Energy 89 (2015) 757–767

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Sequential coordinate random search for optimal operation of LNG (liquefied natural gas) plant

Mohd Shariq Khan [a], I.A. Karimi [a], Alireza Bahadori [b], Moonyong Lee [c, *]

[a] Department of Chemical & Biomolecular Engineering, National University of Singapore, 4 Engineering Drive 4, Singapore 117585, Singapore
[b] School of Environmental, Science & Engineering, Southern Cross University, Lismore 157, Australia
[c] School of Chemical Engineering, Yeungnam University, Dae-dong 712-749, Republic of Korea

ARTICLE INFO

Article history:
Received 17 October 2014
Received in revised form
25 May 2015
Accepted 5 June 2015
Available online 3 July 2015

Keywords:
Coordinate search
Random search
Natural gas
Liquefaction
Optimization
SMR/C3MR

ABSTRACT

This study exploits the sequential coordinate randomization search method for optimizing LNG (liquefied natural gas) process plants. The coordinate search is based on the idea of minimizing the multivariable function considering one variable at a time. The random element is incorporated in the coordinated search for an exhaustive exploration of decision variable space. A simple implementation with few operating parameters makes the proposed approach suitable for the optimization of highly non-linear LNG process plants. The efficacy of the proposed methodology was tested on the well-known SMR (single mixed refrigerant) and propane pre-cooled mixed refrigerant (C3MR) process of NG liquefaction. The main decision variables in SMR and C3MR process plants were identified and optimized in terms of the compression energy. The results were compared with the heuristic results, which revealed the superiority, simplicity and suitability of the proposed sequential coordinate random search algorithm for LNG process plants.

1. Introduction

Energy is the main factor driving the world's economy and making the world a global village, where everyone's needs are interdependent. A continuous supply of energy is needed to sustain economic growth. Depleting crude oil reserves, growing environmental concerns and intense competition in the global market has paved the way for cleaner energy sources, such as NG (natural gas). Strong predictions of a significant increase in the demand for NG, as high as 60% from 2010 to 2030, have been made. A big portion of NG is found in remote locations and requires liquefaction to bring it to the world market. NG liquefaction is energy demanding and consumes approximately 30% of the total energy used in the NG value chain. Therefore, a small improvement in NG liquefaction efficiency will increase the process global competitiveness and have huge cost and energy benefits.

Besides improving liquefaction efficiency, efforts are also focused to extract the cold energy from LNG (liquefied natural gas). Choi et al., provided deep analysis of Rankine cycle used for NG liquefaction and extracted cold energy [6] which could be used for generating electricity. Similar efforts are also done by Sun et al., for recovering cold energy using mixed working fluids in the Rankine cycle [29]. Lee et al., further optimize the multi-component organic Rankine cycle for maximization of cryogenic exergy [19]. A novel power cycle based on cryogenic exergy, extracted from LNG is proposed by Li and Guo [20]. Gomez et al., arranged Rankine and Brayton cycles in series for exploiting cold exergy from LNG [10]. After generating exergy from cryogenic LNG, new method for storing cold energy extracted by liquid/solid phase change is proposed by Ref. [31]. Cold energy extracted from LNG are also used for reverse osmosis desalination powered by transcritical CO_2 as shown in Ref. [36]. Szargut & Szczygie utilize the cryogenic exergy generated from LNG for the production of electricity [30].

Based on the market and project demand, several NG liquefaction technologies have evolved over time. Lim et al. [35] presented an excellent discussion of the current perspectives related to the development of NG liquefaction cycles. Among the technologies discussed, the well-known SMR (single mixed refrigerant) and propane pre-cooled mixed refrigerant (C3MR) processes are the most commercially established NG liquefaction technologies [24,27]. The NG liquefaction plant receives feed from different sources. Therefore, to remain profitable in unprecedented upstream fluctuations, effective operational optimization is needed. To address this operational optimization issue, several studies [7] have

* Corresponding author. Tel.: +82 53 810 2512; fax: +82 53 811 3262.
E-mail address: mynlee@yu.ac.kr (M. Lee).

http://dx.doi.org/10.1016/j.energy.2015.06.021

embarked on taking sophisticated optimization approaches with simplified models [8]. On the other hand, practically applicable results are seldom obtained using simplified models. Therefore, a rigorous model, whose results can be translated to the actual process plant, is needed. The invention of the commercial process plant simulator solves this problem with rigorous thermodynamic libraries and property calculation methods. For the hydrocarbon system, Aspen Hysys is the preferred choice which was employed in this study for SMR and C3MR process model development.

Optimization of LNG process plants has been considered in several studies using deterministic [22,32,33] and evolutionary approaches [1] and most studies claims the superiority of the obtained results [28]. Nevertheless, faced with the abundance of local optima, the deterministic approach lands at local optimum [14]. In stochastic approaches, several tuning parameters make the success of the evolutionary approach dependent on the optimal tuning parameters [5]. To overcome the challenges of the discussed approaches, the SCRS (sequential coordinate random search) algorithm was proposed for operational optimization of NG liquefaction plant. The proposed search algorithm was inspired by the simple implementation of the coordinate descent algorithm [4], where optimization of a multi-variable function was performed by minimizing one coordinate at a time. Once a search cycle is performed over all coordinates and a locally optimal solution is obtained, the first coordinate value is randomized while the others are fixed to previous values. In the next search cycle, the second coordinate value is chosen randomly (over the given variable bound), whereas the others are fixed. In this manner, the SCRS algorithm gravitates towards the optimal solution. Finally the search is terminated when the defined level of the objective function tolerance is obtained.

Considering the amount of energy involve in NG liquefaction small efficiency improvement can rectify in big economic savings [34]. Optimization is one effective way of efficiency improvement in LNG plant, which led to the development of SCRS methodology. The novelty of SCRS approach lies in the merging of two relatively simple optimization techniques for solving complex optimization problem like LNG plant. Simple logic devoid of several tuning parameters gives the SCRS the upper-hand comparing to the deterministic and stochastic optimization techniques for LNG plant optimization. The SCRS methodology works well with LNG process plant but is not limited to LNG processes and can be exploited for any process model developed in a commercial simulator.

2. Abstract explanation of the SCRS (sequential coordinate random search) method

CD (coordinate descent) methods were among the first optimization schemes used for solving uncontained minimization problems [4]. The main advantage of these methods lies in the simplicity of each iteration both in generating the search direction and in performing an update of the variables [23]. CD is based on the idea that an n-dimensional optimization problem can be decomposed into n one-dimensional sub-problems. Each variable is updated sequentially by a cyclic coordinate search, while all other variable remain fixed, by solving the one-dimension optimization sub-problem using any suitable one-dimension optimization algorithm [21]. Based on the selection of the one-dimensional optimization method several variants of CD methods are available. The simplest one-dimensional optimization is inspired by the bisection method. The function is evaluated at the intervals and at the center of the interval, and the update is performed when the optimum is achieved over the defined interval as represented in Fig. 1. Otherwise a new interval with half-length is defined.

The other variant of CD uses the partial gradient or the component gradient and moves in the direction of the component

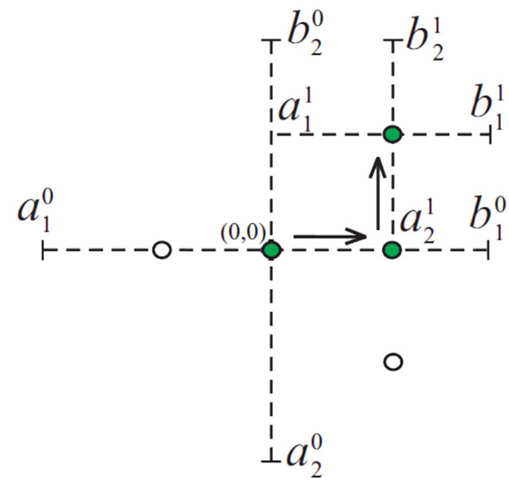

Fig. 1. Coordinate Descent Methods [21].

with the maximal absolute value. For this strategy, a calculation of the convergence rate is trivial provided the considered convex objective function has a component-wise Lipschitz continuous gradient [23]. The complexity of calculating the entire function gradient is proportional to the computational complexity of the corresponding functions, which is frequently defined by the explicit sequences of standard operations. The calculation of the directional derivative of a function may take equal time in calculating the function value. Therefore, CD methods based on directional derivative appear appropriate. On the other hand, when the problem data is distributed in space and time, the CD based on the function value appears to be more promising, which is the case under consideration [23].

Modeling of an LNG process plant in a commercial process plant simulator [12], such as Aspen Hysys or Honeywell UniSim Design, scatters the data in different unit operations, which calculate the desired property when simulated sequentially. Moreover, outsourcing of the optimization algorithm in Microsoft Visual Basics and then commencing the search by connecting the model developed in a commercial simulator using the Microsoft COM (component object model) functionality distributes the system information over digital space. Heurists showed that the sophisticated optimization algorithm, when used to optimize a process plant in a COM fashion, is easy to crash and converge prematurely. Therefore, employing a simple algorithm that is independent of the gradient information is more likely to give promising results. Therefore, the line search-based CD method was used in this study for LNG process plant optimization. The method employed is inspired by the sequential coordinate line search but the decision variable update after the first search cycle was performed randomly for the first coordinate and a solution was obtained. Similarly, the solution updates were performed and an array of solutions was obtained, and the optimum was declared after satisfying the termination criterion.

2.1. Random search with sequential coordinate descent

The conventional random search simply selects a starting vector x^0 and evaluates f(x) at x^0 then randomly selects both search directions and step length simultaneously to define the updated x^1 and evaluate f(x) at x^1. After some stages, $f(x^k)$ is compared with the previous value of f(x) and if the defined stopping criterion is met, the optimum is taken and the search is terminated. The global optimum with a probability of 1 can be achieved for any continuous