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Modeling and simulation of main cryogenic heat exchanger in a base-load liquefied natural gas plant

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Abstract

Recent growth in world-wide consumption of natural gas highlights its immense importance as a source of primary energy. Liquefied natural gas (LNG) is the most economic way to transport natural gas over long distances. Main Cryogenic Heat Exchanger (MCHE) is a very critical equipment in an energy intensive LNG plant. To that end, modeling MCHE is the inevitable first step in the optimization of LNG plant operation. In this paper, we develop a model that is designed to simulate and predict the performance of an existing MCHE without knowing its physical details. The concept of superstructure representation is employed to derive an equivalent 2-stream heat exchanger network. The objective is to address the rating of an existing MCHE or the prediction of its performance rather than finding the area for a design or minimizing the cost. We use a mixed-integer nonlinear programming (MINLP) approach to select the best network that describes an existing MCHE. An example case is also presented to assess the ability of our model in predicting the performance of a MCHE.

Keywords: LNG, cryogenic systems, Main Cryogenic Heat Exchanger, Spiral-Wound Heat Exchanger, superstructure, refrigeration, MINLP

1. Introduction

Natural gas, the cleanest fossil fuel, is the fastest growing primary energy source for the world today. In 2005, natural gas consumption was 2750 bcm [1] or about 23% of the total primary energy consumed worldwide. The total consumption of natural gas is projected to increase by nearly 70% between 2002 and 2025 [2]. But the transportation of natural gas from its source to various demand centers has been a tricky problem. One option is to liquefy natural gas and transport it as LNG by specially built ships. Though the supply chain of LNG has been considered as costly and rigid [3] since the early days, recent reductions in costs throughout the chain, advances in LNG technology, new-generation LNG tankers, etc. have transformed LNG into an increasingly global energy option similar to oil. With energy demand increasing with time, LNG has established itself as the fuel for the future. All these suggest that LNG as an alternate source of primary energy will most likely change the energy scene of this century.

An LNG plant is essentially a large condenser that requires refrigeration, and hence is highly energy-intensive. The refrigeration section is the main consumer of energy in the plant. The operational flexibility and efficiency of the refrigeration section are critical to the overall efficiency. MCHE is the heart of the refrigeration section and is the most important heat-transfer equipment in a base-load LNG plant. It is usually a spiral-wound heat exchanger where natural gas is cooled to and liquefied at around –160 C. Spiral-wound heat exchangers are extensively used in cryogenic processes. They are multi-stream heat exchangers with multiple hot streams exchanging heat with one cold refrigerant. Its features include high density of heat transfer area, partial direct heat transfer via mixing of streams, stream splitting, simultaneous heat transfer between two or more streams, etc. These permit large heat transfer at temperature differences as small as 3 C, and make this type of heat exchanger extremely popular in cryogenic processes such as an LNG plant.

2. Problem Statement

For optimization of a plant such as an LNG plant, we need suitable models. However, a key issue in modeling MCHE is that the designs of most spiral-wound heat exchangers such as MCHE are largely proprietary. Rigorous physicochemical modeling (e.g., CFD modeling) of MCHE is difficult and even impossible due to the fact that almost nothing about its details can be found in the public domain. Moreover, such models present a serious problem in optimization, because of their compute-intensive and time-consuming nature.

However, to optimize the operation of a process involving MCHE, we need a simpler, approximate model that can be solved repeatedly. To overcome this problem, we propose a mathematical programming approach to develop a simpler model for such heat exchanger.
Most research related to complex heat exchangers focuses on design to minimize cost and certain operational targets such as pressure drops. While some literature [4, 5] has addressed optimization based approaches for the optimal design of plate & fin heat exchangers, we are able to locate only one paper [6] on spiral-wound exchangers. This paper uses a numerical approach to compute required heat transfer area. However, all these works are meant for design rather than performance rating and require knowledge about the internals such as number of tubes, bundles, arrangement, etc. They are not aimed at predicting the performance of an existing MCHE. But, as the use of optimization increases in the gas processing industry, modeling and simulation of the entire process is essential for exploring all available options. To this end, we present a superstructure-based modeling of spiral wound heat exchanger and use data from an existing MCHE to derive a network of simple 2-stream heat exchangers, which describes and predicts the performance of the MCHE. Given only the operational data (e.g., temperatures, pressures, compositions, & flow rates of streams at inlets and outlets) of an existing MCHE, the objective is to fit the model outlet temperature with the outlet temperature of an existing MCHE as close as possible for all the hot streams. This model can be used further in optimization studies on the entire LNG process.

3. Methodology

The concept of superstructure is widely used in chemical process network synthesis. Yee et al. [7] presented this idea of superstructure for modeling heat exchanger network by simultaneous targeting of energy and area. However, they addressed the design problem for a general network with utilities rather than an operational problem for a multi-stream heat exchanger. In this paper, we replace a bundle of MCHE with a superstructure which is a network of simple 2-stream heat exchangers only. MCHE has a number of bundles arranged one after another. In each bundle, mixed-refrigerant (MR) flows in the shell side counter-currently with multiple hot streams in the tube side. Every bundle is quite similar to each other in design and operation. The advantage of having similar bundles is that, same model can be applied for all the bundles. In the superstructure, every possibility for a hot stream to exchange heat with every cold stream and vice versa is included. We split MR into a number of cold streams which exchange heat with hot streams by using these 2-stream heat exchangers.
Fig. 1 shows the superstructure for the case where there are two hot streams (H1 & H2) to be cooled by MR in a bundle. MR gets split into three cold streams (C1, C2 & C3). C1 and C2 can exchange heat with H1 and H2 in four possible

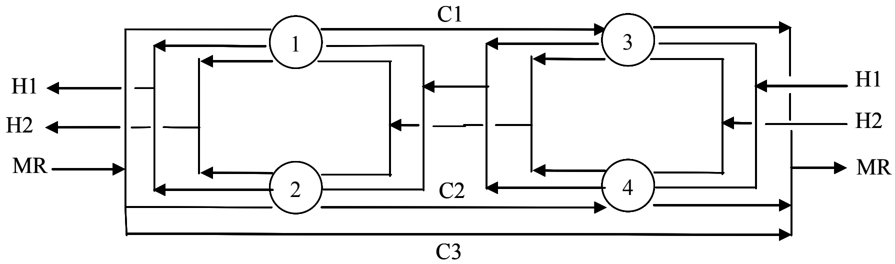

Fig.1. Superstructure representation for a bundle

ways. For each of them, a heat exchanger is shown as circles with a number. C3 is the bypass stream for taking excess MR into account (if there is any). As C3 is not exchanging heat with any stream, there is no heat exchanger for C3. In heat exchanger 1, the cold stream is C1 and there can be only one hot stream, either H1 or H2. If C1 exchanges heat with H1 in heat exchanger 1, H2 can exchange heat with C1 only in heat exchanger 3, and vice versa. If C1 does not exchange heat with any of the two hot streams, heat exchanger 1 will not exist, i.e., the heat transfer area of this exchanger will be zero. Similarly, C2 can exchange heat with H1 or H2 in the heat exchanger 2 and 4, but with only one hot stream in one heat exchanger.

3.1. Modeling Phase Change

So far, superstructures developed for heat exchanger networks only involve heat exchangers for simple cooling or heating purpose. Phase change has not been addressed while calculating the heat duty Q for a heat exchanger. However, a cryogenic process like LNG mainly utilizes the vaporization of MR to cool, liquefy and sub-cool natural gas. Moreover, as the streams are usually mixtures of different components, they change their phases within a temperature range starting from the dew point, T_{dew} till the boiling point, T_{boil}.

Depending on the temperature, any stream can undergo as many as three different types of processes within a heat exchanger. Fig. 2 shows them for hot streams. If a hot stream enters the heat exchanger with a temperature higher than T_{dew}, only the sensible heat Q_{cool} for cooling will be exchanged until it

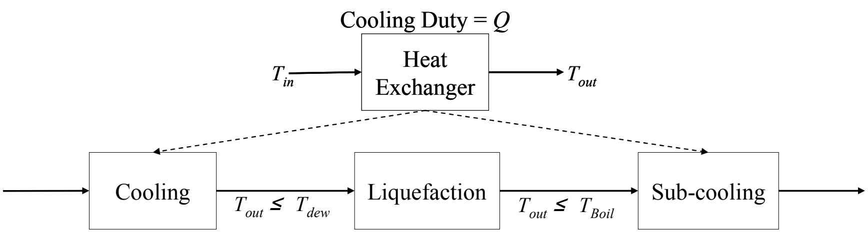

Fig.2. Different scenarios for a hot stream

reaches T_{dew}. From T_{dew} up to T_{boil}, the hot stream will undergo a phase change and heat will be exchanged only in the form of latent heat, Q_{liq}. Once it changes the phase completely, it will only exchange the sensible heat $Q_{sub\text{-}cool}$ for sub-cooling. Therefore,

$$Q_{cool} + Q_{liq} + Q_{sub-cool} = Q \tag{1}$$

$$T_{in} - T_{out} = \Delta T_{cool} + \Delta T_{liq} + \Delta T_{sub-cool} \tag{2}$$

$$Q_{cool} = F\Delta T_{cool} \tag{3}$$

$$Q_{liq} = H_L(V_{in} - V_{out})F / C_p \tag{4}$$

$$Q_{scool} = F\Delta T_{sub-cool} \tag{5}$$

In Eq. (4), V refers to the vapour phase fraction and C_p is the heat capacity. For calculating vapor phase fraction, nonlinear equilibrium flash calculation is applied.

At this point, we need to define binary variables in order to define ΔT_{cool}, ΔT_{liq} and $\Delta T_{sub\text{-}cool}$ as these temperature differences depend on variable outlet temperature T_{out}. For the cold streams, similar formulation applies for modeling heating, evaporation and super-heating.

There will be significant change in heat-transfer coefficient with the change in flow rate. The following correlation for local heat transfer coefficient is derived by simplifying the theoretical method of Bays and McAdams [8] by using experimental data from literature for both shell-side and tube-side heat-transfer coefficients.

$$\alpha = 0.001[F]^{1/4} \quad MW / m^2 - K \tag{6}$$

4. Case study

As an example case, a MCHE with four hot streams (NG, LPG, MRV, MRL) flowing in the tube-side and one cold stream (MR) flowing in the shell-side is considered. The heat capacity flow rates in scaled flow units and actual temperature changes in scaled temperature units are given in table 1.

The computing platform used for the example case is Dell Optiplex GX 280 with Pentium IV HT 3.20 GHz 2 GB RAM and the model is solved by using GAMS/BARON 7.5 with CPLEX 10 (LP) & MINOS 5.51 (NLP). The computation time was 172 CPU s. Model performance (as % deviations from actual) in predicting outlet temperature of hot streams is shown in Table 1. The result shows that our model is capable of predicting the outlet temperatures of the four hot streams with small deviations from the actual outlet temperatures. The model requires further work to match real plant data better.

Table 1. Model performance for the example case

Streams	Heat-capacity flow rate, F	Actual change in temperature, ΔT	% deviations in predicted outlet temperatures	Model Statistics
NG	8.60	1.00	+5.21	504 constraints, 372 continuous variables, 84 binary variables, 164 nonlinear terms, 1132 non-zeros
LPG	0.48	1.00	+7.96	
MRV	3.40	0.72	–4.44	
MRL	14.4	0.52	+5.71	
MR	19.0	0.96	–	

5. Conclusions

In this paper, a superstructure based MINLP approach is presented to model one bundle of MCHE. Also, phase change is modeled for the first time for a heat exchanger network. The model can be extended further for multi-bundle modeling, matching with plant data and matching historic data over time, addressing heat leak to MCHE, etc. As the model is a non-convex MINLP, the global solution is not guaranteed. To overcome this problem, we need to look for reducing the model complexities to make it convex. Further improvements of the model will justify more of its usefulness in real plant operation and optimization.

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