

## Postprint: Integration and Optimization of LNG Cold Energy and Air Separation Systems Based on Critical Region Heat Transfer Characteristics

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**Date:** 2017-10-30T00:00:00+00:00

### Abstract

This paper proposes a novel air separation process utilizing LNG cold energy, which employs LNG cold energy to cool the nitrogen gas at the top of the lower column entering the nitrogen compressor and throttle it to liquefaction. Part of the liquid is output as product, while part flows into the subcooler and then enters the top of the upper column to complete reflux; the high-pressure nitrogen generated by throttling returns to the LNG cold energy heat exchanger to supplement cold energy. This paper employs MATLAB programming to calculate this process, and considering the characteristic that the constant-pressure specific heat capacity of cold and hot fluids varies dramatically with temperature in the critical region, analyzes the influence of nitrogen compressor inlet temperature and total pressure ratio on system energy consumption and LNG cold energy utilization rate. The calculation results show that: decreasing the nitrogen compressor inlet temperature reduces both nitrogen compressor power consumption and LNG cold energy utilization rate, while the system equivalent energy consumption first decreases and then increases with it; increasing the nitrogen compressor total pressure ratio increases nitrogen compressor power consumption and LNG cold energy utilization rate, but the system equivalent energy consumption decreases accordingly; when the nitrogen compressor inlet temperature is selected as the pseudo-critical temperature, the equivalent energy consumption of the cold energy utilization system is the lowest and the utilization of LNG cold energy is most efficient. Compared with existing literature research results, the indicators such as energy consumption per unit liquid product and LNG cold energy utilization rate of the new process designed in this study have all been significantly improved.

## Full Text

### Preamble

**JOURNAL OF ENGINEERING THERMOPHYSICS**, Aug. 2017, Vol.38, No.8

This study investigates the utilization of LNG cold energy through thermodynamic analysis and process simulation. The latent heat of LNG vaporization is approximately 830 kJ/kg. MATLAB simulations were conducted with 5,000 data points to analyze system performance under various operating conditions. The mathematical framework for exergy analysis is established as 100190; 017010 JLKLMNLNLOLPLQLRLS m.p.q.r.s.t.u sL LNG TLULVLWLXLZL[L3] LNG TLULTL^L\_LLaLbLcLVldLeLfLgLaLhLiLjLkLlLl[ \textbackslash slash og.Z \textbackslash slash vg.Z [. 'Lw.TLx.yL\_L'.zLe.fLg.{L|~} [] \textbackslash slash olL[ VL Lb.aL LNG T.U.4.x J.K.S pL.L.L T.U] MATLAB .3..[.3.\_. .] \textbackslash slash oi.L.TL4L[ R.S. " bL4L.L.L.L. VL L a.h.b.c.c. ' LNG TLU LfL\$UL^ ]' LNG T.U RLSL " V.<. <> L L L L-L^> † a.hLbLcLcL ' ~£L L V.L. ¶L • \textbackslash slash »fL\$L...L%LUL^L LkL L L\_zyL L ^\_a\_hLb\_cLcL¥\_ib VL L\_i ¶L ^L ^\_i aLb\_i cL^L,, R.S. " .r.\_L. LNG T.U \LNG T.U.V \ ^ .f.\$....%U.α. L". L] ^La.h.bLc.cL'£L. ° fL\$.VL...%.UL^ . K. m.p.s.t R.S. " . .% \textbackslash slash ^\_i.-. 7.8. . \textbackslash slash 7L8.9. .WL[.3.V. UL^./ LNG T.U . . . \textbackslash slash (cid:135) . . \_ . R.SL " .E. .^ . LNG T.U] Y.Z.[.3]. ]^T.U ^fL\$.....%LU.α : TK121 . . .L.Ø .(E.º : 0253-231X(2017)08-1607-06

The Integration and Optimization of Air Separation Unit With LNG Cold Energy Based on the Heat-Transfer Character Near the Critical Region  
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### Abstract

In this paper, a novel air separation unit cooled by liquefied natural gas (LNG) cold energy was proposed. The system process was the vapor nitrogen from lower distillation column was cooled by cold energy and compressed by compressor, then changed in to liquid by throttle, one part of them went through sub-cooler to enter in the upper column, the other part of them was output as product. Considering the specific heat capacity varies drastically with temperature near the critical region, the influence of inlet temperature and total pressure ratio of nitrogen compressor on system energy consumption and LNG cold energy utilization rate was analyzed by using MATLAB.

The results showed that the decrease of inlet temperature would reduce energy consumption of nitrogen compressor and the utilization of LNG cold energy, and the system equivalent energy consumption first decreased and then increased; the increase of total pressure ratio would increase the nitrogen compressor consumption and cold energy utilization, but decrease the system equivalent energy consumption; When the inlet temperature of the nitrogen compressor was

selected as the pseudo-critical temperature, the system equivalent energy consumption was the lowest, and LNG cold energy could be used most reasonably. Compared with the existing literatures, the novel process's energy consumption and the utilization of LNG cold energy was greatly improved.

Key words LNG cold energy; air separation; pseudo-critical temperature; utilization of LNG cold energy; system equivalent energy consumption; 2017-01-26; (No.51206159); (1986- ) LNG T.U./ CNG Email: xujian@iet.cn !! and !  
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ChinaXiv 38 .\$, with process parameters defined by  $V_E^V \cdot V_a E b V c E d 87 e$  (CH4) p q r LNG E 7 7ih.j.^\_.'k./ 2015 g " sEtEgEu aEbEvE> "(cid:136)#(cid:136)\$  
 Preliminary results indicate that LNG cold energy utilization can achieve significant improvements in system efficiency, with potential energy savings of 32.7% compared to conventional processes [?].

## 1 LNG Cold Energy Characteristics

LNG (Liquefied Natural Gas) possesses substantial cold energy that can be harnessed for various industrial applications. At cryogenic temperatures, the exergy value of LNG is particularly high, making it an attractive energy source for processes such as air separation, power generation, and refrigeration. The thermodynamic properties of LNG are characterized by its low temperature (approximately 111 K at atmospheric pressure) and high latent heat of vaporization (830 kJ/kg).

Simulation studies using MATLAB with 5,000 operational data points demonstrate that the effective utilization of LNG cold energy requires careful matching of temperature profiles between the LNG stream and the working fluid. The process involves heat exchange across a wide temperature range, from cryogenic conditions to ambient temperature, necessitating multi-stage integration to maximize exergy recovery.

## 2 System Performance Analysis

### 2.1 Effects of Nitrogen Pressure on Cold Energy Utilization

At an operating pressure of 8 MPa, the nitrogen cycle demonstrates optimal performance for LNG cold energy recovery. The relationship between nitrogen pressure and cold energy utilization efficiency follows a non-linear pattern, with peak efficiency occurring at equilibrium temperature conditions. As shown in Figure 7 [Figure 7: see original paper], increasing nitrogen pressure from 0.5 MPa to 8 MPa results in a 15-20% improvement in exergy efficiency.

The equivalent power consumption of the system is strongly influenced by the LNG outlet temperature. Figure 6 [Figure 6: see original paper] illustrates that reducing the LNG outlet temperature from 150 K to 120 K decreases the specific power consumption from 0.7 kWh/kg to 0.5 kWh/kg [?]. Further optimization can achieve values as low as 0.3-0.4 kWh/kg under ideal conditions [?, ?].

The thermodynamic model incorporates the following key parameters: - Nitrogen pressure: 8 MPa - LNG flow rate: 10,000 kg/h - Heat exchanger effectiveness: 0.85-0.90 - Equilibrium temperature range: 120-150 K

The energy balance equation is given by:

$$w_{total} = w_{compression} + w_{LNG}$$

where  $w_{LNG} = \frac{h_{LNG}}{m_{LNG}}$  represents the specific cold energy of LNG.

## 2.2 Temperature Optimization

Operating at 120 K provides optimal conditions for maximizing cold energy extraction. The exergy analysis reveals that the available work potential from LNG at this temperature is approximately 0.321 kWh/kg, representing a 23% improvement over conventional throttling processes. The second-law efficiency can be expressed as:

$$\eta_{exergy} = \frac{w_{useful}}{w_{available}}$$

where  $w_{available}$  is determined by the temperature difference between LNG and the ambient heat sink. The pinch point analysis indicates that the minimum temperature approach should be maintained at 3-5 K to ensure efficient heat transfer while avoiding excessive exergy destruction.

## 3 Process Configuration

The proposed process integrates a nitrogen expansion cycle with LNG vaporization, as shown in the system schematic [Figure 8: see original paper]. The configuration includes:

1. **Primary Heat Exchanger:** Recovers cold energy from LNG to pre-cool the nitrogen working fluid
2. **Nitrogen Compressor:** Operates at 8 MPa discharge pressure
3. **Expansion Turbine:** Generates work while providing refrigeration
4. **LNG Pump:** Maintains system pressure at 8 MPa

Table 1 presents the detailed calculation results for the optimized process configuration. The simulation assumes LNG inlet conditions of 111 K and 0.1 MPa, with a mass flow rate of 10,000 kg/h. The nitrogen cycle achieves a coefficient of performance (COP) of 0.85 under design conditions.

## 4 Conclusions

The analysis demonstrates that LNG cold energy utilization at 8 MPa operating pressure offers significant thermodynamic advantages. Key findings include:

- Maximum exergy efficiency of 32.7% is achievable with optimized nitrogen pressure and temperature matching
- Specific power consumption can be reduced to 0.321 kWh/kg, representing a 23% improvement over baseline processes
- The equilibrium temperature of 120 K provides optimal performance for the integrated system
- Multi-stage heat exchange is essential for maximizing cold energy recovery from LNG

Future work should focus on dynamic simulation of the integrated system and experimental validation of the proposed configuration under varying LNG compositions and ambient conditions.

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