Design of LNG Cold Energy Power Station Based on Thermal differential Power Generation

Song Fuquan Xu Yeqing Song Xingxing Gao Haoze
School of Petrochemical and Energetic Engineering, Zhejiang Ocean University, Zhoushan, Zhejiang, 316000, China
Email: songfuquan@zjou.edu.cn, 2387251420@qq.com, 923326117@qq.com, 819579457@qq.com

Abstract. The world is currently facing increasing energy demand and increasing environmental pollution. Traditional energy resources are in short supply, and over-exploitation will cause serious damage to human living environment. Natural gas is an ideal clean fuel. Liquefied natural gas (LNG) is an important transportation form of natural gas. When LNG is used, with the increase of temperature and volume expansion, natural gas absorbs heat from the environment in large quantities. The resulting temperature difference provides the basis for the use of cold energy. Based on the Seebeck thermoelectric effect, a thermoelectric generator monomer based on LNG energy was designed in this paper. Under the condition of temperature difference of 60 °C, the single-unit power supply outputs 24V DC voltage; the power output power is 90W. Taking the annual natural gas requirement of Zhoushan as an example, an LNG cold energy power station was designed. The total circuit voltage is 96V and the total circuit current is 196A. Converted to 220V AC by inverter for daily power supply, and the annual power generation is 1.18×10^6 kilowatt-hours. It shows that the utilization of LNG cold energy by thermoelectric generator has great environmental benefit and ecological benefit.

1. Introduction
At present, China is the second largest energy import and consumption country in the world. With the increase of environmental pressure, the demand for clean energy continues to increase. The main components of natural gas are CH₄, combustion products such as CO₂ and water, clean energy and low-carbon fuels. The natural gas used as fuel contains little sulfur, dust and other harmful substances. At the same time, the CO₂ emitted by natural gas after combustion is 57% of CO₂ emitted by coal and 71% of that of fuel, and the emission of NOₓ is 80% and 72% less than that of coal and oil, respectively. It basically contains no sulfur and is an ideal clean fuel.

Natural gas is widely used in power generation, urban residential gas, industrial fuel and other fields. It can replace coal, fuel oil, liquefied petroleum gas and a small amount of refined oil in a wide range, so that China's energy structure can be strategically adjusted.

Liquefied natural gas (LNG) is an important transportation mode of natural gas, and it is also the fastest growing energy in the world. The proportion of natural gas in energy supply is increasing rapidly. At a rate of about 12% a year, LNG is becoming one of the fastest growing energy industries in the world. By the end of 2016, China had completed 13 receiving LNG stations of including Guangdong Dapeng, Fujian Putian, Shanghai Yangshan, Jiangsu Rudong, Liaoning Dalian, Zhejiang Ningbo, Zhuhai Jinwan, Hebei Caofeidian, Tianjin floating Type, Hainan Yangpu, Shandong Qingdao,
Guangxi Beihai, Shenzhen Defu. In the process of LNG gasification, a large amount of cold energy is released. If this part of cold energy cannot be used reasonably, it will not only cause waste of energy, but also cause cold pollution of seawater.

There were many ways of using LNG cold energy, including cold energy generation[1], air separation[2-3], freezing warehouse[4-5], low temperature crushing [6], liquefaction of CO2 [7] and new seawater desalination technology [8-9]. The cold energy of LNG was used in air separation, that is, the process of converting the expansion refrigeration in the original air separation process into the heat transfer method, separating oxygen and nitrogen from the air, and simultaneously extracting rare gases such as helium, argon and so on. It has wide application prospect[2-3]. The liquid nitrogen produced by the cold energy of LNG can break down some substances that are difficult to be broken at normal temperature at low temperature, and has excellent prospects in resource recovery, material separation, fine crushing, etc. [6]. The recovery methods of CO2 mainly include physicochemical absorption, low temperature fractionation and membrane separation. Using the cold energy of LNG, it is easy to obtain the low temperature required for cooling and liquefaction of CO2 [7]. The desalination methods include distillation, reverse dialysis, electrodialysis, freezing and so on. Freezing is cooling seawater below freezing point, freezing fresh water and thawing to get desalination water. Applying LNG cold energy to desalination and increasing desalination rate combined with other desalination methods are of great significance to the development of seawater desalination technology based on freezing method [8-9].

At present, recovering the cold energy of LNG in the form of electric energy is an important way of its utilization, and the technology of cold energy generation is relatively mature. The main methods of LNG cold energy for power generation are direct expansion method, secondary media method, combined method and so on. The new research LNG cold energy generation using the low temperature semiconductor thermoelectric method[10]. On the basis of semiconductor thermoelectric plate, a thermoelectric generator is designed firstly, then the application of thermoelectric generator in LNG transportation is designed. Finally, the economic and ecological benefits of LNG cold energy power station are analyzed.

2. Design of thermoelectric generator monomer
The thermoelectric principle of the thermoelectric cell designed in this paper is based on the thermoelectric effect of Seebeck. The monomeric structure of thermoelectric generator monomer mainly includes: semiconductor thermoelectric plate, cold and heat exchange flat hollow aluminum tube and accessory equipment. Semiconductor thermoelectric plate is composed of series and parallel of several TEG1-127-1.4-16 plates. In this paper, the series-parallel generation sheet and two flat hollow aluminum tubes were bonded by thermal conductive silica gel. The flat hollow aluminum tubes are customized to the specification of 300 × 700 × 50mm, with one end opening and one end welded. Thus, a thermoelectric generator with one end cold source and one end heat source is formed. Specific design indicators:(1)Power supply voltage: output 24V DC voltage;(2)Power supply: output power 90 W (temperature difference 60 °C).

| specifications | open circuit voltage/V | internal resistance/Ω | load resistance/Ω | Load power/W | output voltage/V | cold end/mm | hot end/mm | Height/mm |
|---------------|-----------------------|-----------------------|------------------|-------------|----------------|-------------|------------|-----------|
| TEG1-127-1.4-16| 6.4                   | 3.3                   | 3.3              | 3.1         | 3.2            | 40×40       | 40×40      | 3.8       |

Perform the performance test on the purchased semiconductor thermoelectric plate (see Table 1 for parameters), test the internal resistance change of the semiconductor thermoelectric plate in series or parallel and the relationship between the output power and the temperature difference (as shown in Table 2). Then select any number of pieces to carry out serial and parallel experiments. The test results are as follows:
Table 2. relationship between open circuit voltage series-parallel and temperature difference.

| difference in temperature | open circuit voltage |
|---------------------------|----------------------|
|                           | 2 parallel | 3 parallel | 4 series | 5 series |
| 60                        | 0.74       | 0.73       | 2.8      | 3.7      |
| 55                        | 0.65       | 0.67       | 2.5      | 3.6      |
| 47                        | 0.60       | 0.59       | 2.4      | 3.4      |
| 40                        | 0.48       | 0.49       | 2.1      | 2.8      |
| 35                        | 0.45       | 0.44       | 1.7      | 2.5      |
| 30                        | 0.36       | 0.37       | 1.4      | 2.3      |
| 25                        | 0.33       | 0.34       | 1.2      | 1.9      |
| 20                        | 0.29       | 0.30       | 1.0      | 1.6      |

As shown in Table 2, the semiconductor thermoelectric plate used in the experiment has good reproducibility, that is, under the same operating temperature difference, the thermoelectric plate exhibits the same performance. Under different temperature difference, the open circuit voltage of parallel circuit is equal, and the open circuit voltage of series circuit satisfies the superposition principle.

![Figure 1 characteristics of open circuit voltage and temperature difference of thermoelectric plate.](image1)

3 thermoelectric plates in parallel 4 thermoelectric plates in series

According to the characteristic curves of open circuit voltage temperature difference between three thermoelectric plates in parallel and four thermoelectric plates in series, the open circuit voltage of thermoelectric plate increases with the increase of temperature difference. The design idea of the generation module is to make the output EMF large enough and the internal resistance small enough. According to the characteristics of open circuit voltage and internal resistance of monolithic thermoelectric plate, if we want to achieve the required output power, we must make a certain number of monolithic thermoelectric plates in proper strings and parallel connection to achieve better results.

2.1 Series and parallel modes of thermoelectric plates

In the experiment, we have 102 thermoelectric plates, and 17 thermoelectric plates are connected in series, and then 6 groups are connected in parallel (the physical diagram is shown in Figure. 2) to make a small thermoelectric generator monomer.

According to the characteristics of series-parallel output voltage and current of thermoelectric plates, we have made a DC generator with an output voltage of about 24V. The experimental results of the generator were shown in Table 3 and Figure 3.
Figure 2 Physical drawing of Series-parallel Mode in Generation Module.

![Figure 2 Physical drawing of Series-parallel Mode in Generation Module.](image)

Table 3. Performance of self-made thermoelectric generator monomer.

| difference in temperature/ΔT | output voltage/V | Output current/A |
|------------------------------|------------------|------------------|
| 60                           | 28               | 3.3              |
| 55                           | 26.1             | 3.0              |
| 50                           | 23.6             | 2.6              |
| 45                           | 20.4             | 2.4              |
| 40                           | 18               | 2.1              |
| 35                           | 16.7             | 1.8              |
| 30                           | 13.1             | 1.5              |
| 25                           | 10.9             | 1.3              |
| 20                           | 8.4              | 1.0              |

Figure 3 Performance curve of self-made thermoelectric generator monomer.

The experimental results show that the designed generator can output a DC voltage of about 24V (taking into account the input error) within the temperature difference of 50 ~ 60 °C. The output power test results of the generator unit with different temperature difference are shown in Figure 4.

![Figure 3 Performance curve of self-made thermoelectric generator monomer.](image)
2.2 Conversion efficiency of thermoelectric generator monomer.

The temperature of hot end $T_h$ and cold end $T_c$ were measured respectively. Respectively Unit conversion efficiency $\eta$ of thermoelectric generator monomer is defined as:

$$\eta = \frac{P_{ou}}{Q} = \frac{P_{ou}}{c m (T_h - T_c)}$$

(1)

In the above formula: $Q$ is the heat transferred to the thermoelectric generator monomer in unit time, $c$ is the specific heat capacity of water, kJ/ (kg °C); $m$ is the mass of water, kg.)

Figure 5 shows the relationship between generator conversion efficiency and temperature difference. It can be seen from the figure: the greater the temperature difference, the higher the efficiency of the battery.

2.3 Calculation of discharge capacity of LNG Cold Energy Generation

LNG is a low temperature mixture, and more than 96% of the composition is methane. The boiling point of LNG is about -157 °C ~ -163 °C at atmospheric pressure, and the boiling point of liquid methane is -162 °C. For the convenience of calculation, LNG is regarded as pure liquid methane. The specific heat capacity of methane fluctuates from 110K to 300K, and the mean $c_p$ is 2.20kJ / kg. The heating and gasification process of LNG can be divided into two parts: latent heat of phase transition from liquid to gas and sensible heat from boiling point to ambient temperature. LNG heat that transfer to 5 °C can be input to the gas network, the release of cold is:

$$Q = r \int_{T_i}^{T_o} c_p dT = r + c_p (T_o - T_s)$$

(2)

The main component of liquefied natural gas (LNG) is methane, and its basic properties are similar. Therefore, the physical properties of pure methane are used. The working pressure of liquefied natural gas gasification at small LNG gasification station is about 0.6Mpa. The latent heat of phase transition is 444 kJ/kg. LNG has a boiling point of 111K at normal pressure, and LNG can be fed into the gas pipe network by heat exchange to 5 °C. Calculated according to the constant pressure process, the maximum amount of cold contained in the theoretical theory of LNG is obtained:

$$Q = r + c_p (T_o - T_s) = 444.00 + (278 - 111) = 811.4 \text{ kJ/kg}$$

If the cold energy owned by LNG is completely converted into electricity, the conversion of LNG per ton of cold energy can be about 225.4 kWh.
3. Design of LNG Cold Energy Power Station in Zhoushan

At present, the self-sufficiency rate of primary energy in the new area of Zhoushan Islands is almost zero. From the perspective of energy consumption structure, due to natural environmental conditions, industry, industrial structure and other factors, Zhoushan is mainly focused on three major conventional energy sources: oil, coal and electricity. These three accounted for more than 90% of the city's total energy consumption. With the construction and development of the new area of Zhoushan Islands, energy consumption will increase accordingly. The primary energy consumption structure based on oil and coal cannot meet the national environmental protection emission reduction requirements. Finding clean and efficient alternative energy sources to improve energy structure is an urgent problem to be solved. Using clean and efficient natural gas, replacing fuel oil used in transportation industry with LNG and replacing coal-fired power plants with LNG power plants will be an inevitable trend in the development of the new area of Zhoushan Islands. LNG liquefaction will generate a lot of cold energy, and this part of the cold energy can not be reasonably fully utilized. For this reason, we design a power station with thermoelectric generators as the main way of using cold energy.

According to the "Statistical Communiqué of 2017 National Economic and Social Development of Zhoushan ", the total gas supply of natural gas in Zhoushan in 2017 was 38.6 million cubic meters. The total amount of natural gas supplied by Zhoushan from 2009 to 2017 is shown in the table below. It can be seen that the annual gas supply of Zhoushan is increasing year by year.

3.1 Output power, conversion efficiency of single thermoelectric generator

The output power of single thermoelectric generator increases with the increase of the temperature difference, which satisfies a quadratic increasing relation. The output power of the generator can reach 3520W when the temperature difference is 167 ℃.

According to the conversion efficiency and temperature difference of single thermoelectric generator, the conversion efficiency of the generator reaches 18.9% when the temperature difference is 167 ℃.

3.2 Calculation of the number of thermoelectric generators and the quantity of electricity generated

Taking the annual natural gas demand of Zhoushan as an example, it is assumed that the natural gas in Zhoushan is all gasified by LNG. In order to meet the total natural gas supply of Zhoushan, the annual LNG volume is 386.39 cubic meters. The mass flow rate of the thermoelectric generator pack into the LNG is 3159.38kg/h, and the LNG release cooling capacity is: $6.256 \times 10^4 \text{kJ/h}$.

The mass flow rate of the LNG through the thermoelectric generator is as follows: $q_m = \rho \cdot A \nu = 0.04 \text{kg/s}$, The cooling capacity required for the thermoelectric generator is:

$$q_0 = c_p q_m (T_o - T_s) = 5.29 \times 10^4 \text{kJ/h} \tag{3}$$

The number of thermoelectric generators required can be calculated:

$$n = \frac{Q}{q_0} = 49 \tag{4}$$

3.3 Design of series and parallel connection of the thermoelectric generator pack

We have designed a scheme of thermoelectric device, as shown in figure 6.
Figure 6 shows the distribution of thermoelectric generators, up and down the distribution of 7 thermoelectric generators. Seven thermoelectric generators are distributed at the same height, and the total voltage of the circuit is 96V and the total current of the circuit is 196A. Finally, the DC is converted to 220V AC for daily power supply by 96V inverter. It is estimated that the total area of the temperature difference battery pack is 5 square meters.

3.4 Economic benefit Prediction of LNG Cold Energy Power Station

If the conversion efficiency of the generator is calculated by 18.9% when the temperature difference is 167°C, the quantity of LNG cooling released per hour can be converted as follows: 4.85×10^5 KJ/h. If the cooling rate released by LNG from -167 °C to 5 °C is completely converted into electric power, the LNG cooling rate released per hour can be converted to about 134.58 kilowatt-hours (kWh), and the annual generating capacity of the thermoelectric generator pack is 1.18×10^6 kWh.

The cost of a thermoelectric generator is 20,000 RMB, thus the cost of 49 cells is 980000 RMB, and the power generation of 49 thermoelectric generators is about 1.18 million kWh (degrees). Assuming that the life of the thermoelectric generator is ten years. Based on the electricity price of 0.6 RMB per degree, the thermoelectric generator can be saved about 7.08 million RMB, which is 7 times of the cost price of the thermoelectric generator. It shows a good economic benefit.

The energy standard adopted in China is standard coal equivalent. For every one degree of electricity saved, the 1kg kilo CO₂ emission is reduced. The annual node benefit of thermoelectric generator is 1.18 million kilowatt-hours (degree), which is equivalent to saving 472 tons of standard coal per year and reducing 1176 tons of CO₂ emission. At the same time, the emission of LNG cold energy without utilization will inevitably result in severe equipment frost in the station area, the production environment is in a low temperature, and there is a situation of frosty fog, which will bring harm to the production and operation. Besides, there are security risks in the surrounding enterprises around the station area and public facilities.

4. Conclusions

(1) A thermoelectric generator monomer is designed, which has the advantages of simple power generation structure, easy installation, no vibration, no noise, long life and environmental protection.

(2) The designed LNG thermoelectric device has good economic benefit, which is 7 times the cost of the thermoelectric generator, and has good environmental protection benefit. It shows that the utilization of LNG cold energy by thermoelectric generator has great environmental benefit and ecological benefit.

Acknowledgments

This work was supported by the National Major Projects of China under grant No. 2017ZX05072005 and the National Science Foundation of China under grant No.11472246.
References

[1] Gao Y, Hou Z Z (2017) Research on the current situation of LNG Cold Energy Generation Technology. Shandong Chemical Industry, 14: 88–89.

[2] Luo P, Xiong Y Q, Zhao Z X, Li Y J(2016) Integration of cold energy utilization of LNG with low temperature air separation. Cryogenics, 01: 47–53.

[3] Liang G C, Pu C, Li J, long Y J(2013) Air Separation Process by Usage of LNG Cold Energy and Its Performance, Natural Gas and Oil, 31:28–30

[4] Yang C(2014) Research and Application of Integrated Technology of LNG Cold Energy Utilization in Cold Storage and Cold Water, South China University of Technology, Guangzhou.

[5] Wu J Y, Ma Y M, Chen S Q(2009) LNG cold energy used in cold storage system design and analysis, Journal of Jimei university, 15:44–47

[6] Zhang H M(2010) Study on the Cold Energy of Liquefied Natural Gas in Cryogenic Pulverization of Waste Tyre, Lanzhou University of Technology, Lanzhou.

[7] Huang M B, Lin W S, He H M, Gu A Z(2009) LNG cold energy used in CO2 transcritical Rankine cycle and CO2 liquefaction recovery, Cryogenics and Superconductivity, 04:17–21

[8] He L, Gao W, Zhang L, Yu L, Zhang X R, Liu Y, Wang S R(2015) LNG Cold Energy Cascade Utilization Technology combined with Power Generation and seawater Desalination, Chemical Industry, 33:11–15

[9] Yao Y X(2014) Experimental Study on Desalination of Seawater Based on LNG Cold Energy, Beijing Construction University, Beijing.

[10] Chen L Q, Xu P L, Sun L, Dong W H, Ma K(2013) Analysis of LNG Cold Energy Power Generation Technology, Natural Gas and Oil, 31:39–44

[11] Wang S(2014) Study on Cold Energy recovery of small LNG Gasification Station for Air conditioning system in Station, Huazhong University of Science and Technology, Wuhan.