Chinese Journal of Chemical Engineering 23 (2015) 998–1008

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Chemical Engineering Thermodynamics

Thermodynamic design of a cascade refrigeration system of liquefied natural gas by applying mixed integer non-linear programming

Meysam Kamalinejad *, Majid Amidpour, S.M. Mousavi Naeynian

Department of Mechanical Engineering, K.N. Toosi University of Technology, Tehran 1999143344, Iran

A R T I C L E I N F O

Article history:
Received 17 March 2014
Received in revised form 19 May 2014
Accepted 31 May 2014
Available online 3 February 2015

Keywords:
Cascade refrigeration cycle synthesis
Cryogenic
Liquefied natural gas
MINLP

A B S T R A C T

Liquefied natural gas (LNG) is the most economical way of transporting natural gas (NG) over long distances. Liquefaction of NG using vapor compression refrigeration system requires high operating and capital cost. Due to lack of systematic design methods for multistage refrigeration cycles, conventional approaches to determine optimal cycle are largely trial-and-error. In this paper a novel mixed integer non-linear programming (MINLP) model is introduced to select optimal synthesis of refrigeration systems to reduce both operating and capital costs of an LNG plant. Better conceptual understanding of design improvement is illustrated on composite curve (CC) and exergetic grand composite curve (EGCC) of pinch analysis diagrams. In this method a superstructure representation of complex refrigeration system is developed to select and optimize key decision variables in refrigeration cycles (*i.e.* partition temperature, compression configuration, refrigeration features, refrigerant flow rate and economic trade-off). Based on this method a program (LNG-Pro) is developed which integrates VBA, Refprop and Excel MINLP Solver to automate the methodology. Design procedure is applied on a sample LNG plant to illustrate advantages of using this method which shows a 3.3% reduction in total shaft work consumption.

1. Introduction

Natural gas (NG) is an attractive source of clean fossil fuel and the third primary energy source after crude oil and coal. It is also the fastest growing and second largest energy source for electricity generation. In 2012, NG consumption was 2987.1 million tons oil equivalent, or about 24% of the total primary energy consumed worldwide. World's primary energy consumption had an average growth rate of 2.6% during the last 10 years, but LNG consumption growth rate was 7.85% [1]. This growth means a promising future for LNG industry. Most NG reserves are offshore and away from demand centers. Liquefying NG and transporting it to distances further from 3000 km is the most economical way to export it to consuming market. LNG industry is very energy extensive and industrial size LNG plants consume around 1181 kJ of energy to liquefy 1 kg of NG [2]. Heat integration inside a cycle or between different cycles of a cascade can greatly reduce shaft work consumption. Therefore, energy is an immediate concern in LNG industry. Such refrigeration system involves some of the largest compressors in the world, usually driven by gas turbines or electric motors using NG as fuel. At most 90% of the entering feed gas to a modern LNG plant is shipped as exported LNG and 10% of the gas is consumed to produce the required shaft work to liquefy the remaining NG. High operating and capital cost of an LNG plant opens a challenging field for more investigation in refrigeration cycle and optimal configuration of compressors to reduce cost.

Obtaining the best refrigeration system configuration has caused many attentions due to its economic importance. Barnes and King [3] investigated the problems of synthesizing refrigeration cycles and provided a two-step approach to identify optimum cascade refrigeration systems. In the first step, a limited number of promising choices for configurations and design parameters were identified using graph decomposition principles. To minimize the cost of the configuration, the problem was represented as a network. Later, Cheng and Mah [4] proposed an interactive procedure for synthesizing refrigeration systems incorporating all the refrigeration features identified by Barnes and King. The refrigerants participating in a cycle were selected based on their allowable operating temperature range and the temperature of the process streams to be cooled. Townsend and Linnhoff [5] and Linnhoff and Dhole [6] used a set of qualitative guidelines based on pinch technology and exergy analysis for placing heat engines and heat pumps to minimize utility consumption. Aspelund [7] proposed a methodology based on pinch analysis to utilize pressure based exergy for sub-ambient processes, such as LNG. Shin *et al.* [8] proposed a mixed integer linear programming (MILP) formulation for optimizing boil-off gas (BOG) compressor operations in an LNG re-gasification terminal, and Del Nogal [9] presented an optimization framework for the design of mixed refrigerant cycles which was suitable for LNG.

These methods are general in applicability and share some heuristics to find number of pressure levels, intermediate stages and partition

* Corresponding author.
E-mail address: meysam.kamalinejad@gmail.com (M. Kamalinejad).

http://dx.doi.org/10.1016/j.cjche.2014.05.023
1004-9541/

temperature, besides focus has been placed on the process optimization of only a specific part of LNG plant and not on the cascade configuration. When applying these approaches to complex multistage refrigerant cycles the shortcoming of these methods arises. The cascade does not converge as a result of both non-linearity in problem formulation and explosion of integer variables. To overcome this problem, a stepwise procedure has been introduced that the main parameters of a refrigeration cascade like partition temperature and pressure level are firstly determined and in the next step the refrigeration configurations and features are decided. CC and EGCC diagrams are added to analysis to give a better conceptual insight to the designer.

The complex nature of the heat and material balance equations in multi stream heat exchangers (MSHXs) and non-linearity of physical properties of natural gas and refrigerant mixtures makes computation of the model highly non-linear, which leads to use MINLP mathematics. In this paper a new method is introduced to find optimal synthesis of an LNG plant by mounting mixed integer non-linear programming on a superstructure and applying several industrial heuristics. MINLP method is a powerful tool for decision making problems and the new procedures applies it to determine the best compression configuration for the refrigeration cascade.

2. Theoretical Principles of Refrigeration and LNG Systems

In NG liquefaction process, acid gases and mercaptans are removed from sour NG. Cascade refrigeration is required to reach very low temperatures. A simplified cascade refrigeration cycle for mega scale LNG plant consists of three sub-cycles, each using a different pure refrigerant, (Fig. 1).

Only one stage for each cycle is shown for simplicity but in real industrial cycles 2 or 3 pressure stages are available by using expansion valves and each stage shall have its own pre-saturator, economizer, de-superheater, *etc.* In the first cycle, propane leaves the compressor at high temperature and pressure and enters the condenser where the cooling water or air is the external heat sink. The condensed propane then enters the expansion valve where its pressure is decreased to the evaporator pressure and the temperature of hot streams decreases to −40 °C. As the natural gas and methane are cooling down and ethane of lower cycle is condensing, the liquid refrigerant propane evaporates. Propane leaves the evaporator as superheated vapor and enters the compressor, thus completing the loop. The condensed ethane in the middle cycle expands in the expansion valve and evaporates as methane condenses and natural gas is further cooled and liquefied. In ethane cycle, temperature of hot streams decreases to −100 °C. Finally, methane expands and then evaporates as natural gas is liquefied and subcooled to −160 °C. As methane enters the compressor to complete the loop, the pressure of LNG is dropped in an expansion valve to the storage pressure [10].

Many refrigeration features are available which can be mounted over simple refrigeration cycles. These options reduce required compression shaft work. A cascade refrigeration system and its P–h diagram are shown in Fig. 2. The lower cycle absorbs heat at temperature levels 1–4 and rejects condensation heat to the upper cycle at temperature levels of 2–3. The upper cycle absorbs rejected heat from the lower cycle by operating at evaporation levels of 5–8, which is colder than levels 2–3. Finally, the heat in the upper cycle is rejected at levels 6–7 to external heat sinks like cooling water and air cooling systems.

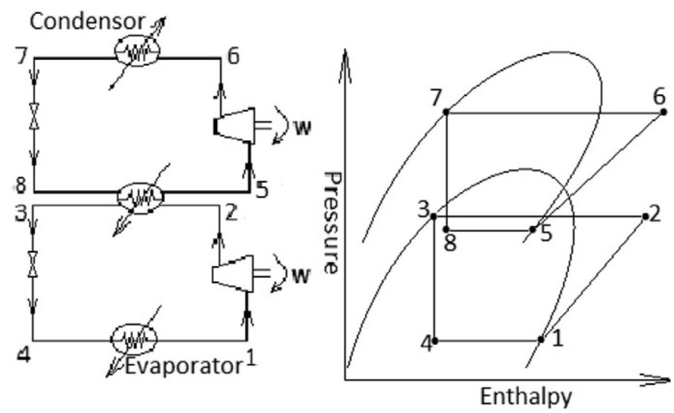

Fig. 2. A simple cascade refrigeration system diagram.

The reasons for using this kind of cascade refrigeration systems are two-folds. First, there are no single refrigerant in a single cycle to cover all temperature range of refrigeration. Second, in terms of energy consumption, using a single refrigerant for the whole refrigeration demand may consume more shaft work than using multiple refrigerants. Some basic features of refrigeration in a superstructure are described in Section 2.1.

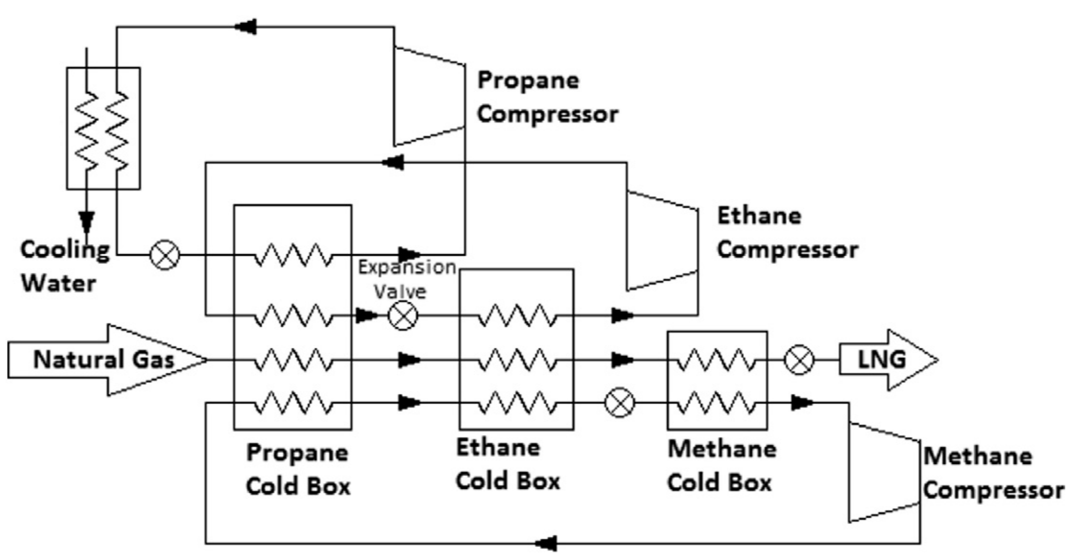

Fig. 1. Schematic of cascade refrigeration cycle.