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COMPARISON OF BOG TREATMENT TECHNOLOGY IN LNG STATION WITHOUT LNG OUTPUT

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ABSTRACT

In order to select economical and reasonable Boil-off gas (BOG) treatment technology for different types of liquefied natural gas (LNG) stations, this paper introduces the related technologies of BOG treatment without LNG Output. Using the same working fluid and operating parameters to simulate then the six technologies of pulse tube cryocooler recovery, liquid nitrogen recovery, nitrogen expansion recovery, jet refrigeration recovery, mixed refrigerant refrigeration recovery, and direct compression process were compared in terms of power consumption, economy. On the basis of comparative analysis of power consumption, the actual usage of the above process, and with the payback period as the criterion, the BOG treatment technology suitable for different types of LNG stations is obtained. It provides a reference for different types of LNG stations to select appropriate BOG recovery technology, handles the unsolved problem about selecting BOG treatment technology, and puts forward a prospect for the development of BOG treatment technology.

Key words: *LNG station; Boil-off gas; Treatment technology; Comparative study*

1. INTRODUCTION

With the development of social economy, the problem of energy shortage and environmental pollution is increasingly prominent, and the use of clean energy has become the theme of energy consumption in contemporary society. Natural gas has become the first choice for energy consumption in most countries due to its advantages such as high calorific value, low pollution, small volume after liquefaction, easy storage and convenient transportation (Kumar *et al*., 2011). LNG stations (which can be divided into small LNG stations, medium LNG stations and large LNG stations according to LNG reserves) store LNG in tanks with good thermal insulation, but still generate BOG (Lee *et al*., 2015). The generation of BOG will increase the working pressure of the station equipment, and make the equipment overpressure work, which will cause greater safety hazards.

Therefore, BOG treatment becomes a key issue for the safe operation of LNG stations (Kurle *et al*., 2016). And the influence of the gas to the greenhouse effect, CH_4 is second only to the CO_2 greenhouse gases, which GWP (global warming potential) is 21 times of CO_2 (United Nations Framewprk Convention on Climate Change, 1998). Therefore, in non-emergency situations, the working pressure of LNG station equipment is reduced by directly discharging BOG will not only cause BOG energy consumption waste and economic damage, but also aggravate the greenhouse effect (Hyeonwon *et al*., 2016). Consequently, the recovery of BOG can solve all kinds of problems caused by BOG to the greatest extent.

In view of the influencing factors of BOG, to improve the thermal insulation performance of the tank focused on controlling the operation pressure of storage tank was proposed. And optimizing the storage tank structure and filling the storage tank with nitrogen was proposed (Hasan *et al*., 2009; Li *et al*., 2012; Gorla *et al*., 2010; Wang *et al*., 2010). and other methods, which be used to reduce the amount of BOG production. But, the generation of BOG has not been eliminated, some treatment technology was still needed to achieve the full recycling of BOG. Thus, researchers have proposed BOG treatment basic technology in the case of 6 kinds of LNG without external transmission, which includes six processes: pulse tube cryocooler recovery (Zhu *et al*., 2015; Hu *et al*., 2016), liquid nitrogen recovery (Herrera *et al*., 2017), nitrogen expansion recovery (Chen et al., 2014), jet refrigeration recovery (Kasperski *et al*., 2014; Smierciew *et al*., 2014), mixed refrigerant refrigeration recovery (Shirazi *et al*., 2010), and direct compression process.

In order to improve the recycling amount of BOG and reduce energy consumption, the following improvements are proposed based on the above basic processes. Such as nitrogen two-stage expansion refrigeration (Tan *et al*., 2006) and nitrogen three-stage expansion refrigeration (Pozivil *et al*., 2003); it was proposed to use expanded high-pressure natural gas to drive compressor (Xue *et al*., 2016; Shin *et al*., 2007); Compressor optimization operation model based on BOG production rate was developed (Shin *et al*, 2008); real-time control of compressor operation; pressurizing and odorizing BOG, and other processes to supply domestic gas in the station or to supply factories with relatively close distances as fuel for production work (Liao *et al*., 2016; Liu, *et al*., 2010; Kurle *et al*, 2015) and so on. For different types of LNG stations, how to choose the appropriate BOG recycling technology is a problem.

At present, scholars have made some technical comparisons in terms of power consumption and economy. The recovery of pulse tube cryocooler with liquid nitrogen recovery from economic perspective was compared (Wang *et al*., 2017). The nitrogen expansion recovery, mixed refrigerant refrigeration recovery and jet liquefaction recovery from the power consumption of the equipment were quantitatively analyzed (Qiu *et al*., 2017). The nitrogen expansion recovery, mixed

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refrigerant refrigeration recovery and jet liquefaction recovery from the power consumption of the equipment were quantitatively analyzed (Lu *et al*., 2016). And some data was selected to calculate the equipment energy consumption for the direct compression process (Liu *et al*., 2016).

However, due to the different BOG working fluids and operating parameters adopted by different researchers, it is impossible to use the relevant literatures to compare the above six technologies in general, and provide appropriate reference for selecting BOG recovery for LNG stations. Therefore, this paper uses the same working fluid and operating parameters, starting from the equipment energy consumption, economy, and actual usage of the above process, the above-mentioned BOG treatment basic technology is uniformly simulated and compared, and finally provides guides for different types of LNG stations to select BOG treatment technology.

2. BASIC PARAMETERS

In order to compare the different processes, BOG composition, process parameters, BOG production of LNG station, and heat transfer medium and main equipment are shown in Table 1-4.

3. COMPARATIVE ANALYSIS

It is assumed that under ideal conditions, there is no energy loss in the piping and equipment in each process. That is, the supplied cooling capacity is completely liquefied by BOG absorption. From the steady-state open system energy equation, the BOG liquefaction equation is simplified, as in Equation 1.

$$Q = m_{\text{BOG}} \times \Delta H_{\text{BOG}} = P \times 3600 = m \times \Delta H \qquad (1)$$

The above formula can be used to calculate the pulse tube cryocooler (110K) recovery and liquid nitrogen refrigeration recovery. At the same time, the remaining four processes are simulated using the Peng-Robinson equation of ASPEN HYSYS. Taking the complete treatment of BOG by each technology as an index, the above six BOG treatment technologies are studied by using the relevant parameters of Table 1-3.

3.1 Power Consumption Comparison

The BOG is recovered by liquid nitrogen. If properly installed, can use height difference to realize liquid arcing, no need to add energy consumption equipment. Therefore, the above data are selected in this section to compare the power consumption of other five BOG processing technologies, as shown in Figure 1.

Fig. 1 (a) is a power consumption comparison of BOG treatment technology in small LNG station. It can be seen that under the condition of low BOG production, the lowest power consumption is the direct compression process, followed by the pulse tube cryocooler recovery. The largest power consumption is the nitrogen expansion recovery. Moreover, the power consumption of nitrogen expansion and jet refrigeration recovery, the power consumption of cryogenic refrigerator recovery and direct compression process is almost equal.

Fig. 1 (b) is a comparison of the power consumption of BOG processing technology for large and medium-sized LNG stations. The smallest power consumption is the direct compression process, and the largest is the nitrogen expansion recovery. The BOG production is in the range of 1000~5000kg/h. Nitrogen expansion recovery is almost the same as the power consumption of jet refrigeration recovery. Nitrogen expansion, jet refrigeration and mixed refrigerant recovery have much higher power consumption than the pulse tube cryocooler recovery and direct compression process under the same BOG production conditions. This is mainly due to the complicated process of the first three processes and the more energy-consuming equipment. And we can see that the power consumption of the above BOG processing technology increases with the increase of BOG production.

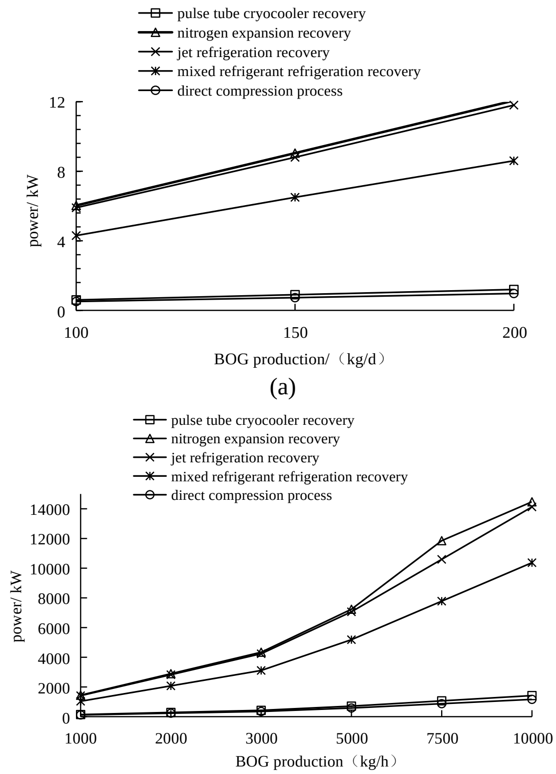


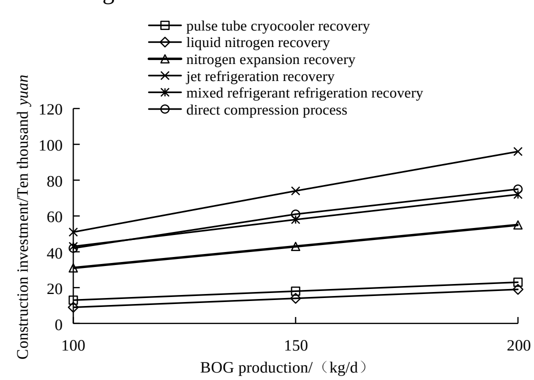
Fig. 1 Power Consumption Comparison of BOG Processing Technology in LNG Station

3.2 Economic comparison

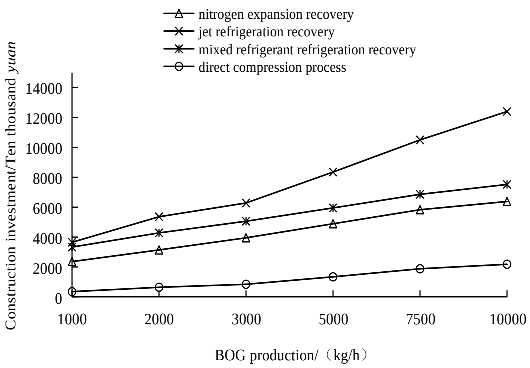
In liquid nitrogen recovery, the price of liquid nitrogen as the heat transfer medium is calculated at 700 *yuan*/ton. The heat transfer medium and circulating water in the other processes have a little loss during the recovery process, the rest can be recycled (Qiu *et al*., 2017), and these are much cheaper than the investment in equipment is relatively low, so the cost of heat transfer medium and circulating water is not considered in the construction investment estimate.

In view of the fact that there are no pulse tube cryocooler and liquid nitrogen tanks that can meet the BOG recovery of large and medium-sized LNG stations, there is no economic comparison between pulse tube cryocooler recovery and liquid nitrogen recovery for large and medium-sized LNG stations. Finally, the construction investment estimate is based on the existing construction costs in different literatures and the way of equipment inquiry, as shown in Figure 2.

Fig. 2 (a) shows the comparison of investment in BOG treatment technology construction of small LNG stations, while Fig. 2 (b) shows the comparison of investment in BOG treatment technology construction of large and medium-sized LNG stations.



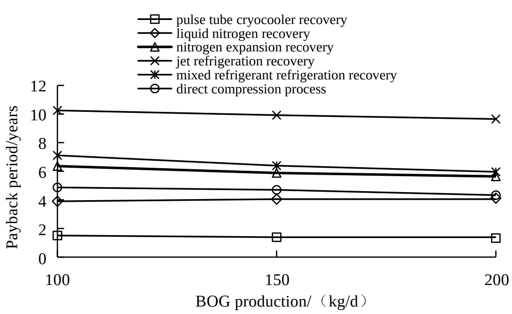
(a)



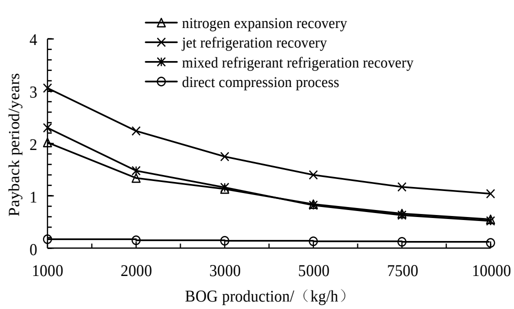
(b)

Fig. 2 Investment comparison of BOG treatment technology construction in LNG station

Assuming that the annual operation days of LNG station are 300 days, industrial power consumption is 0.95 *yuan*/degree and liquefied natural gas price is 3000 *yuan*/ton. The BOG gain can be recovered annually. According to the data in Fig. 1, the electricity charges for each recovery technology during the one-year operation of LNG station can be calculated. The annual profit of each technology is subtracted from the annual operating cost of each technology (electricity fee, liquid nitrogen cost during operation), and the investment payback period is obtained by dividing the construction investment by the annual profit, as shown in Figure 3.



(a)



(b)

Fig. 3 Comparison of payback period of BOG treatment technology at LNG station

Fig. 3 (a) is a comparison chart of the investment payback period of BOG treatment technology investment in small LNG stations. It can be seen that the shortest payback period is pulse tube cryocooler and the longest is jet refrigeration recovery when the BOG production is equal. In addition, the investment payback period of liquid nitrogen recovery technology has a tendency to rise slowly, mainly because the liquid nitrogen recovery cost is too high. According to formula (1), it takes about 3.2 kg of liquid nitrogen to liquefy 1 kg of BOG, and the cost is about 2.23 yuan. As a result, the investment payback period of the technology has increased, and the recovery period of other BOG processing technologies has been slowly decreasing.

Fig. 3 (b) is a comparison of the payback period of BOG treatment technology in large and medium LNG stations. It can be concluded that under the condition of equal BOG production, the payback period of direct compression process is the shortest and that of jet refrigeration is the longest. Under the condition that the BOG production is about 4000kg/h, the investment payback period of nitrogen expansion and mixed refrigerant refrigeration recovery is equal. Under the condition of 4000~5000kg/h, nitrogen expansion and mixed refrigerant refrigeration recovery The investment recovery period is almost equal. When the value is more than 5000kg/h, the investment recovery period of the nitrogen expansion process is slightly higher than that of the mixed refrigerant refrigeration.

When LNG station chooses BOG recovery technology, it should not only consider the factors such as equipment power consumption and investment recovery period, but also choose the recovery technology according to the actual situation. The limitations of BOG recycling technology for small LNG stations are mainly concentrated in the following two aspects: (1) equipment needs to occupy a large area of the site; (2) there is compressor noise, and noise reduction is required. Small LNG stations are mostly located in urban areas, and the land price is expensive. Therefore, we can basically conclude that liquid nitrogen recovery, nitrogen expansion recovery, jet refrigeration recovery, mixed refrigerant recovery and direct compression processes are not suitable for small LNG stations. For large and medium LNG stations, pulse tube cryocooler and liquid nitrogen recovery are not suitable for large and medium LNG stations because of the excessive production of BOG, and the existing technology can not meet the processing requirements.

4. CONCLUSION

Through combing and analyzing the above technologies, we realize that for the purpose of improving recovery efficiency and reducing energy consumption, the development of BOG recovery technology in LNG station has the following trends: (1) Step-by-step optimization of individual technologies to meet the needs of BOG processing of LNG stations and make it more large-scale, complex and intelligent; (2) Process combinations between individual technologies to play various technologies Advantages, such as the combination of BOG liquefaction and directly pressurized outflow in jet refrigeration recovery; (3) Systematic optimization of equipment energy consumption by mathematical model (4) Develop new technologies to make up for the shortcomings of previous technologies.

In addition, on the basis of comparative analysis of power consumption, economy, actual usage, and taking the payback period as the criterion, the conclusions are as follows.

For small LNG stations, it is more economical to choose pulse tube cryocooler to recover BOG. For large and medium-sized LNG stations, when connecting to the external pipeline network, it is more economical to choose direct compression process. If without the external pipeline network, when the amount of BOG generated is less than 4000kg/h, it is economical to choose nitrogen expansion recovery. Otherwise, it is economical to choose mixed refrigerant refrigeration recovery.

Table 1 Molar fraction of BOG components (%)

medium	C_1	C_2	C_3	i-C_4	n-C_4	N_2
BOG	96.46	0.01	0	0	0	3.53

Table 2 Basic parameters of each process

project	basic parameters
BOG pressure (MPa)	0.2
BOG temperature (℃)	-153
Enthalpy difference of BOG before and after liquefaction at 110K (kJ/kg)	511.2
Liquid nitrogen temperature (℃)	-172.7
Liquid nitrogen tank pressure (MPa)	0.8
Latent heat of saturated liquid at 0.8MPa (kJ/kg)	160.4
Direct compression process outlet LNG product pressure (MPa)	6.5
The remaining process exports LNG product pressure (MPa)	0.3

Table 3 BOG production by different types of LNG stations

project	Small LNG station （kg/d）			Medium LNG station (kg/h)			Larger LNG station (kg/h)		
BOG production	100	150	200	1000	2000	3000	5000	7500	10000

Table 4 Main equipment and heat transfer medium of each process

Recycling technology	main equipment	heat transfer medium
pulse tube cryocooler recovery	Cryogenic refrigerator	/
liquid nitrogen recovery	Liquid Nitrogen Tank, Heat Exchanger	liquid nitrogen
nitrogen expansion recovery	Compressor, cooler, expander, heat exchanger	nitrogen
jet refrigeration recovery	Ejector, compressor, heat exchanger	/
mixed refrigerant refrigeration recovery	Compressor, Cooler, Separator, Heat Exchanger	mixed refrigerant
direct compression process	Compressor	/

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NOMENCLATURE

Q The cold amount absorbed by BOG per hour, kJ/h;

m_{BOG} BOG mass flow，kg/h;

ΔH_{BOG} Enthalpy difference before and after liquefaction of BOG per unit mass，kJ/kg;

P Pulse tube cryocooler power，kW;

m Mass flow of liquid nitrogen，kg/h;

ΔH Latent heat of vaporization of liquid nitrogen per unit mass，kJ/kg.

REFERENCES

Kumar S, Kwon H T, Choi K H, Lim W, Cho J. H, Tak K. 2011, “LNG: An Eco-Friendly Cryogenic Fuel for Sustainable Development,” *Applied Energy*, **88(12)**: 4264-4273. https://doi.org/10.1016/j.apenergy.2011.06.035

Lee S, Jeon J, Lee U. 2015, “A Novel Dynamic Modeling Methodology for Boil-Off Gas Re-condensers in Liquefied Natural Gas Terminals,” *Journal of Chemical Engineering of Japan*, **48(10)**: 841-847. https://doi.org/10.1252/jcej.14we201

Kurle Y M, Wang S, Xu Q. 2016, “Dynamic Simulation of LNG Loading, BOG Generation, and BOG Recovery at LNG Exporting Terminals,” *Computers & Chemical Engineering*, **97**: 47-58. https://doi.org/10.1016/j.compchemeng.2016.11.006

United Nations Framewprk Convention on Climate Change (Organization). 1998, “Kyoto Protocol to the United Nations Framework Convention on Climate Change,” *Review of European Community & International Environmental Law*, **7(2)**: 214-217. https://doi.org/ 10.1111/1467-9388.00150

Hyeonwon J, Jaewoo S W. 2017, “Calculation of Boil-Off Gas (BOG) Generation of KC-1 Membrane LNG Tank with High Density Rigid Polyurethane Foam by Numerical Analysis,” *Polish Maritime Research*, **24(1)**: 100-114. https://doi.org/ 10.1515/pomr-2017-0012

Hasan M M F, Zheng A M, Karimi I A. 2009, “Minimizing Boil-Off Losses in Liquefied Natural Gas Transportation” *Industrial & Engineering Chemistry Research*, **48(21)**: 9571-9580. https://doi.org/ 10.1021/ie801975q

Li Y J, Xia Y. 2012, “Influencing Factors and Stability of BOG Generation in LNG Receiving Terminal, *Cryogenics*,” **4**: 38-43. doi:10.3969/j.issn.1000-6516.2012.04.008

Gorla R S R. 2010, “Probabilistic Analysis of a Liquefied Natural Gas Storage Tank, ”*Applied Thermal Engineering*, **30(17)**: 2763-2769. https://doi.org/ 10.1016/j.applthermaleng.2010.07.033

Wang W C, Li Y X, Sun F F. 2010, “Controlling Factors of Internal Pressure and Evaporation Rate in a Huge LNG storage Tank,” *Natural Gas Industry*, **30(7)**: 87-92. doi:10.3787/j.issn.1000-0976.2010.07.024

Zhu T J, Zhang H, Ju Y L, Yang C. Ruan W, Hu J. 2015, “Small Scale BOG Re-Liquefaction System in Skid-Mounted in LNG Filling Station,” *Journal of Chemical Industry and Engineering (China)*, **66(s2)**: 325-331. doi:10.11949/j.issn.0438-1157.20151057

Hu J Y, Chen S, Zhu J, Zhang L. M, Li H. B. 2016, “An Efficient Pulse Tube Cryocooler for Boil-Off Gas Re-liquefaction in Liquid Natural Gas Tanks,” *Applied Energy*, **164**: 1012-1018. https://doi.org/ doi:10.1016/j.apenergy.2015.03.096

Herrera O, Sharafian A, Talebian H, Blomerus P. 2017, "A Review of Liquefied Natural Gas Refueling Station Designs," *Renewable & Sustainable Energy Reviews*, **69**: 503-513.
https://doi.org/ doi:10.1016/j.rser.2016.11.186

Chen M, Xu W D, Duan J, Liu Z. B. 2013, "A New Recovery Process of BOG (boil-off-gas) Using Low-Temperature Nitrogen," *International Conference on Materials for Renewable Energy and Environment. IEEE*, 788-791.
https://doi.org/ 10.1109/ICMREE.2013.6893792

Kasperski J, Gil B. 2014, "Performance Estimation of Ejector Cycles Using Heavier Hydrocarbon Refrigerants," *Applied Thermal Engineering*, **71(1)**: 197-203.
https://doi.org/ 10.1016/j.applthermaleng.2014.06.057

Śmierciew K, Gagan J, Butrymowicz D. 2014, "Experimental Investigations of Solar Driven Ejector Air-Conditioning System," *Energy & Buildings*, **80**: 260-267.
https://doi.org/ 10.1016/j.applthermaleng.2014.06.057

Shirazi M M H, Mowla D. 2010, "Energy Optimization for Liquefaction Process of Natural Gas in Peak Shaving Plant," *Energy*, **35(7)**: 2878-2885.
https://doi.org/ 10.1016/j.energy.2010.03.018

Tan J Y, Wang L, Li S Y. 2006, "Optimization of Natural Gas Liquefaction in the Nitrogen Two-Expanders Cycle," *Journal of Harbin Institute of Technology*, **38(3)**: 370-373.
doi:10.3321/j.issn:0367-6234.2006.03.012

Pozivil J. "Apparatus for Re-liquefying Compressed Vapor: US," US6530241, 2003.

Xue Q, Liu M R, Xiao W T, Wang X L, Zhang J J. 2015, "Optimization and Energy Consumption Analysis of BOG Treatment Processes in LNG Terminal," *Oil & Gas Storage and Transportation (China)*, **35(4)**: 376-380.
doi:10.6047/j.issn.1000-8241.2016.04.005

Shin M W, Shin D, Choi S H. Yoon E. S, Han C. 2007, "Optimization of the Operation of Boil-Off Gas Compressors at a Liquefied Natural Gas Gasification Plant," *Industrial & Engineering Chemistry Research*, **46(20)**: 6540-6545.
https://doi.org/ doi:10.1021/ie061264i

Shin M W, Shin D, Choi S H, Yoon E. S, Han C. 2008, "Optimal Operation of the Boil-Off Gas Compression Process Using a Boil-Off Rate Model for LNG Storage Tanks," *Korean Journal of Chemical Engineering*, **25(1)**: 7-12.
https://doi.org/ 10.1007/s11814-008-0002-9

Liao X M, Zhang Y, Wu T. 2016, "Discussion on the Feasibility of Using BOG for Life in a LNG Filling Station," *Chemical Engineering of Oil and Gas*, **45(5)**: 43-45.
doi: 10.3969/j.issn.1007-3426.2016.05.010

Liu C W, Zhang J, Xu Q, Gossage J L. Thermodynamic-Analysis-Based Design and Operation for Boil-Off Gas Flare Minimization at LNG Receiving Terminals. *Industrial & Engineering Chemistry Research*, **49(16)**:7412-7420.
doi. 10.1021/ie1008426

Kurle Y M, Wang S, Xu Q. 2015, "Simulation Study on Boil-Off Gas Minimization and Recovery Strategies at LNG Exporting Terminals," *Applied Energy*, **156(1)**: 628-641.
https://doi.org/ 10.1016/j.apenergy.2015.07.055

Wang K, Ju Y L. 2017, "Comparison Analysis between the BOG Re - Liquefied Methods of LNG Storage and Transportation Equipment," *Cryogenics and Superconductivity*, **9(3)**: 22-25.
doi:：10.16711/j.1001-7100.2017.09.005

Qiu D P. 2017, "Research of BOG Comprehensive Treatment Methods for LNG Terminal," *Natural Gas Chemical Industry*, **42(5)**: 99-103.
doi:10.3969/j.issn.1001-9219.2017.05.019

Lu X B. 2017, "Comparison and Selection of BOG Recovery Processes," *Natural Gas Chemical Industry*, **42(1)**: 93-97.
doi:10.3969/j.issn.1001-9219.2017.01.023

Liu H, Jin G Q. 2006, "Process Comparison and Energy Saving Analysis of BOG Gas Treatment of LNG Receiving Terminal," *Chemical Engineering Design*, **16(1)**: 13-16.
doi:10.3969/j.issn.1007-6247.2006.01.003