

Thermodynamic Analysis on of Skid-Mounted Coal-bed Methane Liquefaction Device using Cryogenic Turbo-Expander

Shuangtao Chen^{1,*}, Lu Niu¹, Qiang Zeng², Xiaojiang Li², Fang Lou², Liang Chen¹, Yu Hou¹

¹ State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

² Xinjiang Coal Research Institute, Urumqi 830091, PR China

* Corresponding author, Email: stchen.xjtu@xjtu.edu.cn

Abstract. Coal-bed methane (CBM) reserves are rich in Sinkiang of China, and liquefaction is a critical step for the CBM exploration and utilization. Different from other CBM gas fields in China, CBM distribution in Sinkiang is widespread but scattered, and the pressure, flow-rate and nitrogen content of CBM feed vary significantly. The skid-mounted liquefaction device is suggested as an efficient and economical way to recover methane. Turbo-expander is one of the most important parts which generates the cooling capacity for the cryogenic liquefaction system. Using turbo-expander, more cooling capacity and higher liquefied fraction can be achieved. In this study, skid-mounted CBM liquefaction processes based on Claude cycle are established. Cryogenic turbo-expander with high expansion ratio is employed to improve the efficiency of CBM liquefaction process. The unit power consumption per liquefaction mole flow-rate for CBM feed gas is used as the object function for process optimization, compressor discharge pressure, flow ratio of feed gas to turbo-expander and nitrogen mole fraction are analyzed, and optimum operation range of the liquefaction processes are obtained.

1. Introduction

Coal-bed methane (CBM) is a valuable energy resource around the world, and estimated CBM reserves globally is $99\sim 212\times 10^{12}\text{N}\cdot\text{m}^3$. China who has the third CBM reserves in the world does not recover CBM sufficiently and the recovery rate is less than 40%, and emission of CBM can lead to environmental problems. Liquefaction of CBM is an efficiency way to utilize energy and conserve environment ^[1-2]. In Sinkiang of China, the CBM reserve is rich but the CBM distribution is widespread and scattered, which causes the pressure, flow-rate and nitrogen content of CBM feed oscillate significantly. Due to the CBM feed gas feature in China, the skid-mounted liquefaction device is suggested as the most efficient and economical way to recover the CBM.

LNG liquefaction process provides a good example for recovery of CBM ^[3], but CBM has its own liquefaction characteristic. In the CBM, the content in feed gas always contains a large mole fraction of nitrogen, as a result, the pre-treatment will has a nitrogen removal or distillation before or after liquefaction process ^[4-6]. But for the compact feature of skid-mounted device, such pre-treatment equipment will make the process complicated. So in this paper, nitrogen mole fraction in feed gas is a



key factor focused to evaluate the system performance. Claude cycle is modified to construct the skid-mounted CBM liquefaction process. Nitrogen expansion and propane pre-cooling cycle is used in many processes for providing cooling capacity in CBM liquefaction process as usual ^[7-11]. In this paper, a stream from the main feed gas is divided to undergo isentropic expansion through turbine, which aims to reduce the size and complication of our liquefaction process.

2. Process simulation

Software HYSYS is used to simulate the CBM liquefaction process, on the base of basic setting, optimization of feed gas compressed pressure, flow ratio from the compressed main stream and nitrogen mole fraction are researched.

2.1. Basic assumptions and input parameter

A steady-state simulation by using Aspen HYSYS V8.0 is applied to estimate the CBM liquefaction process performance, Peng-Robinson thermodynamic equation is selected to calculate thermodynamic properties of working fluids in the simulation. The following assumptions are set in the process simulation:

- Heat leak and pressure drop in heat exchanger are neglected;
- Isentropic efficiencies of compressor and turbo-expander are kept as 75%;
- Potential and kinetic energy is neglected, all flows and heat transfers are steady state.

Basic parameter including CBM mole components, feed gas temperature and pressure, LNG product pressure, turbo-expander outlet pressure are shown in Table 1. In these liquefaction process simulation, feed gas is assumed that has been purified and only nitrogen and methane components are left.

Table 1. Basic parameter of CBM liquefaction process simulation

Parameters	Value
Methane mole fraction in feed gas (%)	80
Nitrogen mole fraction in feed gas (%)	20
Feed gas mole flow-rate (kmol·h ⁻¹)	1
Feed gas temperature (K)	303
Feed gas pressure (kPa)	100
LNG storage pressure (kPa)	120
Side stream turbo-expander (T-101) outlet pressure (kPa)	120
Compressor water cooler outlet temperature (K)	303
Compressor isentropic efficiency (%)	75
Turbo-expander isentropic efficiency (%)	75

2.2. CBM liquefaction process

The liquefaction process is fabricated by using HYSYS as shown in Fig.1. To meet the need of small scale skid-mounted liquefaction system, a modified Claude cycle is used for constructing the liquefaction process. The pre-treatment for CBM feed gas is neglected in process simulation, the components of feed gas are only nitrogen and methane without water, acidic gases and heavy hydrocarbon.

The feed gas is firstly compressed by two stage compressor, C-100 and C-101, with intermediate water cooler E-100, the compressed feed gas is divided into two streams after it is cooled in cooler E-101 to ambient temperature. One stream is main stream for liquefaction, and another stream is side stream flowing into two-stage turbo-expander system to provide a part of cooling energy in heat exchanger HX-100. For main stream, it undergoes pre-cooling process in heat exchanger HX-100 and then continues to lower its temperature in HX-101 with vapor component from separator V-100 and goes through the J-T valve. In the separator, product LNG and vapor is divided, the later one is reflow through HX-101 and HX-100 in sequence to remove the heat of high temperature main stream.

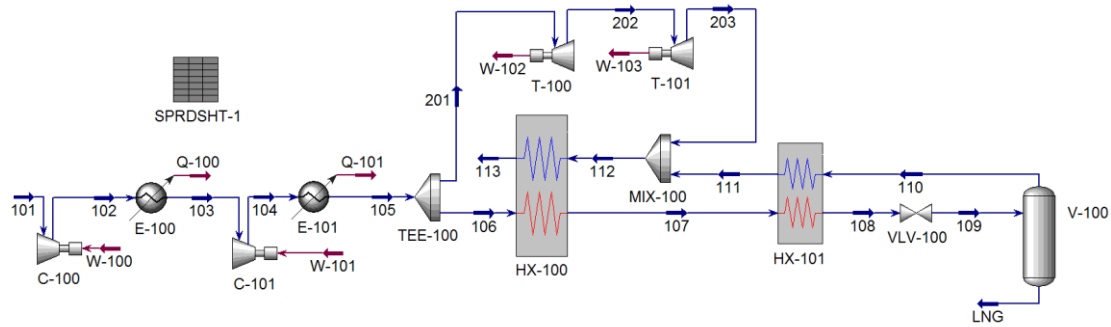


Fig 1. Skid-mounted CBM liquefaction process based on Claude cycle.

2.3. Process performance estimation method

In this CBM liquefaction process, the liquefaction rate y and specific power consumption w are effected by the compressed pressure P_{104} , flow ratio V_s in splitter TEE-100 and nitrogen mole fraction in feed gas significantly, so interaction of these parameters are studied and optimized in this paper. And specific power consumption is used to estimate the process performance, and it is expressed as follow:

$$w = \frac{W_{com} - W_{turbo}}{q_{LNG}} \quad (1)$$

In the equation, W_{com} and W_{turbo} represent power consumption of the two-stage compressor and the power can be produced by all two turbo-expanders respectively, and q_{LNG} represents volume flow-rate of LNG product. In the liquefaction process simulation, the compressed pressure P_{104} variation range is from 1000kPa to 8000kPa, and the flow ratio V_s variation range is from 0.1 to 0.8.

3. Results and discuss

Liquefaction rate, specific power consumption and methane mole fraction in feed gas are applied to evaluate CBM process performance, among the process parameter, compressor discharge pressure, divided flow ratio and nitrogen mole fraction are the key factors to effect process performance. As a result, the optimal simulation parameters can be figured out: one of the key factors is set constant while the other two variables are changed.

3.1. Effects of feed gas compressed pressure and flow ratio

The nitrogen component is set as 50% mole fraction. Liquefaction rate variation with flow ratio in TEE-100 under different compressed pressures can be found in Fig.2. It is can be easily seen that process liquefaction rate increases with the increase of feed gas compressed pressure P_{104} under same flow rate V_s . For the other side, the variation of liquefaction rate with flow ratio under constant compressed pressure is not monotonous all the time. Under low compressor discharge pressure, liquefaction rate declines with the increase of flow ratio, when P_{104} is under 2MPa. But there is always a peak liquefaction rate when the compressed pressure is above 2MPa, and the peak occurs under higher flow ratio with the compressed pressure increase.

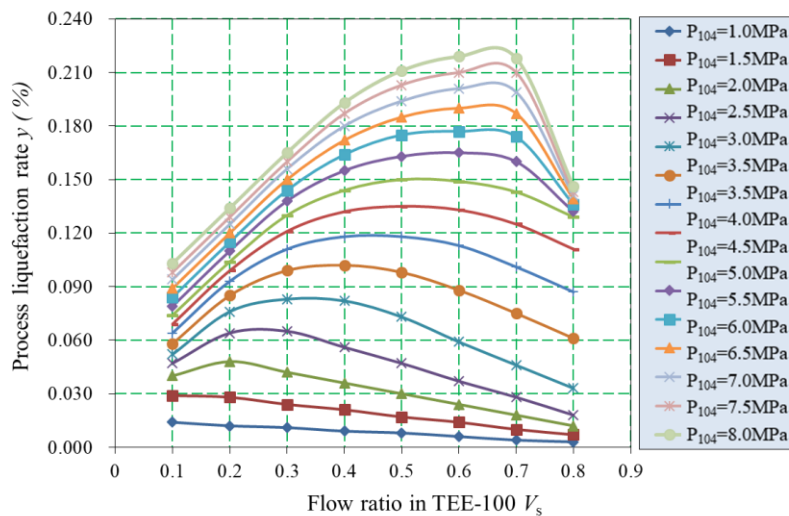


Fig 2. Liquefaction rate variation with flow ratio in TEE-100 under different compressed pressure.

Variation of specific power consumption with flow ratio in TEE-100 at different compressed pressures is shown in Fig.3. Higher compressed pressure means higher power input into the compressor, so the power consumption raises with the increase of compressed pressure under same flow ratio. And it can be found that the power consumption difference is not so significant as far as compressed pressure increases higher than 3.5MPa. It means this CBM process operation pressure should not lower than 3.5MPa which will lead to remarkable specific power consumption increase and low economic effectiveness. By contrast, system working under higher compressed pressure is also unacceptable. Although the liquid production yielding is very high under higher compressed pressure as shown in Fig.2, the compressor absolute power input and equipment investment cannot be beard for the small and compact skid-mounted system. As a result, the following data discuss will be conducted according to previous analysis and process parameters only be discussed in the compressed pressure range of 3.5MPa to 4.5MPa.

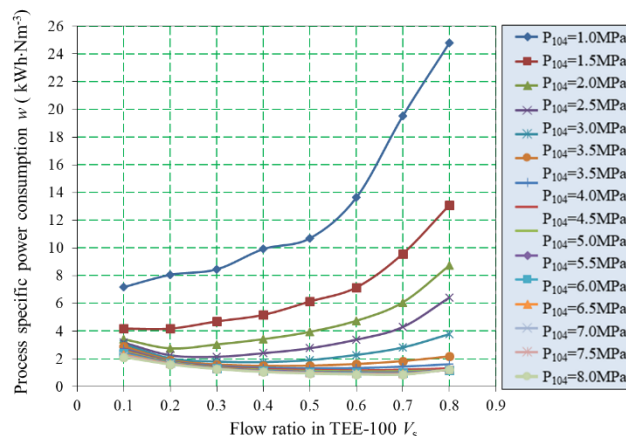


Fig 3. Variation of specific power consumption with flow ratio in TEE-100 under different compressed pressure.

For flow ratio change from 3.5MPa to 4.5MPa, it can be found that there is always a lowest value of specific power consumption w , and the best flow ratio occurs around 0.4 and 0.5. Methane mole fraction variation with flow ratio in TEE-100 under different compressed pressure is shown in Fig.4. The methane mole fraction declines dramatically when the flow ratio is larger than 0.7 in relatively

high compressed pressure. And according to Fig.2 and Fig.3, the liquefaction rate will decrease and the specific power consumption will increase.

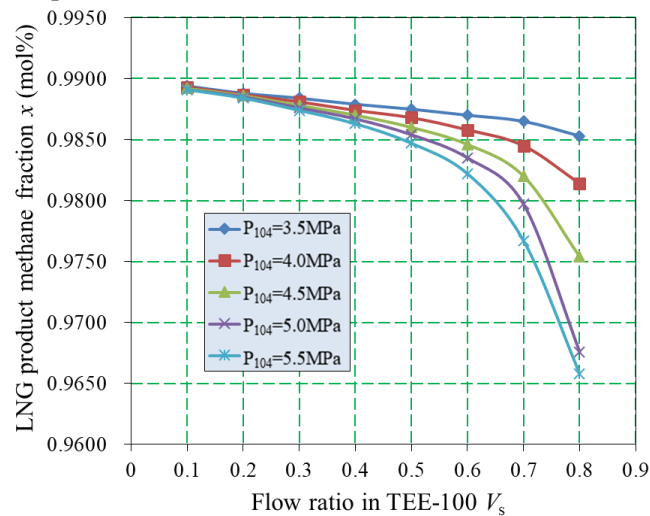
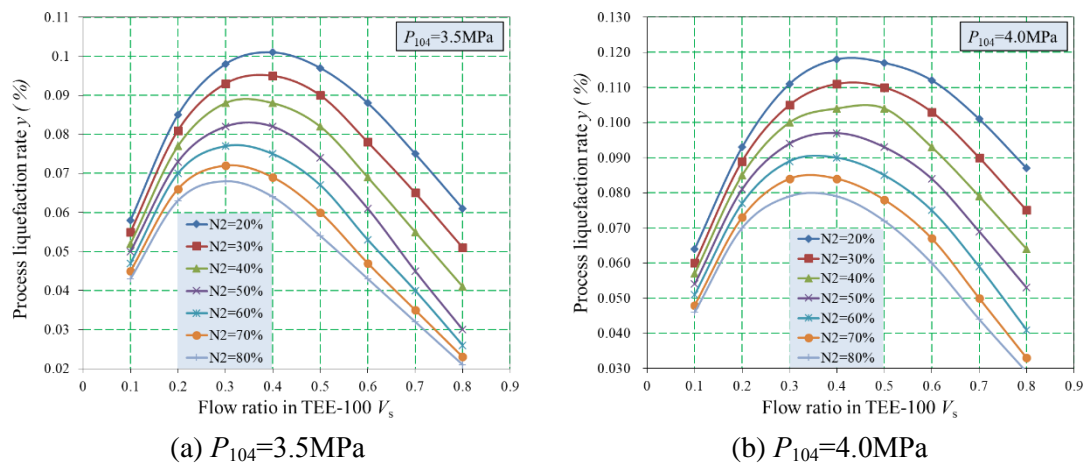
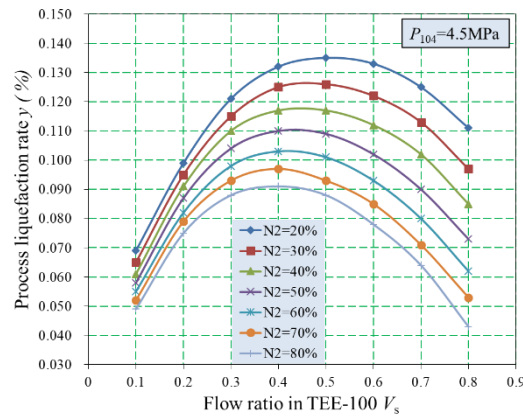


Fig 4. Methane friction variation with flow ratio in TEE-100 under different compressed pressure.

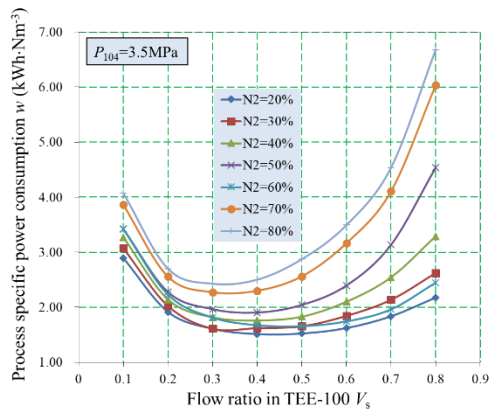
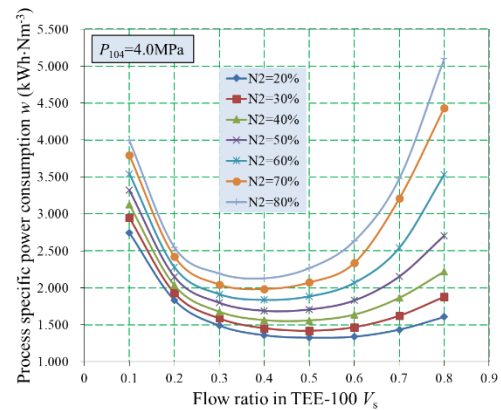
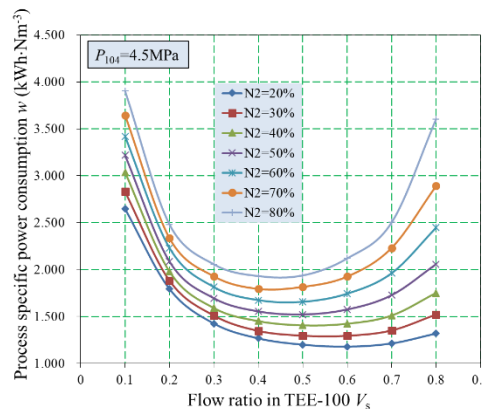
3.2. Effects of nitrogen friction in feed gas

Nitrogen mole fraction is also a key factor to CBM liquefaction process performance. Nitrogen mole fraction from 20% to 80% in feed gas is calculated, and the compressed pressure range is set in 3.5MPa to 4.5MPa. Liquefaction rate variation with flow ratio under different nitrogen mole fraction at $P_{104}=3.5\text{MPa}$, 4.0MPa and 4.5MPa is shown in Fig.5. The highest liquefaction rate always happens when the nitrogen mole fraction is lowest. Tendency of liquefaction rate variation increases first and then decreases with the increase of flow ratio. Under different nitrogen mole fraction, there is a peak liquefaction rate which occurs when flow ratio is between 0.3 and 0.5.



(c) $P_{104}=4.5\text{MPa}$ **Fig 5.** Liquefaction rate variation with flow ratio in TEE-100 under different nitrogen mole fractions when $P_{104}=3.5\text{MPa}$, 4.0MPa and 4.5MPa .

Variation of specific power consumption with flow ratio in TEE-100 under different nitrogen mole fraction when $P_{104}=3.5\text{MPa}$, 4.0MPa and 4.5MPa is shown in Fig.6. For specific power consumption, the highest specific power consumption always happens when the nitrogen mole fraction is highest. The variation of power consumption tends to decline first and raise with the increase of flow ratio, especially under high flow ratio, the power consumption surges. The lowest specific power consumption almost occurs around flow ratio is also $0.3\sim 0.5$.

(a) $P_{104}=3.5\text{MPa}$ (b) $P_{104}=4.0\text{MPa}$ (c) $P_{104}=4.5\text{MPa}$ **Fig 6.** Variation of specific power consumption with flow ratio in TEE-100 under different nitrogen mole fractions

$N_2\%$ when $P_{104}=3.5\text{MPa}$, 4.0MPa and 4.5MPa .

Methane mole fraction variation with flow ratio in TEE-100 under different nitrogen mole fraction and three different compressed pressures are shown in Fig.7. With low nitrogen mole fraction (nitrogen mole fraction=70% and 80%) and low flow ratio ($V_s=0.1\sim0.4$), the methane mole fraction in LNG product varies largely. By contrast, with low nitrogen mole fraction the methane mole fraction is keep almost steady.

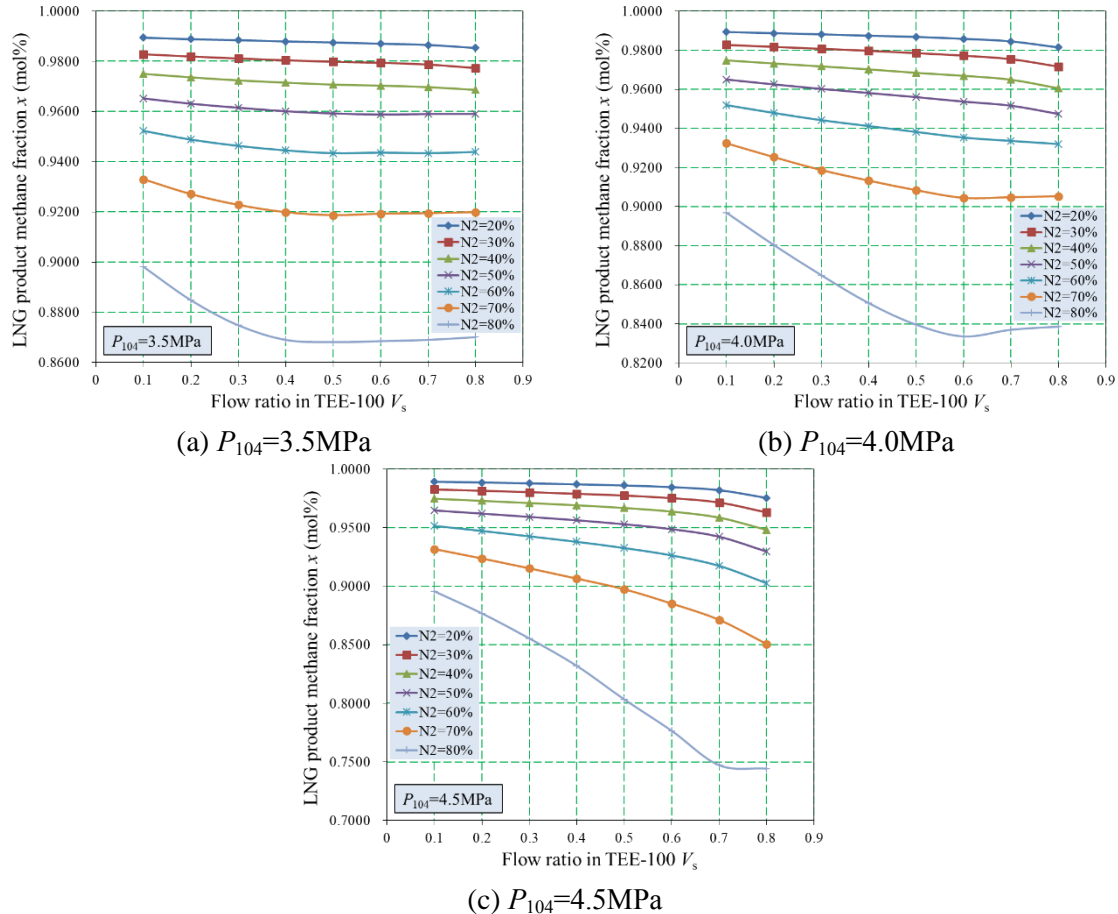


Fig 7. Methane friction variation with flow ratio in TEE-100 under different $N_2\%$ when $P_{104}=3.5\text{MPa}$, 4.0MPa and 4.5MPa .

Under the three different compressed pressures, the liquefaction rate and product purity is highest and specific power consumption is lowest when $P_{104}=5\text{MPa}$. Moreover, from the previous analysis, the system performance always reaches the peak when flow ratio is around 0.4. In a certain operation pressure range, the compressed pressure should be selected as higher as possible in this CBM liquefaction process. For sake of process energy utility, the flow ratio will be set in range of 0.3~0.5.

4. Conclusion

A CBM liquefaction process based on Claude liquefaction cycle is proposed in this paper. Liquefaction rate y , specific power consumption w and methane mole fraction in feed gas x are applied to evaluate CBM process performance, among the process parameter, compressor discharge pressure P_{104} , divided flow ratio V_s and nitrogen mole fraction $N_2\%$ are the key factors to effect process performance. And the interaction between process performance and this significant parameter is analyzed.

Although high compressed pressure can improve system liquefaction rate, it will increase investment and equipment will occupy more room. Given high power consumption and low liquefaction rate under low compressed pressure, the maximum compressed pressure is set in range of 0.35~0.45MPa. The nitrogen mole fraction varies in a wide range, but it is obvious that system performance will be better with low nitrogen mole fraction in feed gas. The process liquefaction rate, specific power consumption and LNG product purity will have better performance when flow ratio is around 0.4. Under such flow ratio, system cooling capacity is utilized sufficiently. In this paper, turbo-expander operates into two-phase region not very deep, so the development of two-phase turbo-expander with booster should give more attention to further performance improvement of CBM liquefaction process.

5. References

- [1] Thakur PC, Little HG, Karis WG. Global coalbed methane recovery and use. *Energy Conserv Manage* 1996; 37(6-8): 789-94.
- [2] Bibler CJ, Marshall JS, Pilcher RC. Status of worldwide coal mine methane emissions and use. *Int J Coal Geol* 1998; 35: 283-310.
- [3] Lin WS, Gu M, Gu AZ. Analysis of coal bed methane enrichment and liquefaction processes in China. In: *Proceedings of the 15th international conference & exhibition on liquefied natural gas*, Barcelona, Spain; 2007. In: *Proceedings of the 15th international conference & exhibition on liquefied natural gas*, Barcelona, Spain; 2007.
- [4] Cavenati S, Grande CA, Rodrigues AE. Separation of CH₄/CO₂/N₂ mixtures by layered pressure swing adsorption for upgrade of natural gas. *Chem Eng Sci* 2006; 61: 3893-906.
- [5] Gao T, Lin WS, Gu M, Gu AZ. CBM liquefaction processes integrated with adsorption separation of nitrogen. In: *Proceedings of the ASME 2nd international conference on energy sustainability*, Jacksonville, USA; 2008.
- [6] Haselden GG. Developments in gas liquefaction and separation. *Int J Refrig* 1979; 2(6): 207-8.
- [7] Terry L. Comparison of liquefaction process. *LNG J* 1998; 21(3): 28-33.
- [8] Finn AJ, Johnson GL, Tomlinson TR. Development in natural gas liquefaction. *Hydrocarb Process* 1999(4): 47-59.
- [9] Johnson GL, Finn AJ, Tomlinson TR. Offshore and smaller scale liquefiers. *LNG J* 1999 (July - August): 19-22.
- [10] Cao WS, Lu XS, Lin WS. Parameter comparison of two small-scale natural gas liquefaction processes in skid-mounted packages. *Appl Therm Eng* 2006; 26: 898-904.
- [11] Gao T, Lin W, Gu A, et al. Coalbed methane liquefaction adopting a nitrogen expansion process with propane pre-cooling. *Applied Energy*, 2010, 87(7): 2142-2147.

Acknowledgments

This project was supported by the National Nature Science Foundation of China (51476122), the Special fund for innovation and development of Xinjiang science and Technology Department (2015013) and the Fundamental Research Funds for the Central Universities.