the design pressure of the urban pipe network along the pipe-line is mostly 1.6~4.0 MPa [3]. Therefore, it is necessary to regulate the pressure at the city gate station, and the natural gas depressurization process will release a large amount of pressure energy [4]. It is estimated that China's natural gas consumption in 2024 will be 420 billion 425 billion cubic meters, an increase of 6.5%-7.7% [5]. According to the plan, China will build a *five vertical and five horizontal* natural gas pipe-line network by 2025 [6]. It is expected that by 2030, the scale of national gas consumption will reach 550 billion m^3, with a total power generation capacity of $6 \cdot 10^{10}$ kW annually [7].

Theoretical evaluation of power generation potential of natural gas pressure energy

System energy efficiency is related to equipment energy utilization efficiency [8]. Energy was regarded as an open system by thermodynamics, and energy analysis was used to

* Corresponding author, e-mail: 380797016@qq.com

evaluate the generation potential of the differential pressure generation system theoretically [9]. When the temperature is constant, energy of natural gas includes pressure energy and temperature energy [10], namely:

$$e_x = e_{x,p} + e_{x,T} \tag{1}$$

where e_x is the exergy of natural gas, $e_{x,p}$ – the gas energy pressure, and $e_{x,T}$ – the specific temperature energy of natural gas. After decompression, the energy that natural gas can provide:

$$e_x = C_p(T - T_1) - C_p T_1 \ln\frac{T}{T_1} + T_1 \frac{\mathrm{R}}{M} \ln\frac{P_1}{P_2} \tag{2}$$

where C_p is the specific heat capacity of natural gas at constant pressure, T – the inlet temperature, T_1 – the exit temperature, R [8.314 Jmol^{-1}K^{-1}] – the molar gas constant, M – the molar mass of natural gas, P_1 – the natural gas import pressure, and P_2 – the natural gas export pressure:

$$e_{x,p} = T_1 \frac{\mathrm{R}}{M} \ln\frac{P_1}{P_2} \tag{3}$$

Theoretical power generation:

$$E_{x,P} = Q \times e_{x,P} \times \eta = Q \times T_1 \frac{\mathrm{R}}{M} \ln\frac{P_1}{P_2} \times \eta_i \times \eta_m \tag{4}$$

where Q is the natural gas-flow, η_i and η_m are the isentropic efficiency and mechanical efficiency, respectively, and $e_{x,P}$ – the pressure exergy.

Project case model verification

By using ASPEN HYSYS simulation software, the pressure regulating station of a city gate station is calculated. The gas-flow rate of the regulator is 360000 Nm^3 per day, and the pressure energy is recovered by a turbine expansion machine. After expansion, the temperature of the natural gas drops to –29 °C and the refrigerant from the compressor is exchanged in the heat exchanger, and the temperature rises to 2 °C and enters the downstream pipe-line. The power output of this project can reach 200 kW. The natural gas operation parameters and power generations of the regulator are shown in tab. 1.

Table 1. Gas operation parameters and power generation parameters of the regulator station

Upstream gas pressure [MPa]	Downstream gas pressure [MPa]	Upstream gas temperature [°C]	Downstream gas temperature [°C]
4	1.65	20	2
Actual generation [kWh]	Simulated power generation [kWh]	Yield difference [kWh]	Deviation value [%]
200	211.1	11.1	5.6

Since the establishment of the simulation model ignores the friction, leakage and entropy change of natural gas during the expansion of the expander, there is a 5.6% deviation between the simulated power generation of the process and the actual power generation of the project, which is basically within the acceptable range of engineering simulation calculation. Therefore, the simulation model of the differential pressure power generation process established by HYSYS SIMULATION software is acceptable.

Research on the process flow of differential pressure power generation system

Under the condition that the normal operation of the natural gas transportation pipe network is ensured, the pressure of the natural gas regulator station is reduced from 3 MPa to 0.4 MPa and the natural gas-flow rate is unchanged at 100000 Nm^3 per day, the upstream natural gas temperature is designed to be 20 °C in combination with the actual ambient temperature of most gate stations. Because the natural gas component contains a small amount of water, the use of natural gas pressure difference power generation, if there is a liquid phase or ice phenomenon of natural gas in the pipe-line, will not only bring losses to the blades of the power generation device, but also bring serious safety risks, so the downstream natural gas temperature design for the limit critical temperature –12 °C.

In order to explore the effect of multistage expansion on the effective output power of differential pressure power generation system, the optimum expansion stage is designed, and the single-stage and multistage expansion processes are compared in the city gate station conditions.

Single-stage expansion pressure differential power generation process design

The single-stage expansion process design is shown in fig. 1.

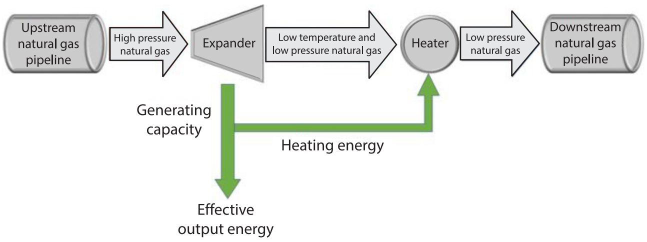

Figure 1. Single-stage expansion process diagram

Table 2 shows the simulation results of single-stage expansion process.

Table 2. Simulation results of single stage expansion process

Generated power [kW]	Heating power [kW]	Effective output [kW]
120.8	102.0	18.8

Two-stage expansion pressure differential power generation process design

The two-stage expansion process uses two expansion machines and a heater in series, and the process flow is shown in fig. 2. In order to explore the optimal working condition design of the two-stage expansion process, nine intermediate pressure values were designed for simulation calculation with the step size of 0.3 MPa. The natural gas pressure parameters are shown in tab. 3.

As can be seen from fig. 3, with the continuous increase of intermediate pressure, the power generation of the first-stage expander gradually decreases from 108.9-2.6 kW. The power of the second stage expander gradually increases from 17.2-155.5 kW. The total generating power of the system gradually increases. When the intermediate pressure is 2.9 MPa, the total power of the system is 158.1 kW. There is an intersection point between the first-stage

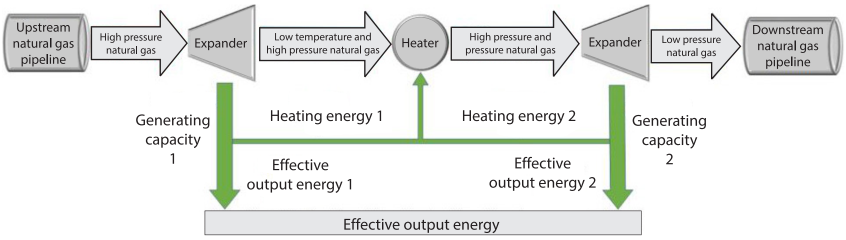

Figure 2. Two-stage expansion process diagram

Table 3. Two-stage inflation process operating parameters

Inlet gas pressure [MPa]	Inlet gas temperature [°C]	Intermediate gas pressure [MPa]	Export gas pressure [MPa]	Export gas temperature [°C]
3	20	0.5, 0.8, 1.1, 1.4, 1.7, 2, 2.3, 2.6, 2.9	0.4	-12

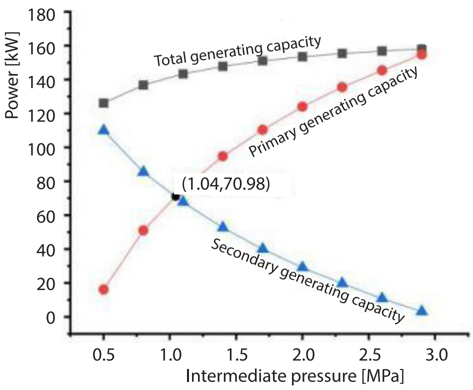

Figure 3. Two-stage power and intermediate pressure relationship diagram

power generation curve and the second-stage power generation curve, and the co-ordinates of the intersection point are (1.04, 70.98). When the intermediate pressure is 1.04 MPa, the two-stage expansion process is an equal expansion ratio process, and the first-stage power generation power and the second-stage power generation power are equal to 70.98 kW. As can be seen from fig. 4, the heat added is positively correlated with the intermediate pressure. As can be seen from fig. 5, the effective output power of the system is negatively correlated with the intermediate pressure. Considering comprehensively, the optimal design of the two-stage expansion process can effectively increase the power of the system, reduce the single-stage expansion load, and extend the service life of the equipment.

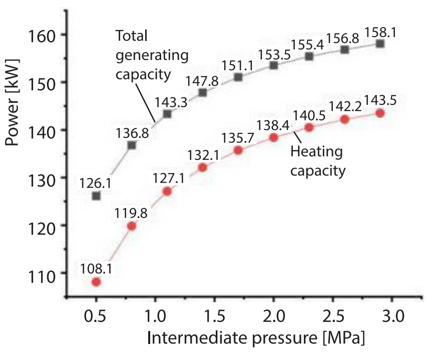

Figure 4. Comparison diagram of two-stage heating and generating power

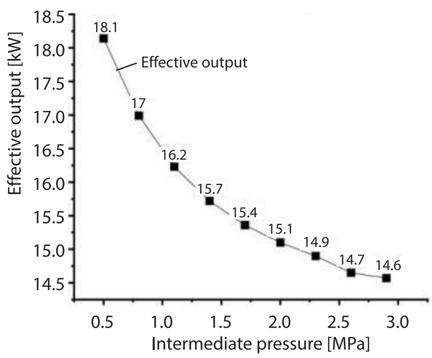

Figure 5. Two-stage effective output power at intermediate pressure curve

Three-stage expansion pressure differential power generation process design

The three-stage expansion process adopts the expansion mode of three expansion machines and two heaters in series. The design of process operation parameters is shown in tab. 4.

Table 4. Three-stage expansion process operating parameters

Inlet gas pressure [MPa]	Inlet gas temperature [°C]	Intermediate gas pressure, *a*, [MPa]	Intermediate gas pressure, *b* [MPa]	Export gas pressure [MPa]	Export gas temperature [°C]
3	20	1.9	0.87	0.4	–12
		1.7	0.82		
		1.5	0.77		
		1.3	0.72		
		1.1	0.66		
		0.9	0.60		

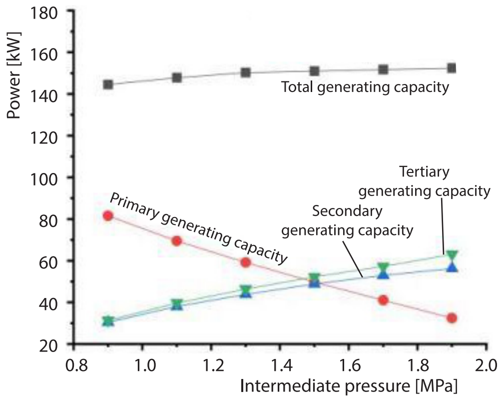

Figure 6. Diagram of the relationship between the three-stage power generation and the intermediate pressure

The three-stage expansion can be seen as a single stage expansion and a two-stage expansion in series. The influence of the two-stage expansion intermediate pressure on the power generation and heating power has been analyzed previously, so only the influence of the single stage expansion and the two-stage expansion intermediate pressure *a* should be analyzed. As can be seen from fig. 6, the total generating power of the system is positively correlated with the intermediate pressure *a*. As can be seen from fig. 7, the value of the three-stage expansion intermediate pressure has little influence on the total heating power of the system. The power of the first stage expander is negatively related to the intermediate pressure, *a*. The power of the second and third stage expander is positively correlated with the intermediate pressure, *a*. The reason for the change is that when the intermediate pressure, *a*, gradually increases from small to small, the pressure drop ratio of the first stage expander (the ratio of the inlet gas pressure to the intermediate pressure, *a*) decreases from large to large, so the power generation power of the first stage expander is negatively correlated with the intermediate pressure, *a*. The pressure drop ratio of the second stage expander (the ratio of intermediate pressure, *a*, to intermediate pressure, *b*) is increasing, and the pressure drop ratio of the third stage expander (the ratio of intermediate pressure, *b*, to downstream natural gas pressure) is also increasing, so the power generation power of the second stage and the third stage expander is positively correlated with the size of the intermediate pressure, *a*, which follows the law of the increase of the pressure drop ratio and the greater the power generation capacity. As can be seen from fig. 8, the selection of intermediate pressure *a* has little impact on the total power generation of the system. When the intermediate pressure, *a*, is 1.9 MPa and 0.9 MPa, the total power generated by the three-stage expansion process reaches the maximum value of 149.4 kW and the minimum value of 141.1 kW, respectively, with an increase of 8.3 kW and a growth rate of 5.9%. The growth trend of the curve is gentle and the fluctuation range is small. When the intermediate pressure, *a*, is 1.5 MPa and the intermediate pressure, *b*, is 0.77 MPa, the three-stage expansion process of the differential pressure power generation system is almost designed under the condition of equal expansion ratio, and this process is considered as the best three-stage expansion process.

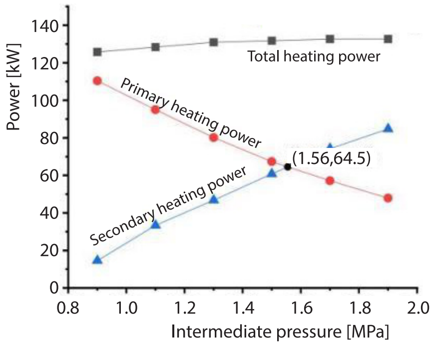

Figure 7. Three-stage heating power and intermediate pressure relationship diagram

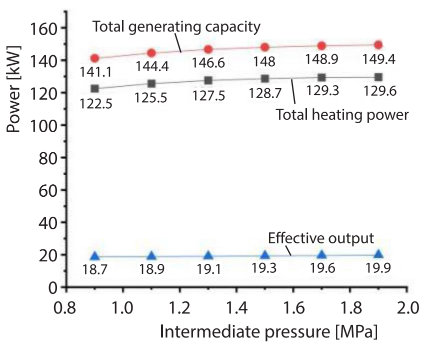

Figure 8. Comparison diagram of tertiary generation, heating and total power

Optimal working condition design at all levels

The optimal design of different expansion stages is shown in tab. 5. According to the simulation results of the optimal conditions of different expansion processes, the effective output power of the two-stage expansion process is 16.3 kW, which is 13.3% lower than that of the single-stage expansion effective output power of 18.8 kW. The maximum effective output power of the three-stage expansion process is 19.3 kW, which is 2.7% higher than that of the single-stage expansion. The cost of multistage expansion machine is higher, so the use of single-stage expansion process is more profitable.

Table 5. Comparison of optimum multistage expansion processes

Number of expansion machines [PCS]	Intermediate pressure, *a* [MPa]	Intermediate pressure, *b* [MPa]	Total generating power [kW]	Total heating power [kW]	Effective output power [kW]
1	–	–	120.8	102.0	18.8
2	1.04	–	142.0	125.7	16.3
3	1.5	0.77	148.0	128.7	19.3

Conclusion

The single-stage expansion process generates 120.8 kW of power. The two-stage process reaches a maximum of 158.1 kW, whereas the three-stage process peaks at 149.4 kW. In the two-stage process, intermediate pressure rises from 0.5-2.9 MPa, causing the effective output power to decrease from 18.1-14.6 kW. For the three-stage process, intermediate pressures between the first and second stages increase from 0.9-1.9 MPa, with a corresponding effective output power rise from 18.7-19.9 kW. The optimal two-stage process yields an effective output power of 16.3 kW, which is 13.3% lower than the 18.8 kW achieved in the single-stage process. Conversely, the maximum effective output power of the three-stage process is 19.3 kW, a 2.7% increase over the single-stage process.

Nomenclature

C_p – specific heat capacity of natural gas at constant pressure, [kJkg^{-1}K^{-1}]
e_x – exergy of natural gas, [Jkg^{-1}]
$e_{x,p}$ – gas exergy pressure, [Jkg^{-1}]
$e_{x,T}$ – specific temperature exerge of natural gas, [Jkg^{-1}]
M – molar mass of natural gas
Q – natural gas-flow, [Nm^{3}h]
P_1 – natural gas import pressure, [MPa]
P_2 – natural gas export pressure, [MPa]
R – molar gas constant, [Jmol^{-1}K^{-1}]
T – inlet temperature, [K]
T_1 – exit temperature, [K]

Greek symbols

η_i – isentropic efficiency, [–]
η_m – mechanical efficiency, [–]

Acknowledgment

The authors would like to express their gratitude to the Robotics Research Centre of Xihua University for its invaluable technical and financial assistance in conducting this study.

References

[1] Zhang, G. J., *et al*., Opportunities and Challenges of Natural Gas Development and Utilization in China, *Clean Technologies and Environmental Policy*, *21* (2019), 6, pp. 1193-1211
[2] Feng, K., *et al*., Research on Provincial Natural Gas Pipe-line Network Lay-out Planning, *Value Engineering*, *43* (2024), 31, pp. 38-40
[3] Zeng, P. S., *et al.*, Research on Evaluation System of Natural Gas Residual Pressure Power Generation System, *Energy Conservation*, *42* (2023), 1, pp. 8-11
[4] Ma, S. J., *et al*., Economic Analysis of Pressure Energy Utilization in Natural Gas Distribution Station, *CIESC Journal*, *69* (2018), S2, pp. 413-419
[5] Wei, J. D., *et al*., Research Progress in Recovery of Residual Energy in Natural Gas Expansion Pressure Difference Power Generation, *Chemical Engineering and Machinery*, *48* (2021), 5, pp. 644-647
[6] Li, Q., *et al.*, Study on Utilization of Natural Gas Pressure Energy for Power Generation Ice Making and Operation Benefit Evaluation, *Journal of Global Energy Interconnection*, *6* (2023), 6, pp. 588-598
[7] Xu, W. D., *et al*., Research Progress and Expectation on Power Generation Technology by Using Pressure Energy of Natural Gas Pipe-Line Network, *Modern Chemical Industry*, *39* (2019), 12, pp. 11-15 + 20
[8] Cheng, S. J., *et al*., Design and Research on the Process of Natural Gas Storage Pressure Energy Generation coupled with Cold Energy Utilization, *Power System Engineering*, *40* (2024), 4, pp. 69-71+73
[9] Chen Q. X., *et al*., Development and Application of Technologies for Pressure Energy Electricity Generation and Ice Making from Natural Gas Pipe-line Network, *Gas & Heat*, *32* (2012), 9, pp. 25-27
[10] Wang, Z. P., *et al.*, Research on Recovery and Utilization of Pressure Energy of Natural Gas Pipe-Line Network, *Gas & Heat*, *40* (2020), 1, pp. 14-16+44-45

Paper submitted: November 15, 2024
Paper revised: November 29, 2024
Paper accepted: December 25, 2024