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Methane addition effect on a dual nitrogen expander refrigeration cycle for LNG production

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ABSTRACT

Genetic algorithm was applied to optimize a typical nitrogen double turbo-expander cycle for LNG production plant. The net required work of the process was considered as an objective function. The effect of methane addition to the nitrogen cycle was studied from 1 to 50 mol percent. The results showed when the concentration of methane in the refrigerant is equal to 26 ± 1 mol percent, the work consumption of the process will be minimized. At this concentration, the net required work of the process will be 8% less than the optimized process case which uses pure nitrogen as a refrigerant. Moreover, the effect of ambient temperature on the energy consumption of the process was investigated from 30 °C to 50 °C. It was observed that when ambient temperature varies from 30 °C to 40 °C the nitrogen flow rate will be constant, approximately. Also the net required work increases significant from 40 °C to 50 °C ambient temperature.

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1. Introduction

World consumption of natural gas as a clean fuel has increased from 2699 to 3393 billion cubic meters (26% grew) during 2004–2014 (BP, 2015). Iran as one of the world's largest holders of gas reserves has a large gas transmission network (about 36,000 km high pressure gas pipeline); therefore, using natural gas in its industrial and domestic energy baskets, widely. In Iran, the gas transmission pipelines have been constructed all over the country except at some mountainous, impassable and remote areas. Small scale LNG is one of the best methods of energy supply for these areas. Moreover, small scale LNG in the form of Floating LNG has been considered a good candidate for collection of offshore associated gas in Iran.

Three main refrigeration cycles have been used for LNG production including: cascade, mixed refrigerant and open-closed loop expansion cycles (Venkatarathnam, 2008; Remeljej and Hoadley, 2006). Generally, the Cascade, propane precooling mixed refrigerant (C3MR) and dual mixed refrigerant (DMR) cycles have been used for the base-load LNG production. However, the single mixed refrigerant (SMR) and nitrogen expansion cycles have been widely used for small scale LNG which have been compared in different references (Castillo and Dorao, 2010; Cao et al., 2006; Gas today, 2010; Wensheng, 2012). Normally, SMR processes have higher efficiency compared with N2-expansion cycles, but N2 cycles are simple processes and more safe (Chang et al., 2009).

Among the different nitrogen expansion cycles, both dual nitrogen turbo-expanders and pre-cooled nitrogen expansion cycles are the most common processes which have been used in LNG plants. The energy consumption of these types of Expansion cycles are about 0.45–0.65 kwh per kg produced LNG, which is competitive with SMR processes with energy consumption of about 0.4 kwh per kg produced LNG. Barclay et al. (2004) expressed the nitrogen expansion cycle is simple in design and is less sensitive to the flow rate and concentration of feed gas.

For increasing the efficiency of a single nitrogen turbo-expander cycle (reverse brayton cycle), different solutions are recommended:

1) Addition of turbo expander to the nitrogen cycle (Neeraas and Sandvik, 2009; Dubar, 1997; He and Ju, 2014; Nilsen and Sverre, 2008; Walther, 2009; Roberts and Brostow, 2008).
2) Addition of pre-cooling section (e.g. carbon dioxide or propane) to the expansion cycle (Yuan et al., 2014; Gao et al., 2010; Fredheim and Paurola, 2008; Roberts and Brostow, 2008).
3) Replacing one of the nitrogen cycles by methane expansion cycle (Foglietta, 2001).

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4) Addition of second component to the pure nitrogen refrigerant (Cao et al., 2006; Gu et al., 2001; Pu et al., 2007; Ding et al., 2016).

He and Ju (2014) proposed a parallel nitrogen expansion liquefaction process for small scale plants. They showed the unit energy consumption of parallel nitrogen expansion process is reduced approximately 4.69% compared to the convention nitrogen expansion processes. Yuan et al. (2014) proposed a single nitrogen expansion process adopting with carbon dioxide pre-cooling cycle for small scale natural gas liquefaction plants, then compared with propane pre-cooling, N2−CH4 expander cycle process and new mixed refrigerant cycle proposed by Cao et al. (2006). They concluded that the advantages of this process are compact in device, safe in operation and there is no need for the preparation of refrigerants. Gao et al. (2010) used nitrogen expansion process with propane pre-cooling system for liquefaction of coalbed methane (CBM) due to its simplicity. Cao et al. (2006) analyzed two typical liquefaction processes for small scale LNG plants. They compared a mixed refrigerant cycle (MRC) with a N2−CH4 expander cycle and concluded that for small scale LNG plants without propane pre-cooling system, the N2−CH4 expander cycle is preferred.

A few literatures express addition of second component to pure nitrogen can improve the efficiency of N2-expansion cycles (Pu et al., 2007; Gu et al., 2001; Ding et al., 2016). Pu et al. (2007) investigated the effect of methane concentration on the energy consumption of two simulated N2-expansion cycles for 40−60% methane mole fraction in the refrigerant. They showed when methane mole fraction in the refrigerant is about 50%, the required energy for LNG production will be minimized for both cases. Gu et al. (2001) compared three refrigeration cycles for peak-shaving application, including propane pre-cooling mixed refrigerant cycle, mixed N2−CH4 expansion cycle (single turbo expander) and two stage mixed refrigerant cycle. The results showed the mixed N2−CH4 expansion cycle has lower efficiency compared to simulated mixed refrigerant cycles.

Ding et al. (2016) simulated and optimized a propane pre-cooled N2−CH4 refrigeration cycle. This optimized process is recommended because of its low power consumption among the nitrogen expansion and mixed refrigerant processes.

There is a lack of thermodynamical study which investigates the addition of second component (i.e. methane) up to 50 mol percent how affects the N2-expansion process efficiency. Also it is extremely required to determine the optimized concentration of the second component in the refrigerant to reach the highest efficiency of the process. In this paper optimization of a dual N2-expansion cycle was studied as the base case. Then the effect of methane addition to the nitrogen cycle (up to 50 mol percent of methane) was studied and the optimum concentration of methane was obtained. Finally the effect of ambient temperature on the net required work of this process was investigated.

2. Process design

The nitrogen dual turbo-expander cycle was simulated by Aspen HYSYS software, as is shown in Fig. 1.

2.1. Process description

The feed natural gas (NG) is passed through the first multiple stream heat exchangers (HEX-1) and decreases its temperature to −5 °C. NG temperature decreases in three steps to about −160 °C after third heat exchanger. High pressure liquefied natural gas which exits the last heat exchanger (HEX-3) is letdown across VLV-1 to produce two vapor and liquid phases. A vapor-liquid separator (V-1) is used to separate low pressure LNG product stream for storage and Boil-Off Gas (BOG) stream. A dual nitrogen turbo-expander cycle is used to produce required refrigeration for LNG production. High pressure nitrogen stream is achieved by a three stage compressor with inter and after air coolers. High pressure nitrogen stream is split between warm and cold turbo expander cycles after passing HEX-1. The cooled nitrogen feed of warm turbo expander cycle (stream 11) is work-expanded to produce the required refrigeration to decreases the temperature of NG and the other part of nitrogen stream (i.e. refrigeration fluid of cold turbo expander cycle) into an intermediate temperature in HEX-2. The cooled nitrogen stream with an intermediate temperature (stream 14) enters the cold turbo expander cycle. This stream work-expanded to lower pressure levels rather than warm turbo expander cycle pressure to achieve the minimum required temperature for liquefaction of natural gas. The output nitrogen cold stream from HEX-3 (stream 16) has a pressure similar to that of the warm expander discharge stream 12. So after mixing of these two streams (12 and 16) the mixed stream 17 is reheated in the liquefaction HEX-2, cooling the warm and cold nitrogen cycle feed gas streams and also cooling and condensing natural gas stream. The reheated nitrogen gas stream is fed to the first stage of nitrogen compression system to rises the pressure of nitrogen stream.

3. Process simulation and optimization

Aspen HYSYS software was used to simulation of the nitrogen double turbo-expander cycle. The process was simulated by some assumptions which listed in Table 1.

3.1. Optimization problem

In order to optimize the energy consumption of the nitrogen double turbo-expander process, optimization was performed by connecting the simulated process to Matlab software to use its genetic algorithm tools. A MATLAB program code adapted from previous work (Moein et al., 2015) was developed to call the Aspen HYSYS simulation by Matlab and also transfer the data produced by GA to Aspen HYSYS. In this situation the GA method acts as a controller and the Aspen HYSYS model is a server. Since the net required work of the process is defined as the objective function of GA method, the net required work calculated by Aspen HYSYS is sent back to MATLAB to evaluate the fitness function value.

As mentioned above in this study the net required work of the process is defined as an objective function which be calculated by Aspen HYSYS. This objective function is a black box that contains an Aspen HYSYS model. Because of the nonlinear property of the mixture (N2−CH4) this objective function has multiple local extremes. On the other hand the black box cannot provide gradient information or a reliable initial value. Therefore, a global search method without a derivative and an initial value is required to overcome these challenges and thermodynamic complexity of the process. So in this research genetic algorithm as a global search method is used to optimization of the process. The genetic algorithm (GA) is a search heuristic that mimics the process of natural evolution, which was invented by Holland (1975) and further developed by his students and colleagues.

3.2. Optimization formulation

In this investigation minimizing of the net required work of the double turbo-expander process is considered as an objective function for GA method as indicated below:

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