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# Optimization of a novel liquefaction process based on Joule–Thomson cycle utilizing high-pressure natural gas exergy by genetic algorithm

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ABSTRACT

A novel liquefaction process based on Joule–Thomson cycle utilizing high-pressure natural gas exergy is specifically proposed and presented in this paper. Thermodynamic and economic optimization of the novel process are performed with the genetic algorithm (GA) in Microsoft Excel VBA connecting Aspen HYSYS. Five different objective functions are selected: minimization of specific energy consumption (SEC), total cost investment (TCI), specific operation cost (SOPEX), total annualized cost (TAC) and maximization of exergy efficiency. The specific energy consumption objective function is equivalent to exergy efficiency, SOPEX, TAC objective functions. Compared to TCI objective function, the other four objective functions can result in an about 49% reduction of SEC, an about 99% increase of exergy efficiency, an about 2% reduction of SOPEX and an about 2.8% reduction of TAC, but an about 95% increase of TCI. The results show that any of SEC, exergy efficiency, SOPEX and TCI objective functions is more suitable for the optimization of this process. Finally, the exergy analysis of each component is given. It can be found that compressors and water coolers produce the highest exergy losses for the equivalent objective functions.



## 1. Introduction

Natural gas, an environment-friendly and superior fuel, is considered as a candidate of other fossil fuels [1]. The current major options for long distance transportation of natural gas from remote gas fields to markets include pipeline [2], LNG (Liquefied Natural Gas) [2–6], CNG (Compressed Natural Gas) [2,7], NGH (Natural Gas Hydrate et al.) [2,8,9] and so on. Pipeline natural gas and CNG transported with the high pressure (up to 10 MPa) must be reduced to a moderate pressure in pressure reduction station by throttling valves before entering the city pipe network. Besides, offshore gas and shale gas also possess high pressure (up to 30 MPa). To avoid the waste of pressure exergy, exergy recovery methods of high pressure natural gas have been paid much attention to.

Apart from power generation and light hydrocarbon, the pressure exergy of high pressure natural gas has also been used for the liquefaction of natural gas [10–15]. Kirillov [10] introduced a technology of LNG production based on throttling-vortex cycle without energy cost. The LNG cooling capacity was produced through utilization of the pressure exergy of the compressed gas from pipeline. However, the disadvantage of the cycle is low liquid yield (2–4%). Gao et al. [11] analyzed the coalbed methane nitrogen expansion liquefaction process with propane pre-cooling by utilizing the pressure exergy of gas resource. The results indicated that coalbed methane, when its nitrogen content is less than 70%, can be liquefied at an acceptable energy cost usually under 0.75 kW h/Nm$^3$. Li et al. [12] obtained that the specific energy consumption of $C_3$/MRC, MRC and $N_2$ expander liquefaction processes were 0.238, 0.263 and 0.4 kWh/Nm$^3$ with the same liquid yield of 0.884 for the special offshore associated gases in South China Sea, respectively. He et al. [13] presented a novel NG expansion liquefaction process with two paralleled expanders to utilize pipeline pressure exergy. The specific energy consumption of this process is very low, at 0.03975 kWh/Nm$^3$, while the liquid yield is only 13.55%. Yuan et al. [14] developed a novel small-scale liquefaction process adopting single nitrogen expansion with carbon dioxide pre-cooling and achieved the liquid yield of 0.77 with specific energy consumption of 0.4511 kWh/Nm$^3$. He et al. [15] designed a novel small-scale liquefaction process utilizing the pipeline pressure without energy consumption. The optimization liquid yield and exergy utilization rate are 12.61% and 19.61%, respectively.

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**Nomenclature**

| | |
|---|---|
| $a$ | attractive parameter(Pa(m$^3$/mol)$^2$) |
| $b$ | effective molecular volume(m$^3$/mol) |
| $C$ | cost ($) |
| $e$ | specific exergy(kJ/kg) |
| $E$ | exergy(kJ) |
| $h$ | specific enthalpy(kJ/kg) |
| $H'$ | hours per annum(h) |
| $I$ | exergy loss(kW) |
| $m$ | mass flow rate(kg/h) |
| $n$ | mole flow rate(kmol/h) |
| $p$ | pressure(kPa) |
| $Q$ | heat load(kW) |
| $R$ | universal gas constant (J • mol−1 • K−1) |
| $s$ | specific entropy (kJ/kg) |
| $t$ | temperature(°C) |
| $T$ | temperature(K) |
| $v$ | specific volume (m$^3$/kg) |
| $V$ | normal volume flow rate (Nm$^3$/h) |
| $W$ | power(kW) |
| $\Delta T$ | temperature difference (K) |
| $U$ | overall heat transfer coefficient (kW/m$^2$·K) |
| $UA$ | overall heat transfer coefficient and area of heat exchanger, kW/K |

*Abbreviations*

| | |
|---|---|
| COM | compressor |
| ex | exergy |
| HX | heat exchanger |
| LMTD | log mean temperature difference (K) |
| LNG | liquefied natural gas |
| NG | natural gas |
| OF | objective function |
| OPEX | operation cost ($/year) |
| PREHX | precooling heat exchanger |
| SEC | specific energy consumption (kWh/Nm$^3$) |
| SOPEX | specific operation cost ($/tonne-LNG) |
| TAC | total annualized cost ($/tonne-LNG) |
| TCI | total cost investment ($) |
| UT | utility |
| WC | water cooler |

*Greek symbols*

| | |
|---|---|
| $\alpha(T)$ | $\alpha$ function of state of equation |
| $\sigma$ | adjustment parameter of penalty function $p(X)$ |
| $\omega$ | acentric factor |
| $\eta$ | efficiency |
| $\Pi$ | pressure ratio |

For example, in the field of offshore LNG production, one of emerging plant markets, additional factors of compactness, ease of operation, and safety must be considered. Other constraints for traditional liquefaction process in marine environment may be imposed, such as mixed refrigerant storage and leak. In this paper, a novel liquefaction process based on J-T cycle by utilizing the pressure exergy of high-pressure natural gas is specifically proposed [16]. Traditional compressors, coolers, heat exchangers and simple throttling parts are used in this novel process with the advantages of on-the-spot feed gas refrigerant, low energy cost, simplicity and flexibility. The optimization of this novel process is presented based on five objective functions: specific energy consumption, exergy efficiency and three critical techno-economic variables (total capital cost, operating expenditure and total annual cost) to identify process performance improvements. Meanwhile, the exergy analysis of every component for the objective functions is given.

## 2. Process design and models

### 2.1. Process description

The schematic diagram of the novel liquefaction process based on J-T cycle is listed in Fig. 1. In the mixer (MIX-3), the feed natural gas (NG) mixes with the stream 103 from the water cooler of the middle-pressure compressor (MP-WC) and the stream 205 from the first precooled heat exchanger (PREHX-1). After being pressurized (HP-C) and water-cooled (HP-WC), the mixed natural gas successively enters both precooled heat exchangers (PREHX-1 and PREHX-2) and is cooled to a temperature of approximately −60 °C. Then, in the first main heat exchanger (HX-1), it continues to be cooled to about −90 °C. After that, the natural gas is divided into two parts (streams 201 and 110). One part (stream 201) is reduced to the middle pressure by the first throttling valve (VLV-1) and returns to HX-1, PREHX-2 and PREHX-1 to recover its cooling capacity. The other part (stream 110) continues to be cooled to about −115 °C and then is divided into two parts (streams 301 and 112). Afterward, the stream 301 undergoes the second throttling valve (VLV-2) and moves back to HX-2, HX-1, PREHX-2 and PREHX-1 to provide its cooling capacity. In the third main heat exchanger (HX-3), the stream 112 is cooled to approximately −142 °C, and then reduced to the LNG storage pressure by the third throttling valve (VLV-3). The LNG can be obtained from the bottom of a vapor-liquid separator (V-100), and then divided into two parts (streams 401 and LNG). The one part (stream LNG) is the LNG product. The other part (stream 401) mixes with the BOG (boiling off gas) (stream 115-V) from V-100 in MIX-1. Then the natural gas (stream 402) provides cooling capacity for HX-3, HX-2, HX-1, PREHX-2 and PREHX-1 successively, and enters the low-pressure compressor (LP-C) and water cooler (LP-WC). After that, the cycle medium mixes with the stream 306 from the PREHX-1, and undergoes the MP-C and MP-WC to supply the stream 103. Besides, the two-stage cascade refrigeration system using R22 and R23 as working medium is adopted as the precooler of the above liquefaction process.

The proposed process in this paper is different from the conventional liquefaction process. In the process, part of cooling capacity for the low-temperature heat exchanger can be provided through the throttling of the high-pressure natural gas itself. Meanwhile, the compression and throttling with multiple pressure levels can improve the temperature matches and reduce the irreversible losses in the heat exchangers. The traditional compressors, coolers, heat exchangers and simple throttling parts are used in the process. The process has the advantages of simplicity, flexibility and reliability.

### 2.2. Given parameters in the process

The pressure and temperature of the feed natural gas are set at 3.1 MPa and 25 °C, respectively. The maximum molar flow rate (stream 104) in the novel liquefaction process is set at 100 kmol/h. Here, the natural gas only consists of pure $CH_4$. The other known parameters in the process are listed in Table 1.