21st European Symposium on Computer Aided Process Engineering – ESCAPE 21
E.N.. Pistikopoulos, M.C. Georgiadis and A.C. Kokossis (Editors)

Optimization of LNG plants – challenges and strategies

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Abstract

In this paper we go through different approaches that have been applied to optimization of processes for liquefaction of natural gas. We discuss the challenges that are present in the different approaches, and strategies that are used to overcome these challenges. We also use our own models of the widely used and well known propane precooled mixed refrigerant process to exemplify these challenges and strategies.

Keywords: LNG, Optimization, Simulation, Control

1. Introduction

Plants for production of liquefied natural gas (LNG) have been in commercial operation since the 1960s, with the first regular exporting facility opening in Algeria in 1964 (Geist, 1983). Several papers addressing optimal design of LNG plants have been published, but few that address operation and control of existing plants. In the cases where operation is sought to be optimized, the approach is debottlenecking through installing new equipment. In this paper we seek to describe the optimal operation problem, and the challenges that arise when solving it.

2. Optimal design and operation of LNG plants

When we talk about optimization of LNG plants, we are discussing one of two: The first is *plant design,* which deals with choosing the optimal equipment size and process setup for the circumstances. The optimal design depends on expected feed gas conditions, economic expectations, climate at the plant location, and environmental and

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safety regulations. The other approach is *plant operation.* Optimal plant operation means to manipulate operation of the plant such that the daily profit is maximized. This corresponds to either minimizing the production costs, or maximizing the production. Which objective one seeks to optimize, depends on the short-term situation – if product prices are high, it is better to produce as much LNG as possible. If prices are low it is desirable to produce only the amount one is committed to deliver, at minimum cost.

3. Earlier work on LNG optimization

The technical conferences held every 3 years since 1968, have been the main arena for exchange of knowledge on the different aspects of the LNG value chain. Most papers focus on experiences with new process units, or on increasing plant capacity through debottlenecking. Only in the last decade has mathematical optimization of liquefaction plants received attention in published literature.

The first systematic tool in use for improving liquefaction efficiency was exergy analysis, which started to gain attention during the 1970s (Durr et. al, 1998). It has since remained in use as a means of pinning down the sources of efficiency losses to particular parts of the processes. See also (Liu et.al., 1998).

Pillarella et.al. (2005) use an SQP algorithm to optimize design of a propane precooled mixed refrigerant process, whereas Jensen and Skogestad (2006) use a similar algorithm on the simpler PRICO process (design *and* operation). However, derivative-free methods have seen wider use than continuous methods. Shah et.al. (2007) use a genetic algorithm to optimize design for gas-phase refrigeration, Aspelund et.al. (2010) use the Tabu search method on the PRICO process. Another approach which is also used is to simulate the model for a range of values for the key parameters to identify the optimal solution. In Paradowski et.al. (2004), the C3-MR process is studied by varying refrigerant composition and compressor speed. There are no studies which use a standard commercial process simulator to optimize a pure operation problem with a method that uses gradient information. In this paper we discuss some of the challenges that may explain why.

4. Challenges in optimization

The most obvious challenge in optimization arises if the process simulator used for calculation of objectives and constraints is not guaranteed to converge to a solution every time it is called by the optimization routine. This means the model has to be formulated in such a way that it is easy to converge. In particular, this means iteration loops within the process simulator should be avoided. If convergence cannot be guaranteed, a continuous method is not feasible. Aspelund et.al. (2007) handle this approach by adding a penalty to the objective if the simulation does not converge.

Unisim® is a typical example of a sequential-modular solver, and it is important to choose the right variables to specify, so as to make convergence as simple as possible.

Another aspect is that most process models, including those of LNG plants, include recycle streams that need to be converged as part of the simulation. It is often better to let the convergence of these recycles be part of the optimization, rather than letting the process simulator take care of them. Thus the process model will not be converged at every iteration of the optimization – this is called infeasible-path optimization (Biegler and Hughes (1982), Biegler (2010)).

5. Example process: C3-MR. Modeling, degrees of freedom

The Air Products C3-MR process has been the most widely utilized process for natural gas liquefaction, since its invention in the 1970s (Chiu, 2008). The name stems from the fact it uses a propane (C3) precooling cycle and a mixed refrigerant (MR) liquefaction cycle. The plant includes units for removal of water, sulfur and CO_2 and a fractionation column - for simplicity, these units are omitted in this work. For a description of the process and discussion of design issues, see Newton et.al. (1986). The model has been made in Unisim® Design. The model uses simplified compressor models (with constant efficiency η = 0.80). For the multistream heat exchangers, specifications are made on the product *UA* of heat transfer coefficient *U* and heat transfer surface *A* between every hot stream and the cold stream. MR consists of C_1-C_3 and N_2. The Peng-Robinson equation of state is used for thermodynamic properties.

The C3MR model has got 13 variables we may manipulate; Two flows of C3 in the precooling loop, total flow of MR, the amount of cooling in the condenser, four pressures in the C3 loop, two pressures in the MR loop and three molar fractions in the MR. The condenser duty is kept at maximum, the LNG exit temperature LNG is at its maximum value and superheating of propane to the compressor is at its constraint value, so three constraints are always active - thus we have 10 degrees of freedom.

6. Simulation examples

6.1. Problem description

When optimizing the liquefaction part of the C3MR process, the temperatures of natural gas (NG) and mixed refrigerant (MR) out of the precooling section are assumed given, as well as pressure, composition and flowrate of NG. The objective is then to manipulate the 6 remaining variables so that the work used for compression of MR is minimized, keeping a sufficiently low LNG exit temperature. Heat exchanger UA values are fixed. There are three possible model formulations for this problem:

1. Specify the UA values inside the Unisim model, and let Unisim solve recycles.
2. Specify the UA values inside Unisim, recycles included in optimization problem.
3. Specify stream temperatures rather than UA values, adding the UA specifications as equality constraints in the optimization.

6.2. Robustness of different model formulations and optimization efficiency

To illustrate how the model formulation affects robustness and accuracy, we have performed simulations with the three formulations mentioned above. High and low refrigerant pressure and refrigerant flow have been varied over the range they are allowed to vary over in optimization. 75 calls to the flowsheet resulted in about 20 failures when the recycles were solved by Unisim, rendering that approach inefficient. When the internal recycles in Unisim were inactive, the simulation would generally converge, but occasional failures in the heat exchanger model occurred. When specifying temperatures, convergence failures did not occur.

Optimizations have been carried out using Matlab. With formulation 1, the frequent flowsheet convergence failures lead to unreliable gradient calculations. In optimization this makes convergence of the optimization problem unlikely, because the optimization algorithm fails to recover from infeasible intermediate points. With formulations 2 and 3, the gradient calculations rarely fail, but progress towards a feasible solution is typically slow and often fails. In the cases where convergence is achieved, the solution is typically very near to the initial point. This is surprising, since the nominal point is calculated using a given minimum ΔT. As shown by Jensen and Skogestad (2008), this formulation will be sub-optimal when going from design to operation, thus one would expect that the solution would differ more from the initial point.

6.3. Possible strategy to simplify optimization

A reoccurring problem when optimizing is that intermediate points often become infeasible, such that convergence of the overall flowsheet becomes difficult. A way of getting around this is to reformulate the problem with different free variables x. The new variables should at optimum remain close to constant with changing disturbances. From the nature of the process, some variables suggest themselves; cold end temperature difference, and the ratio between the molar flowrates of NG and MR. In the precooling part of the plant, expressing the superheating in terms of molar enthalpy rather than temperature turns a non-smooth function into a smooth one. One may link this strategy and the control strategy of *self-optimizing control* (Skogestad, 2000) which means “select variables to control at constant set points such that near-optimal operation is maintained when disturbances occur”. Using process insight, it is possible to identify variables, or variable combinations, that will remain nearly constant over major parts of the disturbance space. One may also use an approach called the *null-space method* (Alstad and Skogestad, 2000).

7. Conclusions

We have summarized the approaches that have been taken to optimization of natural gas liquefaction plants, the methods and some of the most common challenges.

It is clear that when using an approach where the optimization and flowsheet solution are done by different programs, the choice of specified variables has a huge effect on the robustness of the solution procedure. For the example process, temperature specifications are the most robust. We have also shown that an infeasible-path approach is more likely to find a solution, but that the solution cannot always be trusted to be the true optimum.

Future work may include attempting to use the "self-optimizing control" approach to find which variables one should specify in order to make the optimization problem simple and robust. We would also like to generalize the approach to other chemical processes, as the challenges presented here are not in any way unique to refrigeration processes.

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Site-wide process integration for low grade heat recovery

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Abstract

Large quantities of unrecovered low-grade heat are wasted across the process industry. Wide range of technologies and design options for recovering low grade heat are available, including heat pumps, organic Rankine cycle (ORC), energy recovery from gas turbine exhaust, absorption refrigeration, and boiler feed water heating. However, it is not straightforward to identify the most appropriate technology to be implemented, due to complex design interactions inside energy systems in process industry.

Process integration of technologies using low-grade heat in the context of a process site has been considered. Simulation model for heat recovery processes has been developed to evaluate techno-economic performance of each technology and to assess the impact of quality and quantity of available low-grade heat sources on the site. Site-wide potential for the utilization of low grade heat has been evaluated with site analysis tool, and the integration of design options for using low-grade energy are systematically screened and compared in a holistic manner. A case study has been carried out to demonstrate the applicability of design methodology proposed in this work and significant benefits of using an integrated approach when implementing low-grade energy upgrading and/or recovery in the context of industrial application.

Keywords: low grade heat, heat integration, site analysis, heat pump, ORC, absorption refrigeration

1. Introduction

Low grade heat is often wasted in process industries, although energy-efficient upgrade, use and recovery of low grade heat can lead to significant energy savings (Al-Rabghi et al., 1993). Improving energy efficiency of industrial energy systems has been regarded as one of important topics in process engineering communities. However, most of studies so far have been focused on the generation and use of high grade energy sources, for example, generation of very high pressure steam and its utilization in power production or distribution to downstream processes. Recent study indicates that significant amount of low grade heat is still being wasted (Yu et al., 2008) and therefore, it is required to develop the methodology which evaluates energy saving potentials associated with low grade heat recovery and provides design guidelines for utilizing such low grade heat in process industries in a most economic and sustainable manner. Another strong incentive to investigate the recovery of low grade heat is related to potential benefits from the integration of industrial energy systems with district energy infrastructure, in which low grade heat from industrial sites can be effectively utilized, for example, as a heat source to local communities. The study aims to develop integrated design frameworks which can systematically evaluate techno-economic viability of technologies using low grade heat in the context of total site. Low grade heat