ISSN: 2688-8645

A Review of Residual Pressure Utilization of Natural Gas

Cong Lei*, Zhewei Ye

School of Mechanical Engineering, Southwest Petroleum University, Chengdu, 610500, China

Abstract

Natural gas needs to be depressurized before wellhead to gas gathering station or long-distance pipeline to users. At present, choking technique is widely used at wellhead and pressure regulating station, which will cause a lot of energy loss. Considerable economic and social benefits will be generated, if these residual pressures can be recycled. In this article, the pressure energy contained in the natural gas wellhead and pressure regulating valve station will be calculated based on exergy analysis. The technology and present situation of residual pressure utilization of natural gas are summarized. The existing problems and future research directions in the process of residual pressure utilization are pointed out through cases. At present, there are many studies on the use of residual pressure in the pressure regulating station, but there are relatively few studies in the natural gas wellhead. Residual pressure utilization technology improves energy utilization efficiency and makes an important contribution to energy conservation and emission reduction.

Keywords

Natural Gas; Exergy Analysis; Residual Pressure; Pressure Energy Utilization; Energy Recovery.

1. Introduction

As a clean and highly efficient energy, natural gas plays an important role in alleviating energy crisis, reducing air pollutants, optimizing resource structure, etc.[1]. Since the 1980s, the production of the China's natural gas has been growing rapidly. It has also accelerated the construction of natural gas pipeline network [2].

The pressure of the natural gas high-pressure pipeline is mostly about 10MPa, and the ordinary household natural gas pipeline is about 0.23MPa. Different users have different needs. The pressure of natural gas should be reduced through the pressure regulating gate station before the natural gas is delivered to users [3]. There is a lot of unused residual energy in the process of reducing pressure [4] [5].

Natural gas wellhead pressure is usually between 20 and 70 MPa. Before conveying, the pressure needs to be reduced to the allowable conveying pressure of the pipeline. The pressure difference between the two can usually reach more than 10 MPa. So there is a lot of pressure energy resources at the gas wells wellhead. [6] [7].

Throttle valves are commonly used to reduce pressure in wellhead and natural gas regulator stations. This process will cause a lot of energy loss [8]. This part of energy can be recovered and utilized in a reasonable way. The efficient use of energy can be realized and Significant economic benefits can be generated [9]. This is of great significance to energy saving and emission reduction, reducing resource waste and improving the economy of natural gas pipeline network operation [10].

At present, researchers at home and abroad have gained some experience in natural gas residual pressure utilization technology. However, more research is needed to achieve the widespread promotion and use of this technology. A systematic summary of this technology is

ISSN: 2688-8645

needed. In this article, the current status of residual pressure utilization technology is summarized according to the research progress of natural gas pressure utilization at home and abroad. The problems existing in the application process was summarized, and the future development direction of residual pressure utilization of natural gas is prospected. It is convenient for future researchers to carry out more extensive and in-depth research in this field.

2. Residual Pressure of Natural Gas

2.1. Pressure Drop in Each Gathering Process

2.1.1. Wellhead to Gas Gathering Station

Natural gas needs to be purified and depressurized before entering the gas gathering station from the wellhead. Taking A operation area of T oilfield as an example. The maximum pre-valve pressure of throttle valve is 92.17MPa. The maximum pressure difference can reach 77.53Mpa [11].

2.1.2. Gas Gathering Station to Long-Distance Pipelines

Domestic and foreign long-distance natural gas pipeline pressure is about 10 MPa. Natural gas needs to be separated and purified at the gas gathering station before entering the long-distance pipeline. The pressure should be adjusted to the allowable pressure range of the gas pipeline network before transmission. There is significant pressure drop.

2.1.3. Long-distance Pipelines to City Gate Station

The pressure of urban natural gas pipeline network is generally below 4MPa. According to the needs of different users, the pressure of natural gas decreases from about 10 MPa to below 4 MPa. There is also a large pressure drop in the process.

Pressure of city gas pipeline network is divided into 7 levels. The maximum pressure of the pipe is 4 MPa and the minimum pressure is 0.01 MPa. The available pressure energy is abundant [12]. Table 1 is the pressure classification of urban natural gas pipeline network.

Table 1. Pressure classification of urban natural gas pipeline network [13]

Types of urban pipe network	Classification	Pressure/MPa
High pressure natural gas pipeline	High pressure natural gas pipeline level A	2.5~4.0
	High pressure natural gas pipeline level B	1.6~2.5
Medium pressure natural gas pipeline	Medium pressure natural gas pipeline level A	0.8~1.6
	Medium pressure natural gas pipeline level B	0.4~0.8
Low pressure natural gas pipeline	Low pressure natural gas pipeline level A	0.2~0.4
	Low pressure natural gas pipeline level B	0.01~0.2

2.2. Exergy Analysis

Exergy analysis method can be used to calculate the specific available pressure energy in the process of natural gas pressure drop. The larger the pressure drop gradient of natural gas, the more pressure exergy and cold exergy [14].

From the perspective of thermodynamics, natural gas pipeline was regarded as an open system. Exergy analysis method was used to analyze the system.

The specific enthalpy exergy in this system can be obtained as,

$$\begin{aligned} e_{x,h} &= h - h_0 - T_0\left(s - s_0\right) \\ &= h - h_0 - T_0\left(c_p \ln\frac{T}{T_0} - \frac{R}{M}\ln\frac{P}{P_0}\right) \end{aligned}$$

$$=\left(h-h_0-T_0c_p\ln\frac{T_0}{T}\right)+T_0\frac{R}{M}\ln\frac{P}{P_0}=e_{x,t}+e_{x,p} \tag{1}$$

The pressure exergy in the natural gas expansion process can be expressed as,

$$e_{x,p}=T_0\frac{R}{M}\ln\frac{P_1}{P_2} \tag{2}$$

The temperature exergy can be expressed as,

$$e_{x,t}=c_p\left(T_2-T_0\right)-T_0c_p\ln\frac{T_2}{T_0} \tag{3}$$

The temperature after expansion can be obtained as,

$$T_2=T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \tag{4}$$

$$n=\frac{k}{k-\varphi^2\left(k-1\right)} \tag{5}$$

Table 2. Symbols

$e_{x,h}$	specific enthalpy exergy, *J/kg*	P_0	absolute pressure of ambient, *MPa*
h	specific enthalpy of natural gas in its state, *J/kg*	$e_{x,t}$	temperature exergy, *J/kg*
h_0	specific enthalpy of natural gas in the ambient state, *J/kg*	$e_{x,p}$	pressure exergy, *J/kg*
T	temperature of the natural gas, *K*	n	exponent of an adiabatic non-isentropic process
T_0	ambient temperature, *K*	k	isentropic expansion index
s	specific entropy of natural gas, *J/(kg·K)*	T_1	Natural gas inlet temperature, *K*
s_0	specific entropy of natural gas in the ambient state, *J/(kg·K)*	T_2	Natural gas outlet temperature, *K*
c_p	isobaric heat capacity, *J/(kg·K)*	P_1	Natural gas inlet pressure, *MPa*
R	molar gas constant, take 8.314*J/(mol·K)*	P_2	Natural gas outlet pressure, *MPa*
M	molar mass of natural gas, *kg/mol*	φ	velocity coefficient of turbine expander, take 0.95
P	absolute pressure of the natural gas, *MPa*		

Natural gas contains about 95% methane. To simplify the calculation, assume that natural gas contains only methane.

Taking the isentropic expansion index of methane as 1.29. The value of *k* is calculated as 1.26.

According to the throttling situation of operation area A of an oilfield, the available energy at the wellhead was calculated.

Taking the one-year gas delivery volume from Sinopec Sichuan Gas East to a city as an example. The available energy of the city gate station is calculated. The related data are shown in Table 3, and the calculation results are shown in Table 4.

After calculated, there are Significant pressure energy in natural gas wellheads and pressure regulating stations. Many natural gas regulating stations are located in remote locations, and are even powered by battery equipment. The maintenance costs is relatively high [15]. Appropriate methods can be adopted to recover the residual pressure of natural gas. It can not only solve the electricity demand of some fields and gas gate stations, but also greatly improve the utilization rate of energy. It can make an important contribution to the cause of energy conservation and emission reduction.

Table 3. Related data table

Items	Values
Ambient temperature, *K*	298.15
Ambient pressure, *MPa*	0.1
Gas constant of methane, *J/(kg·K)*	518.75
Isobaric heat capacity, *J/(kg·K)*	2.223
Gas wellhead	
Natural gas flow, m^3/h	8.57×10^3
Initial temperature, *K*	313.15
Density, kg/m^3	0.6
City gate station	
Transportation temperature, *K*	293.15
Natural gas flow, m^3/h	5.7×10^4
Density, kg/m^3	0.7174

Table 4. Calculation results of available energy in wellhead and pressure regulating station

Gas wellhead	Pressure drop (*MPa*)	64.88→13.71		
	Pressure exergy (*kJ/kg*)	240.41	Available pressure energy (*kJ/h*)	1.24×10^6
	Cold exergy (*kJ/kg*)	22.4	Available cold energy (*kJ/h*)	1.15×10^5
Pressure regulating station	Pressure drop A(*MPa*)	10→4	Pressure drop B(*MPa*)	4→0.4
	Pressure exergy (*kJ/kg*)	141.72	Pressure exergy (*kJ/kg*)	356.13
	Cold exergy (*kJ/kg*)	13.14	Cold exergy (*kJ/kg*)	68.55
	Available pressure energy (*kJ/h*)	1.45×10^7	Available pressure energy (*kJ/h*)	5.79×10^6
	Available cold energy (*kJ/h*)	5.37×10^5	Available cold energy (*kJ/h*)	2.8×10^6

3. Utilization of Residual Pressure

With the rapid development of natural gas industry, residual pressure utilization technology of natural gas has attracted extensive attention. With the joint efforts of many researchers, some phased results have been achieved. Its research fields are wide, involving power generation, ice making, liquefaction peak regulating, compressed gas, light hydrocarbon separation, dry ice making, air separation and so on [16] [17].

Expander is a device for outputting mechanical work outward by reducing pressure through gas expansion. It has the characteristics of not producing any pollutants when working [18]. Expander has been applied very early in the process of residual pressure recovery of blast furnace gas [19]. In 1984, China's first turbine expander was successfully applied to No.2 blast furnace of Shanghai Meishan Metallurgical Company [20]. At present, turbine expander has been widely used in residual pressure recovery of blast furnace gas. There are many similarities between coal gas and natural gas. The expander can also be used for the recovery of residual pressure of natural gas by reasonably improving the process flow [21].

At present, the most common natural gas residual pressure recovery method is to use the expander instead of the traditional throttle valve [22][23]. It can not only achieve pressure drop of natural gas, but also convert the pressure energy into mechanical energy and cold energy [24]. In addition, some researchers have also used the star spinning motor [25], nozzle driven impeller rotation [26], venturi ejector device [27] and others to recover the natural gas pressure energy.

The mechanical energy produced by the expansion is often used to drive the power generation system, compress the gas, drive other rotating equipment and so on [28]. Connecting generators to generate electricity is the main utilization ways of mechanical energy [29]. The cold energy produced after expansion is often used in ice making, liquefaction peak regulating, air separation, cold storage and so on [30]. Natural gas pressure can be recovered and utilized in various ways and the utilization way is shown in Figure 1.

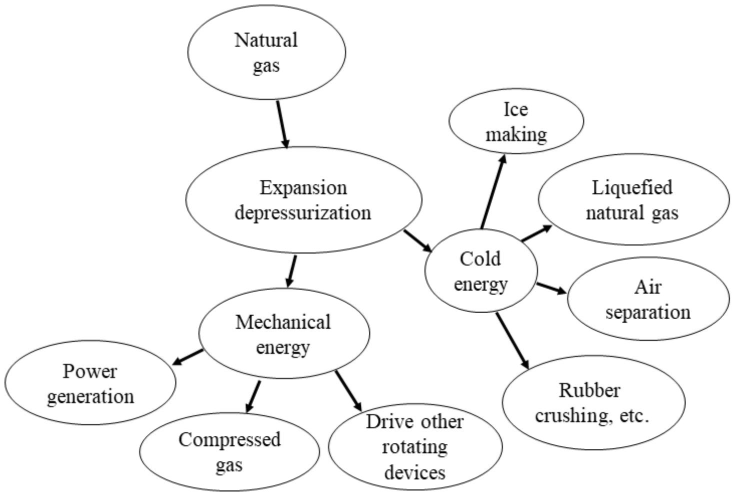

Figure 1. Residual pressure utilization way of natural gas

3.1. Expansion Power Generation

3.1.1. Principle

There is a large amount of unutilized pressure energy in the cascade depressurization of natural gas. According to the current research results, the pressure energy is widely used in the expander power generation[31][32]. The principle of pressure power generation is to use expander or other equipment to convert the pressure energy of high pressure natural gas into mechanical energy. Then through the generator, the mechanical energy is converted into electrical energy. [33]. Figure 2 shows a process flow that directly utilizes natural gas pressure energy expansion for power generation [34].

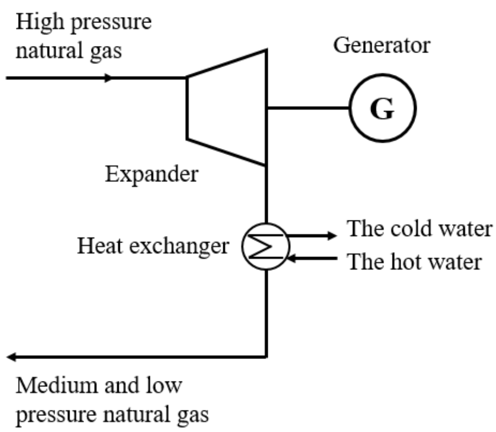

Figure 2. Direct expansion power generation [34]

The electricity generated by the expander can be directly applied to the power consumption equipment of pressure regulating station and gas field. The excess electricity can be added to the grid. It improves the economics of natural gas production and transportation.

3.1.2. Literature

The research on the application of natural gas pressure to power generation in foreign countries is early and the technology is relatively mature. The Soviet Union was the first country to study the use of residual pressure of natural gas. As early as 1969, the Soviet Union tried to use residual pressure for power generation [35].

In 1983, San Diego Gas & Electric installed an expander to recover the pressure of natural gas for electricity generation. In 2001, Tokyo Electric Power Company of Japan built a power station using the natural gas pressure energy to generate electricity and the power generation of it is 7700kW [36]. In 2006, Shen et al. [37] proposed the use of natural gas pipeline pressure to liquefied natural gas and power generation.

Some researchers point out that using turbine expander to recover natural gas pressure energy is one of the most feasible energy recovery technologies [38]. In 2009, London's natural gas distribution network started a project to recycling pressure energy from gas pipelines by turbine expander and combine them with biofuel generators [39].

In January 2009, the UK 's National Grid and the 2OC Corporation jointly installed a micro-turbine expander on the east London gas pipeline to collect pressure from the gas pipeline for power generation [40].

In 2012, KOGAS launched a natural gas differential pressure power generation project at a natural gas station in Gyeongsangnam-do. The maximum output power of the turbine generator is 300KW, the average actual output power is 260KW, and the maximum annual output power is 2286MWh [41]. In the same year, the natural gas differential pressure power generation project of Langson Energy Company in the United States was put into operation. The annual power generation of the project is $120\times10^4 kW\cdot h/a$, and the annual economic benefit can reach $72\times10^4 yuan/a$.

Poivil Jaroslav [42] used HYSYS to simulate and study the effect of turbine expander instead of pressure reducing valve in gas residual pressure recovery process. The effects of isentropic efficiency of turbine expander on output power and inlet temperature of expander were studied. Ref. [43] proposed a natural gas residual pressure power generation scheme consisting of a two-stage expansion system. Its performance is studied by numerical dynamic simulation. The formation risks of methane hydrate were evaluated under different operating conditions and transient behaviors.

In order to prevent ice blockage and hydrate formation, it is necessary to preheat natural gas before entering the expander [44]. Sepehr Sanaye [45] proposed a thermal cogeneration system to recover pressure energy for power generation. The scheme uses a gas engine to preheat natural gas. Ref. [46] added a solar heating system when preheating natural gas after considering the huge potential of solar energy in Iran. Clifford Robert Howard [47] designed a fuel cell system of a turbine expander. It used molten carbonate fuel cells to preheat natural gas before it passed through the expander.

Domestic natural gas residual pressure power generation technology was first put forward in 1983, and many field tests have been done [48]. In 2010, Peng Lei [49] proposed a scheme to generate power by high-pressure natural gas differential pressure. The scheme retrofitted the bypass pipeline of the pressure regulating station and increased the equipment such as turbine expander. The economic benefit is calculated and the result shows that the theoretical payback period is 1 year. In 2014, Liu Jingwei [50] proposed a reciprocating pneumatic motor system scheme. It realizes the conversion of wellhead natural gas pressure energy to mechanical energy. Chen Yue [51] proposed an idea of recovering wellhead pressure energy by using integrated technology of natural gas wellhead. It is based on axial differential pressure power generation technology.

The differential pressure power generation project of Qiuyuling gate Station in Shenzhen is an early instance in China. The annual energy saving of this project is $81.7\times10^4 kW\cdot h/a$. The annual ice production is 28720t/a and the annual income is about $500.2\times10^4 yuan/a$ [52]. The process flow diagram is shown in Figure 3.

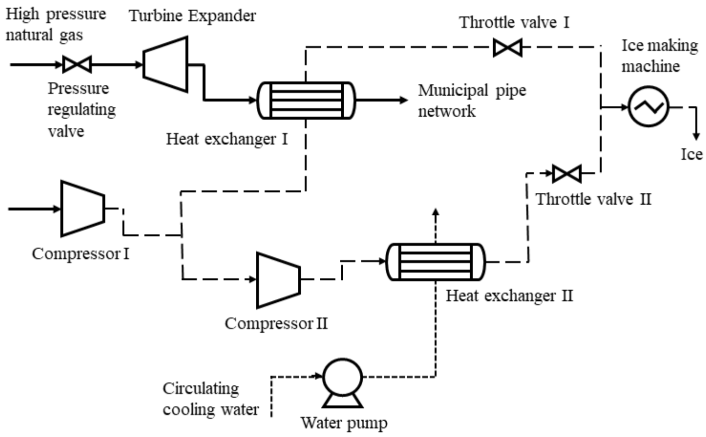

Figure 3. Process flow chart of natural gas differential pressure power generation and ice making project at Qiuyuling gate Station [52]

In 2016, natural gas pressure energy power generation device was used in Wuxi Lantian cogeneration project. The rated natural gas flow is $39557 Nm^3/h$ and the rated generating power is 300kW [53]. In 2021, a natural gas purification plant introduced branch plant using residual pressure power generation project officially put into operation. The cumulative power generation exceeded 1 million degrees.

Xiong Yaxuan et al. [54] proposed an expander pressure regulating power generation system. The thermodynamic model of the system is established to analyze the power generation performance of the system. The results show that the daily power generation of the system is enough to meet the demand of the pressure regulating facilities. Li Baixue proposed a natural gas pressure energy combined power generation system. Organic Rankine cycle is added to the expander power generation system. The regulated low-temperature natural gas provides cold energy for the ORC to generate electricity again.

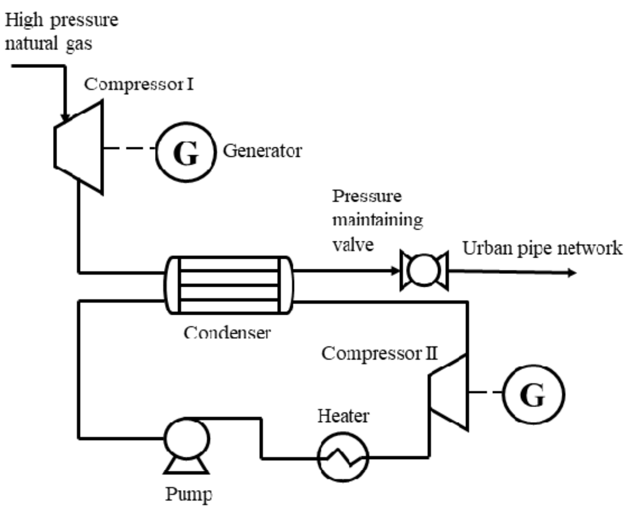

Figure 4. Combined power generation flow chart [55]

ISSN: 2688-8645

Wu Huanjie [56] proposed a power generation process using natural gas pressure energy in a regulator station. The process adds a bypass natural gas power generation system to the original voltage regulation path. It has good operating flexibility. Wenpan Xu et al. [57] proposed a power generation system for pressure energy recovery of natural gas city gate stations. CO_2 Rankine cycle is used to recover the cold energy produced and convert it into electricity. Under the design conditions, the energy efficiency of the system reaches 42.54%, and the exergy efficiency reaches 88.77%.

Compared with turbine expander, screw expander is not afraid of natural gas with liquid. Some researchers [58] [59] proposed a scheme that screw expander can be used to recover natural gas residual pressure and generate electricity.

3.1.3. Raising Efficiency

How to improve the efficiency and economy of residual voltage power generation is the direction of the majority of researchers' efforts. LI Chenghao et al. [60] pointed out that the isentropic efficiency of expander has a great influence on the net power output of the system. Sergey Osipov et al. [61] proposed the idea of improving the conversion efficiency of pressure energy into electrical power by introducing turbine expansion facilities into gas turbine units. Yao Sheng believes that the rotational speed of expander is the key to power generation efficiency. He used Aspen Plus to build a model to study the effect of screw expander speed on system efficiency. The results show that the system efficiency is the highest when the expander speed is 2500 $r/\min$. Highest effective efficiency up to 57% [62].

The temperature of natural gas at the inlet of the expander generator set will affect the generating efficiency of the machine set [63] [64]. Farzaneh-Gord Mahmood et al. [65] proposed a natural gas pressure energy power generation system consisting of preheating equipment and turbine expander. The effects of preheating temperature and working efficiency of turbine expander on the available work are studied. The results show that the power generation can meet the demand of the Khangiran Gas Refinery. Raising the preheating temperature can increase the work efficiency of system.

Li Mingfei [66] analyzed the influence of different natural gas inlet temperatures on the generation efficiency of expander generator sets. The results show that the output power of the expander is proportional to the inlet temperature of natural gas. For every 10K increase in inlet temperature, the output power will increase by about 120KW. A. A. Mukolyants et al. [67] analyzed the influence of inlet gas temperature and low potential source temperature on the power of expander generator set. The results show that the power of the expander reaches its maximum when the inlet gas temperature is 70°C and the low temperature of the heat source is 30°C.

3.1.4. Problems

(1) The flow rate of natural gas is unstable, and it is more obvious at the wellhead. There are also fluctuations in user demand at different times. It will have a great impact on the stability of power generation. When the flow rate changes greatly, instantaneous overpressure or underpressure will occur. It will affect the normal operation of the expander.

(2) The wellhead has large flow fluctuation and high pressure, so the requirements for supporting technology and equipment are high.

(3) Natural gas is a dangerous gas. The leakage of natural gas will cause safety hazards, so the sealing of the expansion unit is a problem that needs to be guaranteed.

(4) The change of natural gas flow will cause the resonance of expansion device. It is not conducive to the normal operation of the unit. When the vibration is large, it will produce greater noise pollution.

ISSN: 2688-8645

(5) When the flow rate and pressure difference are large, the high speed operation of the expander leads to high temperature of the lubricating oil system. It will cause safety hazards and affect its service life.

(6) When the spindle speed of the expander is too high, it is necessary to match the gear box with large reduction ratio. The manufacturing accuracy of the large gear box is low. Too high speed will also affect the strength and life of the gearbox.

(7) The composition of natural gas at the wellhead is complex. It contains water, acidic substances and solid impurities. It has a great influence on the expander and is difficult to be directly used for expansion power generation.

(8) Too low temperature after natural gas expansion will cause ice blockage and natural gas hydrate formation. Natural gas usually needs to be preheated. The economic benefit relationship between preheating and power generation has become a problem to be considered.

3.2. Refrigeration

When the pressure of the system decreases, the temperature will also decrease. The system absorbs heat from the environment and produces large amounts of cold energy. The traditional throttling process usually wastes this part of cold energy. In order to prevent the adverse effects of low temperature of natural gas, it frequently needs to be preheated. The cold energy is not used and increases the consumption of other energy. So it is necessary to use this part of cold energy reasonably.

There are many technologies to convert the residual pressure energy into cold energy during the high-pressure natural gas depressurization process. The core equipment includes throttle valve, pulse tube refrigerator, eddy current tube, turbine expander and gas wave refrigerator [68]. Among then the turbine expander is the most commonly used. The eddy current tube has the characteristic of energy separation, which can divide the high-pressure gas into cold air and hot air respectively. The cold air can reach the minimum of -46℃, and the hot air can reach the maximum of 127℃ [69].

The cold energy generated in the process of high pressure natural gas expansion and pressure reduction can be used for ice making, liquefied natural gas, cold storage, rubber crushing, air separation, light hydrocarbon recovery, air conditioning refrigeration and so on.

3.2.1. Peak Regulating of Natural Gas

Natural gas consumption of users is not uniform in different time and different seasons [70]. Natural gas peak regulating technology is often used in engineering to ensure the stability of gas consumption. The principle is to store excess natural gas when the gas consumption is low, and then export the stored natural gas when the gas consumption is peak [71]. Improving the stability of natural gas supply.

LNG (liquefied natural gas) is a relatively simple and efficient form of storage of excess natural gas. The cold energy generated by the pressure drop of high pressure natural gas can be used to produce LNG. The LNG can be used for peak shaving of urban natural gas [72] [73] In 1968, Northwest Gas Company of the United States established a natural gas liquefaction unit for peak balancing. The liquefaction process of expansion machine is adopted in this unit. The inlet pressure of this device is 2.67MPa, the outlet pressure is 0.49MPa and the liquefaction rate of natural gas is 10% [74].

In 2006, Xiong Yongqiang [75] proposed a liquefied natural gas scheme suitable for urban surge stations for peak shaving. The scheme utilizes expansion refrigeration and heat integration technology. The liquefaction rate of natural gas was increased to 16.8 % by optimizing the heat exchanger network. In the same year, Lun Liyong et al. [76] proposed a scheme of produce liquefied natural gas to peak regulating by using the cold energy production by high pressure natural gas passing through the expander and eddy current tube. The following is a natural gas expander flow chart of liquefied natural gas.

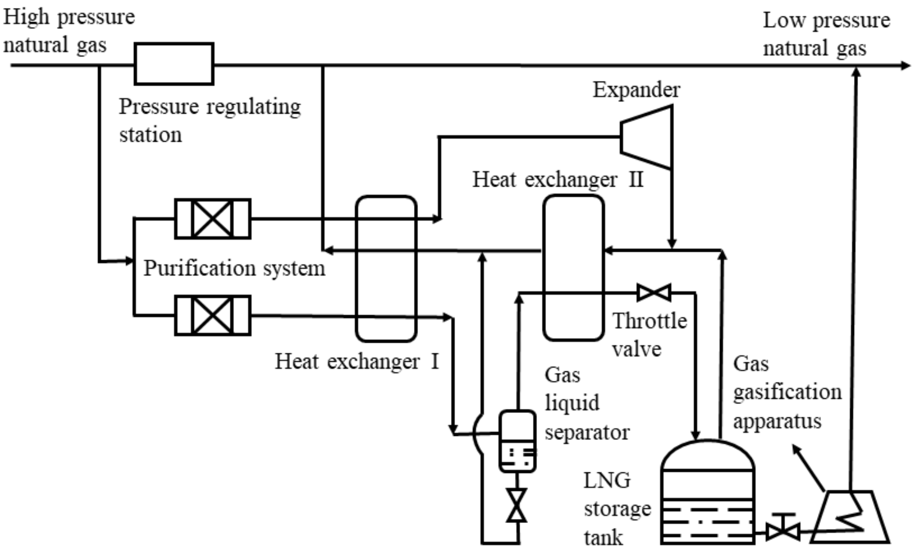

Figure 5. Natural gas expander liquefied natural gas flow chart [76]

In 2014, Ma Guoguang et al. [77] proposed a process of using differential pressure produced LNG in the offtake station. The effect of pressure difference on natural gas liquefaction rate was studied. The results show that the liquefaction rate increases with the increase of pressure difference. When the liquefaction efficiency reaches 18.34 %, the liquefaction efficiency is basically no longer affected by the pressure difference.

In 2016, Tan et al. [78] proposed a differential pressure natural gas liquefaction process suitable for high pressure natural gas reducing stations. The process can be used in urban natural gas peak shaving.

He TB [79] proposed a new natural gas liquefaction process using natural gas differential pressure. The process has low unit energy consumption but lower liquefaction efficiency. The equipment with more exergy loss in the system are heat exchanger and expander. This provides direction for subsequent optimization.

NGH (natural gas hydrate) can also be used for peak shaving. Zheng Zhi et al. [80]put forward the idea of combining the cold energy produced in the process of natural gas pressure regulation with the preparation process of natural gas hydrate. It simplifies the preparation process of NGH and enriches the way of recovery and utilization of natural gas residual pressure. In 2010, Fan Shuanshi et al. [81] proposed a process for preparing natural gas hydrate peak shaving using pipeline pressure energy. The process effectively solves two problems of natural gas residual pressure utilization and natural gas city peak shaving.

In addition, the cold energy produced by NGH gasification can also be used for air conditioning, cold storage, etc. [82].

3.2.2. Air Separation

The principle of air separation is mainly to use the cold energy obtained by natural gas expansion to supply to the air separation system to liquefy the air. Using rectifying tower to separate different components in air according to their physical properties. The separated nitrogen and oxygen can also be used for rubber crushing [83], low temperature drying, etc.

In 2011, Wang Xiaodong et al. [84] proposed a scheme to use the cold energy generated by the expansion of high-pressure natural gas in the air separation process. The schematic diagram of the specific process is shown in the figure below.

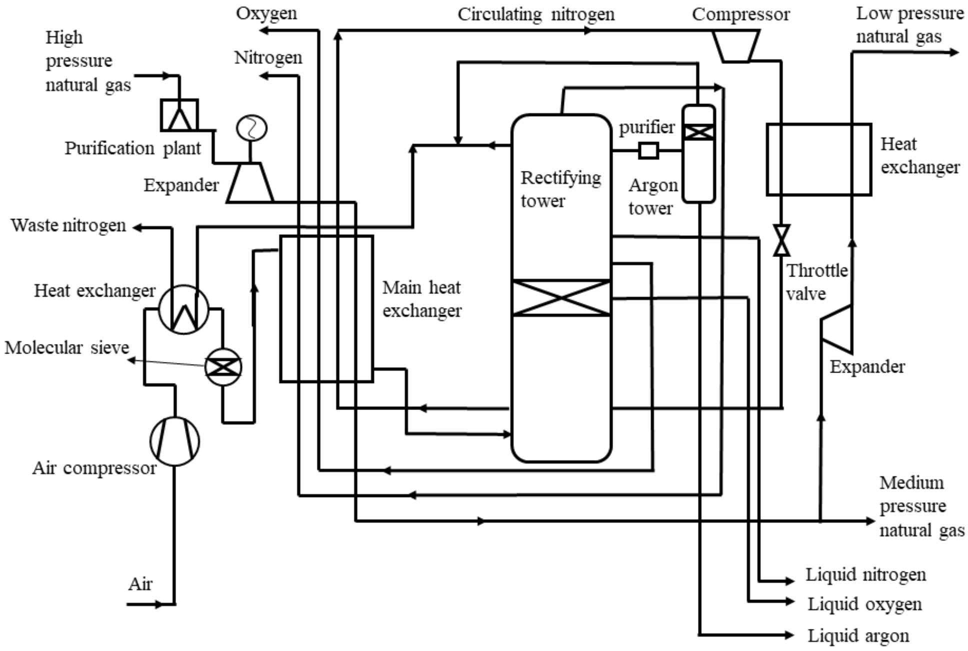

Figure 6. Application diagram of natural gas residual pressure in air separation [84]

The conventional air separation process system uses a distillation column nitrogen external circulation refrigeration. Shao Yan et al. [85] proposed a new air separation process for nitrogen expansion refrigeration based on the integrated process. Replacing the original nitrogen cycle refrigeration with natural gas differential pressure refrigeration. The heat energy generated by refrigerant compression is reused, which reduces energy consumption. Under the same operating conditions, the process reduces liquid product consumption by 58% and increases exergy efficiency to 52.5%. Significantly improve the utilization efficiency of natural gas pressure energy.

3.2.3. Others

Traditional cold storage uses compressed nitrogen expansion refrigeration, which requires a lot of electric energy. The pressure energy of natural gas can be used for cold storage refrigeration to save costs [86]. Cold energy from natural gas expansion can also be used for making dry ice [87], light hydrocarbon recovery [88] and air conditioning refrigeration [89] et al.

3.2.4. Problems

(1) Instability of natural gas flow also affects refrigeration.

(2) The refrigeration efficiency of gas wave refrigerator is low.

(3) The exergy efficiency of heat exchanger is low.

(4) The consumption capacity of power generation or refrigeration in the area near the gate station and the wellhead is limited. If the gate station is far away from the user, the utilization of cold energy is not ideal. The remote areas lack of cold energy transport conditions and utilization environment.

(5) The distribution of city gate stations is scattered, and the comprehensive utilization of cold energy is difficult.

3.3. Integrated Process

The efficiency of single utilization technology of natural gas pressure energy is low [90]. The integrated process can improve the utilization efficiency of natural gas residual pressure and has higher economic benefits. Different regions have different conditions and energy needs. It is necessary to adopt appropriate integrated technology according to regional characteristics to maximize the use of resources.

In 2005, Wang Songling et al. [91] proposed a gas-steam combined cycle system to realize the comprehensive utilization of natural gas pressure energy. Wang Lianyong et al. [92] proposed the idea of cascade utilization of natural gas pressure energy. The comprehensive utilization efficiency of natural gas residual pressure is improved.

In 2016, a new integrated process scheme of natural gas pipeline network pressure energy for power generation and compression dry ice production was proposed [93]. A coupling process of expansion, power generation, and compression is used. The problem of low power generation efficiency caused by unstable natural gas flow and unstable user load is avoided. Residual pressure power generation and dry ice production are realized simultaneously. In 2017, Yu Guangcan et al. [94] proposed an integrated ice-making process for natural gas residual pressure power generation. The simultaneous power generation and ice making are realized. The variation of average power generation and ice production in a day is analyzed by Aspen. The recovery efficiency of cold energy is improved by precooling natural gas.

In 2020, Zhang Anan et al. [95] constructed a framework of micro energy grid combining natural gas pressure energy with electricity, gas, cold, heat and other energy sources. Natural gas residual pressure energy power generation and cold energy utilization are organically integrated. The stability of energy supply and the comprehensive utilization efficiency of pressure energy are improved.

The comprehensive utilization technology of natural gas pressure energy is aimed at the efficient utilization of energy. It conforms to the concept of energy saving and emission reduction and has great application prospect in the future. At present, the comprehensive utilization process of natural gas pressure energy mostly stays in the theoretical research stage. More experiments and researches are needed to apply it to actual production.

4. Conclusion

Significant residual pressure in nature gas wellhead and pressure regulating station can be utilized based on the exergy analysis. The traditional throttling process leads to a large waste of residual pressure resources. It is necessary to use reasonable technology to recycle natural gas residual pressure. Residual pressure utilization technology can not only improve the economy of natural gas pipeline operation, but also make an important contribution to energy conservation and emission reduction in the world.

Residual pressure utilization of natural gas has a good development prospect. In this article, these results are obtained by exergy analysis and investigation of the current situation of natural gas residual pressure utilization at home and abroad.

(1) The available pressure energy and cold energy generated by natural gas pressure drop are calculated by examples based on exergy analysis. The results show that the recoverable pressure exergy at wellhead under corresponding conditions is 240.41kJ/kg. The recoverable pressure exergy at pressure regulating station under corresponding conditions is 141.72kJ/kg and 356.13kJ/kg. Both wellhead and pressure regulating station contain significant pressure energy can be used.

(2) The application of natural gas pressure energy is extensive, including power generation, ice making, peak shaving, air separation, LNG preparation, light hydrocarbon recovery and so on.

(3) At present, there are many research and examples of pressure energy utilization in natural gas gate stations. There are many theoretical studies on wellhead pressure energy utilization technology, but few examples.

(4) There are many difficulties in the utilization of residual pressure of wellhead natural gas, but the pressure energy resources are more abundant.

(5) The comprehensive utilization rate of natural gas pressure energy can be improved by use integrated process.

More tests and studies are needed to make the utilization technology of natural gas residual pressure more mature. Gas wells and pressure regulating stations are scattered, and energy demand is different in different regions, so it is difficult to use pressure energy. It is recommended to propose appropriate solutions based on the actual situation and energy needs of different regions.

In the future, the problem of utilization after pressure energy recovery can be solved by overall planning the industrial chain of pressure energy utilization. In the pressure regulating station, comprehensive utilization technology can be used to improve the efficiency of pressure energy utilization. At the wellhead, research work can be carried out in combination with the characteristics and technical difficulties of different gas wells. In the case of high pressure and large flow changes, the mechanical properties, sealing and service life of the expander need to be analyzed. The research on reducing the energy loss of each module is also the key to improving the utilization efficiency. This is of great significance for building a resource-saving society and world energy conservation and emission reduction.

References

[1] Lei, L., C. yue. 2014. Discussion on pressure energy recovery before natural gas pipeline station. China Petroleum and Chemical Standards and Quality (12):169.

[2] Gao, S.L., Y. D. Ping, Z. H. Liang, L. X. Xi, S. B. Yue, X. W. Dong, et al. 2014. Research progress on pressure energy recovery and utilization technology of natural gas pipeline network. Gas &amp (10):1-5.

[3] Li, Z.D., C. Q. Lin, C. Y. Wang, W. J. Dong, L. L Li, W. Hao, and L. Yang. 2022. Electric power generation technology of natural gas pressure reduction: Insights from black box-gray box hierarchical exergy analysis and evaluation method. Petroleum Science 19(1): 329-338.

[4] Duan, W., Z. Hui, Y. Z. Biao, L. Z. Guo, L. X. Xi, and X. L. Lin. 2015. Research on the application of residual pressure power generation technology of natural gas pipeline network in the construction of intelligent pipeline network. City Gas (10):33-36.

[5] Wen, J., X. M. Fang. 2007. Recovery and utilization of pressure energy of natural gas pipeline network. Natural Gas Industry (7):106-108.

[6] Wei, J.D., L. Z. Dong, Z. Y. Ru, X. Yuan, and C. Q. lin. 2021. Research progress of waste energy recovery technology of natural gas expansion differential pressure power generation. Chemical Machinery 48(5):644-647.

[7] Yan, J. Z. 1988. Utilization of wellhead pressure energy. Oil-gas Field Surface Engineering (1):61-62.

[8] Chen, J. 2017. Fluid pressure energy recovery technology in natural gas transmission and distribution process. Petrochemical Technology 24(3):195.

[9] Wang Y., Y. H. Hong, H. Li, D. D. Fei, and Z. Liang. 2018. Application of natural gas differential pressure power generation technology in surge gate station. Petroleum and Petrochemical Energy Saving 8 (5):8-11.

[10] Wang, Z. P., C. Shuang, F. Qian, and Z. Xi. 2020. Research on pressure energy recovery and utilization of natural gas pipeline network. Gas &amp 40(1):14-16, 44-45.

[11] Zhao, W. D., Y. J. Yi, and W. Bo. 2022. Analysis and utilization of wellhead residual pressure resources in Tarim gas well. Xinjiang's Oil and Gas 18(2):84-91.

[12] Zheng, Z., W. S. Li, W. Tin, S. Qi, and X. Lei. 2009. Present situation and prospect of fluid pressure energy recovery technology in natural gas transmission and distribution process. Natural Gas and Oil 27(01):11-5+67.

[13] Zheng, Y., J. Q. Qing, and Z. Y. Ton. 2020. Feasibility analysis of residual pressure power generation project of natural gas high pressure pipeline network. China Chemical Trade 12(18):14-15.

[14] Wang, Y. J. 2015. Recycling of pressure energy in natural gas gate station. Metallurgical Power (7):23-26.

[15] Wang, Y. P., T. Xiao, W. H. Mei, Q. J. Feng, and S. L. Mei. 2022. Natural Gas Pressure Reduction Station Self-powered by Fire Thermoelectric Generator. Journal of Thermal Science 31(3):840-853.

[16] Zhang, H., L. X. Xi, X. W. Dong, X. L. Lin, D. Wei, and Z. Jun. 2015. Research on residual pressure combined cooling and power system of natural gas high pressure pipeline network. Gas &amp 35(7):35-37.

[17] Wang, S. 2015. Research on pressure energy power generation technology scheme of natural gas pipeline network in Beijing. Beijing University of Architecture.

[18] Dragan, R., M. Taher, and N. Bhatia. 2020. Turbo-Expander Generators for Supplemental Power Generation in LNG Liquefaction Plants. IEEE Transactions on Industry Applications 56(6):6094-6103.

[19] Wang, S. M., G. F. Fang, D. Chao, and L. Z. Yu. 2019. Review of pipeline residual pressure utilization technology research. Technology Innovation and Application (11):161-164.

[20] He, N. 1996. Overview of Pangang No.4 Blast Furnace Top Residual Pressure Power Generation Device. Panzhihua Technology (1):33-35+47.

[21] Chen, Y. 2013. Theoretical analysis and calculation of natural gas residual pressure power generation. Gas Turbine Technology 26(3):65-68.

[22] Zeng, W. L. 2015. Gas dynamic performance analysis of pressure energy recovery of natural gas pipeline by turbine expander. Journal of Jianghan Petroleum University of Staff and Workers (4):47-49.

[23] Ebrahimi, S., S. Mohammad, R. Farzaneh, and S. Yadollah. 2021. Optimal detailed design and performance assessment of natural gas pressure reduction stations system equipped with variable inlet guide vane radial turbo-expander for energy recovery. Journal of Natural Gas Science and Engineering. doi: 10.1016/j.jngse.2021.104222.

[24] Sun, W. C. 2019. Process development and experimental test of natural gas pipeline pressure energy power generation for pipeline cathodic protection. South China University of Technology. doi: 10.27151/d.cnki.ghnlu.2019.002562.

[25] Wang, G. Y. Application Research on Residual Pressure Power Generation System of Natural Gas Regulating Station. Beijing University of Architecture.

[26] Gou, X. H. 2017. Research on natural gas wellhead residual pressure power generation equipment and key technologies. Chongqing University of Science & Technology.

[27] Qiao, X. H., T. F. Tai, and Z. G. Xing. 2010. Recovery and utilization of high pressure natural gas pressure energy by venturi ejector. Energy Conservation 29(05):63-65+3.

[28] Li, J. 2015. Discussion on the application of natural gas pressure power generation technology. New Technology & New Products of China (09):45. doi: 10.13612/j.cnki.cntp.2015.09.044.

[29] N.V. Kholod, V.V. Kholod, V.A. Kirii, and Y. P. Yas'yan. 2021. Efficient Utilization of Energy of Natural Gas Pressure Drop. Chemistry and Technology of Fuels and Oils 57(2): 209-215. doi: 10.1007 /s10553-021-01240-z.

[30] Jiao, Y. 2016. Analysis of pressure energy utilization of natural gas pipeline network. Management & Technology of SME (11):81-83.

[31] Shen, A. Y., X. Y. Qiang. Analysis of pressure energy utilization process of natural gas pipeline network. Gas & Heat 28(11):31-35.

[32] Chen, W. K., S. R. Hua, Z. Wei, C. X. Ming, L. S. Jie, G. Yong, et al. 2021. Application of natural gas residual pressure power generation device in imported branch plant. Energy Conservation in Petroleum & Petrochemical Industry 11(11):5-8+76.

[33] Ha, J. M., H. S. Ho, Y. H. Seok, and K. K. Chun. 2012. Turbo Expander Power Generation Using Pressure Drop at Valve Station in Natural Gas Transportation Pipeline. Journal of the Korean Institute of Gas 16(3): 1-7. doi: 10.7842/kigas.2012.16.3.001.

[34] Shen, A. Y., X. Y. Qiang. 2008. Exergy analysis of pressure energy utilization process of natural gas pipeline network. Gas & Heat 28(11):31-35.

[35] Wang, D. Q., D. Y. Fei. 2020. Present Situation and Prospect of Residual Pressure Utilization in High Pressure Transportation of Natural Gas. Petroleum & Petrochemical Material Procurement (6):64.

[36] Yi, M. 2009. Japan uses natural gas differential pressure power generation. Rural Electician 17(09):48.

[37] Shen, D. M., F. Fernandes, and J.R. Simöes-Moreira. 2006. Using gas pipeline pressure to liquefy natural gas or generate electricity. Hydrocarbon Processing 85(1): 47-48,50.

[38] Danieli P., C. Gianluca, and L. Andrea. 2020. Thermodynamic and Economic Feasibility of Energy Recovery from Pressure Reduction Stations in Natural Gas Distribution Networks. Energies 13(17): 4453. doi:10.3390/en13174453.

[39] Andrei I., V. Tudorache, C. Tarean, and N. Toma. 2014. Recovery of Wasted Mechanical Energy from the Reduction of Natural Gas Pressure. Procedia Engineering 69: 986-990. doi: 10.1016/j. proeng. 2014.03.080.

[40] Xu, X. X., H. Y. Qian, and K. Z. Tao. 2013. Potential analysis of pressure energy recovery and utilization in Sichuan-East gas transmission station. Natural Gas Technology and Economy 7 (02): 48-51+79.

[41] Hyoung, T. K., H. You, K. S. Choi, and S. Han. 2020. A Study on Interconnecting to the Power Grid of New Energy Using the Natural Gas Pressure. Journal of Electrical Engineering & Technology 15(1):307-314. doi: 10.1007/s42835-019-00324-5.

[42] Jaroslav, P. 2004. Use of Expansion Turbines in Natural Gas Pressure Reduction Stations. Acta Montanistica Slovaca 9(3): 258-260.

[43] Borelli, D., D. Francesco, L. C. Ermanno, and S. Corrado. 2018. Energy recovery from natural gas pressure reduction stations: Integration with low temperature heat sources. Energy Conversion and Management 159(1): 274-283. doi: 10.1016/j.enconman.2017.12.084.

[44] Wojciech, K. 2010. The Possibility of Energy Generation within the Conventional Natural Gas Transport System. Strojarstvo: časopis za teoriju i praksu u strojarstvu 52(4): 429-440.

[45] Sanaye, S., M. N. Amir. 2012. Modeling and optimizing a CHP system for natural gas pressure reduction plant. Energy 40(1): 358-369. doi: 10.1016/j.energy.2012.01.060.

[46] Arabkoohsar, A., M. Farzaneh-Gord, M. Deymi-Dashtebayaz, L. Machado, and R. N. N. Koury. 2015. A new design for natural gas pressure reduction points by employing a turbo expander and a solar heating set. Renewable Energy: An International Journal 81: 239-250. doi: 10.1016/j. renene. 2015. 03.043.

[47] Howard, C., O. Patrick, and P. Brant. 2011. An investigation of the performance of a hybrid turbo expander-fuel cell system for power recovery at natural gas pressure reduction stations. Applied Thermal Engineering 31(13): 2165-2170. doi: 10.1016/j.applthermaleng.2011.04.023.

[48] Yu, P. R. 1983. Talking about the utilization of natural gas pressure energy. Natural Gas Industry (2): 63-65.

[49] Peng, L. 2010. Feasibility analysis of residual pressure power generation project of natural gas high pressure pipeline network. Communication & Shipping 24(03):35-38+51. doi: 10.16487/ j.cnki. issn 2095-7491.2010.03.015.

[50] Liu, J. W. 2014. Study on the theory and scheme of converting wellhead natural gas pressure energy into mechanical energy. Southwest Petroleum University.

[51] Chen, Y. 2022. Discussion on natural gas wellhead integration technology based on differential pressure power generation. Technology Innovation and Application 12(25):161-165. doi:10. 19981/ j.CN23-1581/G3.2022.25.038.

[52] Chen, Q. X., X. W. Dong, and A. C. Ming. 2012. Development and application of natural gas pipeline network pressure energy power generation ice technology. Gas & Heat 32(09):25-27.

[53] Tang, Y., C. X. Dong, and Y. L Lan. 2019. Research on utilization scheme of natural gas pressure energy in power station. Modern Industrial Economy and Informationization 9(10):45-46. doi: 10.16525/j.cnki.14-1362/n.2019.10.18.

[54] Xiong, Y. X., W. Nan, X. Peng, and W. Gang. 2021. Study on power generation performance of expander gas pressure regulation. Gas & Heat 41(04):58-63+70+101. doi: 10.13608/j.cnki.1000-4416.2021.04.012.

[55] Li, B. X. 2016. Application of pressure energy and cold energy in gas pressure regulation process for power generation. Huazhong University of Science and Technology.

[56] Wu, H. J., W. Y. Zhen, L. Y. Fu, and P. Z. Bin. 2019. Development and application of pipeline natural gas pressure energy power generation technology. Urban Gas 534(08):22-26.

[57] Wen, P. X., Z. Pan, G. F. Fei, L. A. Jie, W. W. Ze, and W. J. Feng. 2022. Performance analysis of a power generation system for pressure energy recovery at natural gas city gate stations. Applied Thermal Engineering 213: 118714.

[58] Diao, A. N., X. Q. Yan, Z. Q. Ming, and W. Yu. 2013. Development and application of natural gas screw expander. Chemical Engineering of Oil & Gas 42(04):378-381.

[59] Diao A. N., W. Y. Li, G. Yi, and F. M. Zhi. 2018. Development and application of screw expander in natural gas pressure energy recovery at city gas station. Applied Thermal Engineering 142: 665-673.

[60] Cheng, H. L., Z. S. Yang, C. X. Yu, L. Jie, and Z. Z. Yong. 2020. Proposal and analysis of a coupled power generation system for natural gas pressure reduction stations. Journal of Central South University 27 (2): 608-620.

[61] Osipov, S., Z. Olga, B. Nikolay, K. Daria, Z. Arkadiy, R. Luká, et al. 2020. Increasing the efficiency of using the natural gas potential energy in turbo-expander units for power generation. AIP Conference Proceedings 2323(1): 1-6.

[62] Yao, S. 2015. Simulation and experimental study on the residual pressure power generation system. Tianjin University.

[63] Mukolyants, A. A., I. V. Sotnikova, D. K. Ergasheva, F. T. Shadibekova, and A. A. Taubaldiev. 2021. Heating of natural gas before expander - generator unit. Journal of Physics: Conference Series 2094(5). doi: 10.1088/1742-6596/2094/5/052049.

[64] Klimenko, A. V., V. S. Agababov, P. N. Borisova, S. N. Petin, and A. V. Koryagin. 2018. Influence of process parameters on thermodynamic efficiency of expander-generator units at the plants for technological decompression of transported natural gas. Thermophysics and Aeromechanics 25(4): 613-622. doi:10.1134/S0869864318040133.

[65] Farzaneh-Gord. M., D. D. Mahdi. 2008. Recoverable Energy in Natural Gas Pressure Drop Stations: A Case Study of the Khangiran Gas Refinery. Energy Exploration & Exploitation 26(2): 71-82. doi:10. 1260/014459808785260508.

[66] Li, M. F. 2019. Analysis on technical scheme of natural gas residual pressure power generation in gas power station. Energy Conservation 38(03):17-20.

[67] Mukolyants A. A., I. V. Sotnikova, D. K. Ergasheva, A. A. Taubaldiev. 2021.Expander-generator set for utilization of natural gas overpressure energy. E3S Web of Conferences 289: 7034. doi: 10.1051/e3sconf/202128907034.

[68] Zhao, H. L., H. Yu, Z. Min, and C. C. Zheng. 2005. Discussion on refrigeration method of natural gas liquefaction plant. Natural Gas Industry (10):144-147+22.

[69] Sun, J. 2010. Research and application progress of pressure energy recovery equipment in urban gate station. Gas & Heat 30(07):18-20.

[70] Farzaneh-Gord, M., M. Sadi. 2008. Enhancing energy output in Iran's natural gas pressure drop stations by cogeneration(Article). Journal of the Energy Institute 81(4): 191-196. doi: 10.1179/014426008X371004.

[71] Chen, J. 2017. Fluid pressure energy recovery technology in natural gas transmission and distribution process. Petrochemical Industry Technology 24(03):195.

[72] Lun L. Y., Xie Y B, and Zhang X D. 2008. LNG Scheme for Natural Gas Peak-shaving in Cities Based on the Recovery of Pressure Energy in the Gas Transportation Pipelines. ICCR 2008 Fourth International Conference on Cryogenics and Refrigeration Engineering.

[73] Yang, Y., Y. Qiang. 2017. Research on LNG production technology by using pressure energy of natural gas pipeline network. Management & Technology of SME (7):191-192.

[74] Gao, J. 2015. Research on LNG production technology by using pressure energy of natural gas pipeline network. Southwest Petroleum University.

[75] Xiong, Y. Q., H. Bi, and L. D. Xiao. 2006. Pipeline natural gas liquefaction process for gas peak shaving and light hydrocarbon recovery. Natural Gas Industry (05):130-132+3+2.

[76] Lun, L. Y., X. Y. Bai, and Y. X. Liang. 2006. Liquefaction peak shaving scheme based on pressure energy recovery of pipeline natural gas. Natural Gas Industry (07):114-116+161.

[77] Ma, G. G., G. Jun, J. X. Xia, and W. X. Dong. 2014. Study on differential pressure liquefied natural gas using distribution station. Chemical Engineering of Oil & Gas 43(06):622-625+638.

[78] Tan, H. B., Z. Q. Xuan, S. N. Nan, L. Y. Zhong. 2016. Proposal and design of a natural gas liquefaction process recovering the energy obtained from the pressure reducing stations of high-pressure pipelines. Cryogenics 80(1): 82-90. doi: 10.1016/j.cryogenics.2016.09.010.

[79] He, T. B., Y. L. Ju. 2013. Design and optimization of natural gas liquefaction process by utilizing gas pipeline pressure energy. Applied Thermal Engineering 57: 1-6. doi: 10.1016/j. applthermaleng. 2013.03.044.

[80] Zheng, Z., W. S. Li, C. S. Wei, S. Qi, and X. Lei. 2009. The idea of using natural gas pipeline pressure energy for NGH gas storage and peak shaving. Oil & Gas Storage and Transportation 28(10):47-51+84+92.

[81] Fan, S. S. C. Y. Juan, Z. H. Ping, X. W. Dong, and L. X. Mei. 2010. A new peak-shaving technology for preparing natural gas hydrate by using pipeline pressure energy. Natural Gas Industry 30(10):83-86+124-125.

[82] Chen, Q. X., X. W. Dong. 2010. Study on pressure energy utilization of natural gas pipeline network and hydrate joint peak regulation. Gas & Heat 30(08):27-30.

[83] Xiong, Y. Q., H. Bi, L. D. Xiao, and X. W. Dong. 2007. Natural gas pipeline pressure can be used for waste rubber crushing refrigeration device. Modern Chemical Industry 243(01):49-52. doi: 10.16606/j.cnki.issn0253-4320.2007.01.012.

[84] Wang, X. D., W. C. Yang, Y. D. Hong, W. Z. Xin, G. J. Bing, and Z. Yue. 2011. Recovery and utilization of residual pressure and cooling capacity of air separation plant in natural gas transportation process. Energy Conservation 30(09):24-28+2.

[85] Shao, Y., Z. Chen. 2018. Research on integrated process of natural gas pressure energy utilization and air separation. Journal of Beijing Institute of Petrochemical Technology 26(01):39-43.

[86] Luo, D. X. 2010. The technology of recovering gas transmission pressure of high pressure pipe for cold storage. Urban Gas 422(04):3-5.

[87] Fu, R. Y., D. J. Zhao, P. Y. Hui, Z. R. Wei, and P. J. Ron. 2016. Technical research on dry ice production by natural gas pressure energy power generation. Guangdong Chemical Industry 43(13):59-60+56.

[88] Yang, W. Y., L. Yue, and L. Y. Jun. 2015. Natural gas light hydrocarbon recovery process design and optimization of operating parameters. Chemical Industry and Engineering Progress 34(10):3589-3594. doi: 10.16085/j.issn.1000-6613.2015.10.011.

[89] Li, J. J. 2011. Research on the recovery and application of cold energy in the process of natural gas pressure regulation in urban gate station. Chongqing University.

[90] Zhang, H. 2014. Research on integrated utilization process of pressure energy in natural gas pipeline network. South China University of Technology.

[91] Wang, S. L., L. L. Yong, X. Y. Bai, and C. H. Gang. 2005. Combined cycle concept based on pressure energy recovery of natural gas pipeline network. Journal of Engineering for Thermal Energy and Power (06):75-78+111.

[92] Wang, L. Y., L. Chao. 2014. Pressure Recovery and Cascade Utilization of Energy in the Process of Natural Gas Transportation. Environmental Technology and Resource Utilization II 675-677: 1517.

[93] Xu, W. D., C. Zhong, L. X. Xi, X. L. Lin, Q. Di, and Q. Zhen. 2016. Natural gas pressure energy is used in the integrated process of power generation and dry ice production. Journal of South China University of Technology (Natural Science Edition) 44(11):41-48.

[94] Yu, G. C., L. Q. Feng, L. X. Yu, and P. D. Yu. 2017. Design and actual capacity simulation of ice-making system for natural gas residual pressure power generation. Shanghai Energy Saving 346(10):608-613. doi: 10.13770/j.cnki.issn2095-705x.2017.10.010.

[95] Zhang, A. A., F. Y. Tin, L. Dong, L. Qian, and W. J. Zhong. 2020. Gas-electricity demand response model of micro-energy grid considering comprehensive utilization of natural gas pressure energy. Automation of Electric Power Systems 44(08):19-27.