Computers and Chemical Engineering 96 (2017) 87–102

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Bi-level optimizing operation of natural gas liquefaction process

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ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form 15 October 2016
Accepted 19 October 2016
Available online 20 October 2016

Keywords:
Natural gas
Liquefaction
Refrigeration
LNG
Optimizing control

ABSTRACT

The production of liquefied natural gas (LNG) is a highly energy intensive process, as required liquefaction temperature is approximately −160 °C at atmospheric pressure. In this study, we propose a novel bi-level optimizing operation system for an LNG process, which consists of a real-time steady-state optimizer (RTSSO) and a decentralized control system. The RTSSO computes the optimal operating conditions such that the compressor power is minimized, while the decentralized control system performs real-time feedback actions to attain the target operating points against various disturbances. Special attention was given to the decentralized control system so that i) the process operation can be rapidly stabilized, and ii) the developed system can be seamlessly applied to an actual process. The performance of the proposed operation system was validated in a numerical LNG plant that precisely replicates an actual plant that produces 100 t of LNG per day.

1. Introduction

Natural gas (NG) is the fastest growing fossil fuel. Worldwide, the total consumption of NG is anticipated to increase by nearly 70% between 2002 and 2025 (EIA, 2005). There are several stimulators for this growth that mainly originate from its clean properties, *i.e.* approximately half of the CO_2 emissions of conventional coal power generation, minimal SO_x and NO_x emissions, and the introduction of carbon price policies (Gómez et al., 2014; Kumar et al., 2011; Taylor et al., 2012). Large amounts of NG are found in remote locations where pipeline transportation in gaseous phase is infeasible or uneconomical (Lee et al., 2012; Moein et al., 2015). Thus, in many cases, transporting liquefied NG (LNG) by ships is preferred (Park et al., 2016; Won et al., 2014). The liquefaction of NG facilitates the shipment as the volume is reduced by a factor of 600 (Kumar et al., 2011).

The LNG production process (hereafter, referred as LNG process for simplicity) consists of expensive and delicate pieces of equipment, such as compressor and cold box, and so stabilizing process operation is an important issue in real industrial plants (Jensen and Skogestad, 2009). In addition, because the required liquefaction temperature is approximately −160 °C at atmospheric pressure (Mortazavi et al., 2012), utility management such as heat and electricity is also a crucial issue for LNG producers to secure competitiveness (EIA, 2003).

Similarly to other chemical processes such as distillation (Lei et al., 2013; Mizoguchi et al., 1995; Rewagad and Kiss, 2012), crystallization (Aamir et al., 2010; Ma et al., 2002; Nagy and Braatz, 2012), simulated moving bed (Abel et al., 2005; Natarajan and Lee, 2000; Klatt et al., 2002), and batch-wise reactors (Kiparissides et al., 2002; Lee et al., 1999; Seo et al., 2007; Won et al., 2009, 2010), the stability and economics of the LNG process can be greatly improved by introducing an optimal operation system. However, published works on this subject appear to be limited. The majority of studies reported to-date has focused on the design issues, including energy analysis (Kanoğlu, 2002; Li and Ju, 2010; Morosuk et al., 2015; Remeljej and Hoadley, 2006; Vatani et al., 2014), alternative process configuration (Chang et al., 2011; Kikkawa et al., 1997; Lee et al., 2012; Wang et al., 2012), heat exchanger design including refrigerant type optimization (Aspelund et al., 2010; He and Ju, 2014; Khan et al., 2013; Khan and Lee, 2013; Lee et al., 2002; Nogal et al., 2008; Xu et al., 2013), and dynamic modeling of cryogenic systems (He and Ju, 2016; Rodríguez and Diaz, 2007; Singh and Hovd, 2007). Only few groups have aimed at developing energy-thrifty operation system for a simple refrigeration cycle (Jensen and Skogestad, 2007a,b) and simplified commercial LNG processes (Husnil et al., 2014; Michelsen et al., 2010) focusing on the decentralized control technique. No published literatures have demonstrated efforts towards optimizing control of a realistic industrial LNG plant.

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http://dx.doi.org/10.1016/j.compchemeng.2016.10.009

Nomenclature

d	Disturbance
E	Compressor power consumption
g	Constraint
Abbreviation	
CV	Controlled variable
DOF	Degree of freedom
HMR	Heavy-key mixed refrigerant
IMC	Internal model controller
JT	Joule-Thomson
LMR	Light-key mixed refrigerant
LNG	Liquefied natural gas
MCHE	Main cryogenic heat exchanger
MR	Mixed refrigerant
MV	Manipulated variable
NG	Natural gas
PID	Proportional-integral-derivative
RNGA	Relative normalized gas array
RTSSO	Real-time steady-state optimization
WEDT	Warm end delta temperature
Symbols in control structure	
FC	Flow controller
FFC	Flow fraction controller
HC	Hand controller
LC	Level controller
LS	Low selector
PC	Pressure controller
PPC	Compression ratio controller
SC	Speed controller
TC	Temperature controller
TDC	Temperature difference controller

Accordingly, the objective of this study is to propose a novel bi-level optimizing operation system for the LNG process. The operation system consists of two major parts: the real-time steady-state optimizer (RTSSO) and the decentralized control system composed of multiple PID controllers. The RTSSO, whenever invoked, determines new optimum operating points. Special attention is paid to develop the sophisticated decentralized control system that runs continuously and conducts the regulation of process. We develop two separate control systems, where each is dedicated to liquefaction and refrigeration units, in addition to the integrated control system that can solve the energy imbalance issues that arise when controlling the liquefaction and refrigeration units independently.

The performance of the proposed operation system is validated in a numerical 100 ton-per-day LNG plant, which is delicately developed to replicate an actual plant in Incheon, Korea. It serves as not only an operating training system but also as the testing site for the new operation system so that it can be seamlessly implemented to the actual plant. Therefore, all detailed features of the actual plant, such as safety interlock logics and operational constraints of equipment and instrument, are precisely reflected in the numerical plant.

2. Process description

Fig. 1 shows the process flow diagram of the 100 ton-per-day LNG plant being constructed in Incheon, Korea. In this plant, the Korea Single Mixed Refrigerant (KSMR) cycle which was developed and patented by Korea Gas Corporation (KOGAS) was adopted as a liquefaction process (Lee et al., 2013). Among the process sections, the liquefaction and refrigeration units to cool and liquefy NG require the largest amount of energy.

Table 1
Design conditions for the LNG process.

Condition		Value
LNG temperature at the exit of MCHE (°C)		−150.7
Feed gas temperature (°C)		12.1
Feed gas pressure (bar)		63.4
Feed gas composition	Nitrogen	0.0496
	Methane	0.8690
	Ethane	0.0510
	Propane	0.0213
	i-Butane	0.0044
	n-Butane	0.0045
	i-Pentane	0.0001
	n-Pentane	0.0001

As illustrated in Fig. 1, there are two major process circuits in liquefaction and refrigeration units: NG circuit and mixed refrigerant (MR) circuit. Each is described separately.

The pre-treated NG from feed gas intake facility is a mixture of nitrogen, methane, ethane, propane, butane, and pentane at approximately 63.4 bar and 12.1 °C as given in Table 1. It is cooled to −16.3 °C as it passes through the top bundles of main cryogenic heat exchanger (MCHE). The scrub distillation (SD) column performs two main functions: (i) the removal of heavy hydrocarbons to avoid freezing at the cold end of the MCHE and (ii) the recovery of ethane and propane for refrigerant make-up. The bottom product of SD is routed to the fractionation section for further separation into ethane, propane, butane, and heavier hydrocarbons. The vapor overhead from SD is partially condensed at the middle bundle of MCHE before being fed to scrub distillation reflux drum (SDRD), where vapor and liquid are separated. The vapor is then sent to the bottom section of MCHE and is reduced at a temperature below −150 °C, which causes the NG to be liquefied. The LNG is then sent to separator SR3 through the control valve V3. The bottom liquid of the separator SR3 is pumped to LNG storage tank, while the boil-off gas from the top is used as a fuel or otherwise routed to flare header.

The MR circuit is a closed refrigeration loop that supplies the cooling demands to MCHE. The MR is composed of nitrogen, methane, ethane, and propane. It is pressurized by a series of compressors that are driven by independent motors and operate at different speed. The pressure of MR reaches approximately 52.5 bar inside separator SR2. The liquid and vapor from SR2 consist mainly of heavy and light components, respectively. The heavy-key MR (HMR) is sub-cooled through the top bundle of MCHE and then is let down in pressure through Joule-Thomson (JT) valve V1. This low pressure stream reenters MCHE as a cooling medium and provides the cooling demand to pre-cool feed gas and light-key MR (LMR) from SR2. In addition, this stream sub-cools the HMR from SR2 and is finally superheated at the end of the MCHE. The fully vaporized MR is then recycled to the compressor CP5. The LMR from SR2 is condensed and sub-cooled in MCHE. It exits at the cold end of MCHE and is reduced in pressure across the JT valve V2. This low pressure stream is then completely vaporized and superheated by exchanging heat with the NG streams and with LMR and HMR from SR2. Finally, it is returned to the compressor CP1.

Two independent temperature controllers that manipulate the bypass valves V4 and V5 are installed to adjust the degrees of feed gas pre-cooling and SD condenser cooling. All the compressors are centrifugal types and are equipped with the anti-surge recycle line (dashed lines in Fig. 1), suction drum, and fan-type discharge cooler. The anti-surge valves are manipulated by independent safety control logic. A distributed control system from Yokogawa Co. is used