E3S Web of Conferences **22**, 00140 (2017) DOI: 10.1051/e3sconf/20172200140
ASEE17

A novel vortex tube-based N_2-expander liquefaction process for enhancing the energy efficiency of natural gas liquefaction

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Abstract. This research work unfolds a simple, safe, and environment-friendly energy efficient novel vortex tube-based natural gas liquefaction process (LNG). A vortex tube was introduced to the popular N_2-expander liquefaction process to enhance the liquefaction efficiency. The process structure and condition were modified and optimized to take a potential advantage of the vortex tube on the natural gas liquefaction cycle. Two commercial simulators ANSYS® and Aspen HYSYS® were used to investigate the application of vortex tube in the refrigeration cycle of LNG process. The Computational fluid dynamics (CFD) model was used to simulate the vortex tube with nitrogen (N_2) as a working fluid. Subsequently, the results of the CFD model were embedded in the Aspen HYSYS® to validate the proposed LNG liquefaction process. The proposed natural gas liquefaction process was optimized using the knowledge-based optimization (KBO) approach. The overall energy consumption was chosen as an objective function for optimization. The performance of the proposed liquefaction process was compared with the conventional N_2-expander liquefaction process. The vortex tube-based LNG process showed a significant improvement of energy efficiency by 20% in comparison with the conventional N_2-expander liquefaction process. This high energy efficiency was mainly due to the isentropic expansion of the vortex tube. It turned out that the high energy efficiency of vortex tube-based process is totally dependent on the refrigerant cold fraction, operating conditions as well as refrigerant cycle configurations.

1 Introduction

The refrigeration and liquefaction in LNG plant demands the high capital investment and consumes a tremendous amount of energy. It normally occupies about 35% of the capital cost, and up to 50% of the operating costs [1]. In terms of energy consumption, liquefaction of 1 kg natural gas consumes 1,188 kJ of energy [2], which is equivalent to the 30–35% of the total required energy for the LNG production. This energy consumption varies according to cite conditions and the type of available liquefaction processes. Now

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DOI: 10.1051/e3sconf/20172200140

a days, several processes are available for baseload natural gas liquefaction with different energy efficiency, capacity, complexity, environmental and safety impact. The N_2-expander process as one of representative natural gas liquefaction processes has a high environmental and safety impact but the major issue is the low energy efficiency.

The optimization of design and operational parameters is one of the most popular approach for improving the energy efficiency of N_2 refrigeration processes. Various optimization techniques have been reported to enhance the energy efficiency of the N_2 refrigeration process [3-6]. Another alternative to improve the energy efficiency of the LNG plant is to enhance the refrigeration cycle units like compressors, cryogenic heat exchangers, and expansion devices.

By improving the refrigeration cycle units like compressors, cryogenic heat exchangers, and expansion devices is another main alternative approach to improve the energy efficiency of LNG plant [7]. A vortex tube with its great potential for liquefaction applications was first introduced by Georges J. Ranque (1933) and experimentally investigated by German physicist Rudolf Hilsch (1947) [8] hence it is known as Ranque-Hilsch vortex tube. The significant merits of the vortex tube are, compactness with no moving parts, low in cost, maintenance free and adjustable cold and hot streams [9, 10]. The construction of the vortex tube consists of inlet nozzle(s), diaphragm, vortex generator, chamber, cylindrical tube, conical valve, hot outlet and cold outlet. The simple schematic diagram of vortex tube is shown in Figure 1.

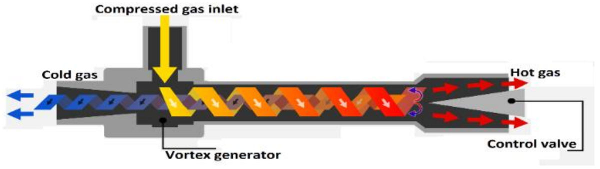

Figure 1. The schematic diagram of vortex tube [11].

The working principle of vortex tube depends upon the pressure gradient that causes the energy separation (in terms of hot and cold) from compressed gas. The compressed gas is introduced tangentially into the tube chamber through the one or more nozzles. The swirls more like a typhoon is formed through the interchangeable vortex generator. The compressed gas leaves the tube from the two outlets: one is from the cold side and other from the hot side. A small conical control valve at the hot gas side is installed to control the temperatures, cold and hot fraction corresponding to the specified application of vortex tube. It has been demonstrated that the refrigeration cycle associated with isentropic expansion has higher COP (coefficient of performance), which is defined as the ratio of useful cooling effect provided to required compression energy, in comparison with isenthalpic expansion-based refrigeration cycles [12], as proven in Maxwell thermodynamic relation (i.e., $dH = TdS+VdP$). Mohiuddin and Elbel [13] has investigated that the overall expansion process in the vortex tube is an isentropic.

This study addressed the potential benefits of vortex tube coupled with turbo expander to enhance the energy efficiency of N_2 expansion LNG process. The structure and design parameters of the proposed process were optimized to achieve the maximum benefits of proposed vortex tube-based configuration corresponding to the minimum required compression power. The modified knowledge-based optimization method was proposed and successfully applied to optimize the proposed LNG process.

2 Vortex tube-based LNG process: simulation and process description

The energy separation behavior was rigorously modeled using the CFD software ANSYS FLUENT®. The proposed LNG process has been then modeled in a commercial simulator ASPEN HYSYS® by embedding the CFD model results.

2.1 CFD model of vortex tube

In the present study, a CFD model was used to investigate the energy separation in the vortex tube with Nitrogen at cryogenic temperature as the working fluid (refrigerant) using the CFD software ANSYS FLUENT®. The standard k-ε turbulence model was used to investigate the flow behavior in the vortex tube. For meshing, ICEM-CFD application was used to generate the 5mm hexahedral structural mesh. The CFD model was based on the experimental investigation for an Exair™ 708 slpm vortex tube by Skye et al. [14]. The total temperature distribution for working fluid nitrogen at inlet temperature 139 K and 7 bar pressure is shown in Fig. 2. Inlet conditions for vortex tube were chosen according to the available properties data of nitrogen at cryogenic temperatures [15]. The static pressure at the cold exit boundary was fixed at 2 bar and the static pressure of hot exit boundary was adjusted in the way to vary the cold mass fraction. The CFD results which were embedded in the ASPEN HYSYS®, are summarized in Table 1.

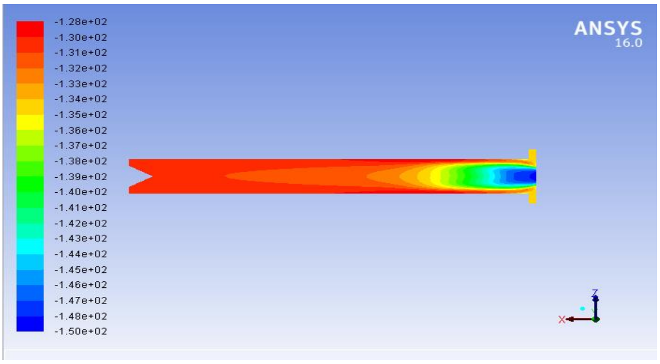

Figure 2. Total temperature contours of nitrogen at 139K and 7 bar.

Table 1. CFD results for working fluid Nitrogen.

Property	Value
Inlet temperature (K)	139
Inlet Pressure (bar)	7
Cold side temperature (K)	123
Cold side Pressure (bar)	2
Cold mass fraction	0.25
Hot side temperature (K)	145
Hot side Pressure (bar)	3

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2.2 Process simulation and description

The process simulation basis and feed conditions are summarized in Table 2. The well-known Peng-Robinson [16] was used to calculate the thermodynamic properties and the Lee-Kesler [17] EOS was used to calculate the enthalpies and entropies. The proposed LNG process is demonstrated in Fig. 3. Note that in Fig. 3, different streams with the name as 'stream-x' (x = 1, 2, 3, 4......) are used for the process description. In this process, nitrogen as a refrigerant stream-1 was compressed to high pressure 77.5 bar (stream-2) through five compressor stages each equipped with after-coolers. To avoid the high compression power and reduce the irreversibility of the process, the compression ratio was chosen in the practical range 1:3. A hybrid cooling system combined by air/water cooler (AC-1) and a cryogenic plate fin exchanger (CHE-01) was used to cool down the high pressure stream-2 before entering the expander. After expansion, the stream-5 at 139 K and 7 bar was introduced into the vortex tube. The cold side stream of vortex tube (stream-6) was used to cool down stream-3 (3–4) through CHE-01 and stream-8 was again introduced into the expander K-3. Stream-9 was used to liquefy the compressed natural gas through CHE-02. The feed natural gas was compressed to 95 bar through a booster compressor K-NG. Stream-10 from CHE-02 as a superheated vapor and stream-7 from CHE-01 were mixed in the mixer and recycled to achieve complete cycle. LNG product was obtained with 8% boil-off gas at the pressure of slightly higher than atmospheric, i.e., 1.209 bar.

Table 2. Process simulation basis and feed conditions.

Feed natural gas [18]	Value
Temperature (K)	303
Pressure (bar)	50
Flow rate (kg/h)	1
Composition	Mole %
Methane	91.30
Ethane	5.40
Propane	2.10
i-Butane	0.50
n-Butane	0.50
i-Pentane	0.01
n-Pentane	0.01
Nitrogen	0.20
After-coolers outlet temperature (K)	303
LNG Tank pressure (bar)	1.209

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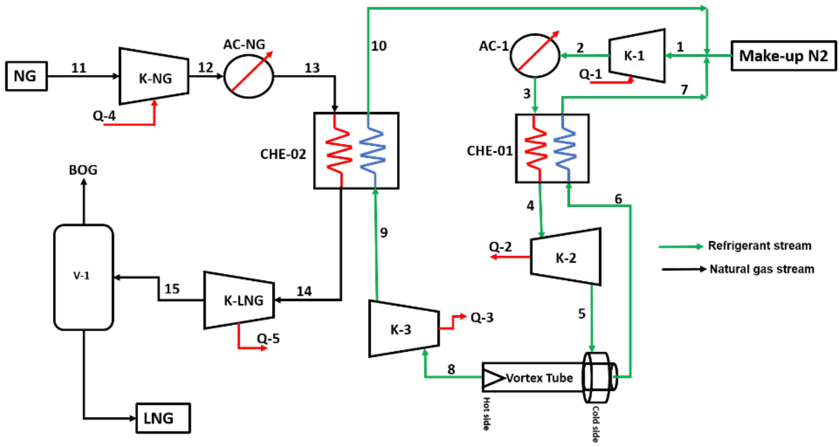

Figure 3. The process flow diagram of vortex tube-based LNG process.

3 Process Optimization

The knowledge-based optimization method [18, 19] was modified to employ for the optimization of the proposed LNG process. Figure 4 illustrates the modified knowledge-based optimization algorithm used in this study.

The minimization of specific compression energy in the proposed LNG process was chosen as an objective function for optimization. Since the refrigerant flow rate and operating pressures have pronounced impact on the overall required compression power and process irreversibility, these were chosen as the key decision variables in the optimization of the proposed LNG process. Table 3 shows these decision variables with lower and upper bounds.

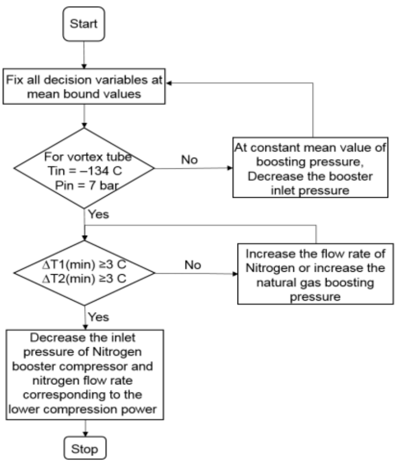

Figure 4. Proposed modified knowledge-based optimization algorithm.

The refrigerant pressure before and after the turbo-expander booster compressor is being designated as 'P_1' and 'P_2', respectively. The minimum internal temperature approach (MITA) value as a major constraint was chosen as 3 °C in both cryogenic exchangers considering the LNG cryogenic exchangers transfer the heat with MITA value as small as 1–3°C [20].

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Table 3. Decision variable bounds.

Decision variables	Lower bound	Upper bound
Boosting pressure of natural gas, P_{NG}, bar	70	120
Pressure of stream-1, P_1, bar	25	45
Pressure of stream-2, P_2, bar	55	110
Flow rate of nitrogen, m_{N2}, kg/hr	4.5	9.5

Objective function was formulated as:

$$Minimize\ f(X) = Min.\left(\sum_{i=1}^{4} wi/m_{LNG}\right)$$

Where 'X' is the vector of decision variables, $X = (P_{NG}, P_1, P_2, m_{N2})$

4 Optimization Results

Table 4 compares the optimization results of the proposed and conventional N_2-expander processes. The results showed the specific compression energy can be saved significantly up to 20% in comparison with the commercial N_2-expander LNG process.

Table 4. Optimization results.

Parameters	Proposed vortex tube - based LNG process	Conventional N_2-Expander process [18]
Boosting pressure of natural gas, P_{NG}, bar	95	50
Pressure of stream-1, P_1, bar	32	–
Pressure of stream-2, P_2, bar	77.50	100
Flow rate of nitrogen, m_{N2}, kg/hr	5.618	8.257
Specific compression energy (kJ/kg-LNG)	2143.80	2681.64
Specific energy savings	20%	–

4.1 Optimization results in terms of composite curves

The composite curve matching technique is widely used to measure the efficiency of any process where cooling and heating are dominantly involved. For an energy efficient liquefaction process with low specific compression energy, each hot (natural gas) and cold (refrigerant) composite curve should be located as closely as possible. The composite curves of proposed LNG process (Figures 5a and 5b) also illustrate the clear difference with the composite curves of the commercial N_2-expander LNG process (Figures 5c and 5d).

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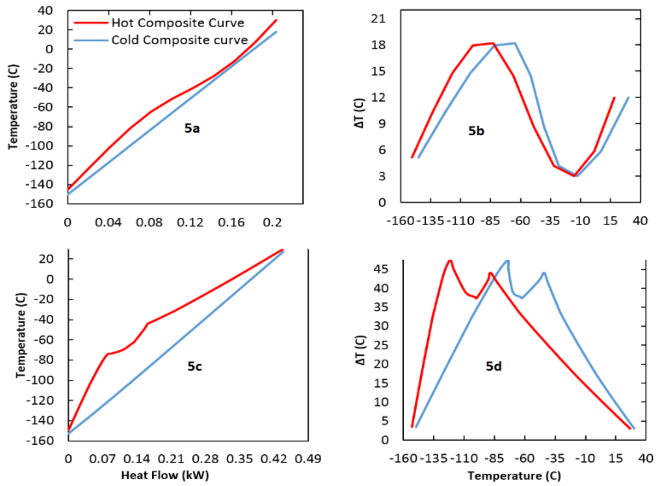

Figure 5. Comparison of composite curves.

5 Conclusions

An enhancement in the refrigeration cycle of LNG process, it improves the energy efficiency in terms of required specific compression power. The proposed vortex tube-based LNG process showed superior performance to liquefy natural gas with significantly less energy in an eco-friendly manner in comparison with the existing well-established N_2-expander LNG process. The modified knowledge-based optimization algorithm proposed was successfully applied to achieve the maximum benefit of newly added expansion device (vortex tube) as well as to make this liquefaction process feasible on the commercial scale. Based on the optimized results, it was found that the specific compression power could be reduced by improvement in an expansion step of LNG process. By using other heuristic evolutionary algorithm, further minimization in specific compression power of proposed LNG process might also be possible. It was also found that the isentropic expansion efficiency of vortex tube could be further improved by optimizing the geometric and operational parameters with respect to LNG process. It turned out the vortex tube has a promising potential to enhance the refrigeration effect as well as energy efficiency of the industrial gases liquefaction processes.

This research was supported by Basic Science research Program Foundation of Korea (NRF) funded by the Ministry of Education (2015R1D1A3A01015621) and also by Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education.

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