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Single and multiple objective optimization of a natural gas liquefaction process

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A B S T R A C T

Benefit from the development of process simulation technology, the optimal operating conditions of the natural gas liquefaction process can be obtained by simulation modeling and analysis. Based on the concept of the evolution theory, the genetic algorithm is an effective tool for the optimization of the liquefaction process. A single nitrogen expansion process with carbon dioxide pre-cooling is modeled in Aspen HYSYS, which is connected to MATLAB by ActiveX technology to establish a hybrid simulation platform. Taking the unit energy consumption and the liquefaction rate as the objective functions, the multi-objective optimization problem of the liquefaction process is constructed. The penalty function is employed to realize the conversion of the constraints. The simple and the fast elitist non-dominated sorting genetic algorithm are adopted to solve the single and multi-objective optimization problem of the liquefaction process, respectively. Results indicate that the simple genetic algorithm achieves low unit energy consumption and high heat transfer efficiency with the main objective method, while the results of the fast elitist non-dominated sorting genetic algorithm better realizes the synthetical performance of the process. The economic analysis shows that the initial investment is the key factor which restricts the economic performance of the project.

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1. Introduction

With the expansion of the world population and the environmental concerns caused by coal and petroleum, the global demand for natural gas will grow fastest of the fossil fuels over the period to 2035 [1], with an increasing rate of 1.9% per year, led by demand from Asia. The continuing growth of shale gas in North America [2] will switch it from importer to exporter [3]. The change of regional production and demand of natural gas leads to the increase of traded gas, which will be satisfied by increasing liquefied natural gas (LNG) supplies. According to BP energy outlook 2035 [1], LNG will have overtaken pipelines as the dominant form of traded gas by the year of 2035.

Natural gas liquefaction is energy intensive and consumes approximately 30% [4–6] of the total energy used in natural gas processing. The energy consumption of liquefaction is determined by the type of installation [7], equipment, and efficiency. The specific energy consumption of different processes is shown in Table 1, in which the discrepancies among processes come from different levels of optimization and the employment of different equipment and efficiencies. Therefore, the optimization of a specific liquefaction process is particularly important, so as to improve process efficiency. The target of optimization is to obtain the suitable operating conditions (e.g. temperature, pressure and flow rate) under certain constraints, so that the process may achieve the best performance, which contributes to the reduction of the system energy consumption and operating costs, as well as the improvement of the economic efficiency and market competitiveness.

The optimization of the liquefaction process is a nonlinear extremum problem with many variables and constrains, which is difficult to converge by traditional mathematical programming methods. Different approaches have been employed to conduct the optimization. An optimal synthesis of process cooling duties at different temperatures was addressed [12], in which the best refrigerants were selected from the candidate refrigerants manually. Lee et al. [13] proposed a systematic synthesis method for the

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Table 1
Specific energy consumption of the liquefaction processes [7–11].

Type of process	Specific energy consumption (kJ/kg)
Cascade process	1180–1390 [9,10]
SMR	1240–1490 [8,9]
C3MR	1050–1370 [7,9–11]
Single N_2 expander	2370–3450 [9,11]
Double N_2 expander	1420–2020 [9,11]

selection of refrigerant compositions by nonlinear programming (NLP) techniques. To determine the refrigerant compositions and operation parameters in a mixed refrigerant cascade process, Vaidyaraman and Maranas [14] adopted NLP to evaluate the dependent variables. A methodology combining the traditional pinch analysis with exergy calculations was described to optimize the compression and expansion work [15] for a liquefaction process. Although relatively good results have been obtained by the above methods, it is not easy to the find the global optima for these gradient-based optimization techniques [16] due to the non-convexity and non-linearity and many local optima of this kind of problem. The optimization toolbox based on simulation software is one of the effective ways to solve this issue. Aspelund et al. [17] developed a gradient free optimization-simulation method modeled with the simulator Aspen HYSYS based on the tabu search and the Nelder-Mead downhill simplex method. Four different liquefaction models [18] are analyzed in Aspen HYSYS and optimized by the VBA optimizer, including a C3MR cycle, a modified dual mixed refrigerant cycle and two SMR cycles. Taking the specific power consumption as the objective function, a pressurized liquefaction process is optimized by the sequential search method using HYSYS simulation [19].

Based on Darwin's theory of evolution and Mendelian inheritance, the genetic algorithm [16] is able to handle multiple individuals in population and to evaluate multiple solutions in computation space without gradient information, to achieve a random search and global optimization. With genetic operators of selection, crossover and mutation, this method shows good performance [20] in solving discrete and nonlinear problems. Based on mathematical programming, the genetic algorithm has been applied to the design of mixed refrigerant cycles [21]. Taking the minimum of the compressor power consumption as the objective function, Taleshbahrami and Saffari [22] have adopted the genetic algorithm to realize the optimization of a C3MR cycle with a power consumption decrease by 23% compared to the base case. The evolutionary search [23] has been employed to optimize the energy consumption of a liquefaction process, where satisfactory and robust results have been achieved in comparison with the sequential quadratic programming method. With the genetic algorithm, He and Ju [24] have conducted an optimization of mixed refrigerant cycle with natural gas liquids recovery process, where the unit energy consumption has been reduced by 9.64%. The genetic algorithm has been chosen as the optimization method for a single mixed refrigerant cycle [25] to determine the optimum operating conditions. The hybrid genetic algorithm is used as the optimizer for the development of a robust refrigerant mixture for liquefaction of highly uncertain natural gas compositions [26].

Although the genetic algorithm reduces the complexity of the optimization problems with relatively satisfactory results in various liquefaction processes, the former research is concentrated on the single objective optimization, where a certain indicator as energy consumption [27], overall heat transfer coefficient [28] or figure of merit [29] has been applied to evaluate the process to simplify the calculation. However, many parameters reflect the performance of the liquefaction process including the energy consumption, LNG production, exergy efficiency and so on. That is to say, the optimization problem with more than one objective function is worth of studying.

Based on the single nitrogen expansion process with carbon dioxide pre-cooling [30,31], an optimization problem with many variables and two objective functions is constructed in this paper. The penalty function is used to transform the constraint conditions. A hybrid simulation platform is established to connect Aspen HYSYS with MATLAB by ActiveX technology. The simple and the non-dominated sorting genetic algorithm with elitist approach [32] are adopted to solve the single and multi-objective optimization problem of the liquefaction process, respectively, by which reasonable results are achieved. Based on the optimization results, the economic analysis is conducted.

2. Process description

The nitrogen expansion process [33] is reported to be the most adaptive process in consideration of economic performance and safety with relatively high energy consumption. The pre-cooling unit is effective to improve heat transfer efficiency as well as reduce process energy consumption [34], where carbon dioxide is preferred for process safety.

Fig. 1 shows the schematic diagram of the N_2 expansion process with CO_2 pre-cooling [30,31]. Natural gas (101) undergoes a two stage cooling in heat exchangers (HEX-102, HEX-103). HEX-102 is used for pre-cooling, and HEX-103 serves for sub-cooling. Heavy hydrocarbons (104) are removed in V-101, and valves (VLV-101, VLV-102) are employed for throttling temperature reduction. Flash gas (110) flows back into the heat exchangers (HEX-102, HEX-103) for the recovery of cryogenic energy. After the expansion (EX-301) of the two-stage compression (C-301, C-302), carbon dioxide (307) is used to pre-cool feed gas and nitrogen. Nitrogen (207, 208) is used as the refrigerant for gas condensing and sub-cooling through the compression (C-201, C-202) and expansion (EX-201) cycle.

2.1. Feed conditions

In order to facilitate a comparison analysis with the base case, the feed gas components and equipment parameters are mainly borrowed from Yuan et al. [30], except that a pressure drop of 10 kPa in heat exchangers and water-coolers is set [29], as it is shown in Table 2.

2.2. Simulation basis

2.2.1. Mathematical model of equipment

The main equipment of a natural gas liquefaction process comprises compressors, coolers, expanders, throttle valves, separators and heat exchangers.

The required power of compressors is given by:

$$W_{com} = \dot{n}(h_{out} - h_{in}) \\ W_{com,a} = W_{com}/\eta_{com} \quad (1)$$

where W_{com} is the theoretical power consumption of compressors, kW; $\dot{n}$ is the molar flow, kmol/s; h is the molar enthalpy, kJ/kmol; $W_{com,a}$ is the actual power consumption of compressors, kW; η_{com} is the mechanical efficiency of compressors; the subscript out represents the parameter of the outlet; the subscript in represents the parameter of the inlet. The energy balance relation of coolers is shown in Equation (2).

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