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Delta-operator-based adaptive model predictive control and online optimization of a natural gas liquefaction process

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HIGHLIGHTS

- A novel energy optimizing control system for a natural gas liquefaction process.
- Combined optimizer, model predictive controller, and model parameter estimator.
- Performance validation in a numerical 100 ton-per-day LNG plant.

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ABSTRACT

The production of liquefied natural gas (LNG) is an energy-intensive process. The required temperature is approximately −160 °C at atmospheric pressure. As a result, energy efficiency is the major concern in the process operation. Addressing this issue, we propose a new energy optimizing control system for the LNG process. It consists of an online steady-state optimizer, a model predictive controller (MPC), and a model parameter estimator. The optimizer computes optimum compression ratios and warm-end delta-temperature, while the MPC steers the process toward the target operating conditions. Particularly, the MPC was developed in a delta-form for better numerical stability during continuous operation of a multiple-input multiple-output system with widely distributed time constants. To minimize process perturbation by identification experiments, the model for controller design was derived from a rigorous LNG simulator. To cope with the model error from the true system, a small number of tunable parameters were introduced so that they can be corrected online by model parameter estimator during the process operation. The performance of the developed operation system was demonstrated in a numerical 100 ton-per-day LNG plant, which was precisely constructed to replicate an actual plant in Incheon, Korea.

1. Introduction

Natural gas (NG) is the cleanest fossil fuel, producing significantly lower carbon emissions than coal or oil. As concern for global warming increases, the demand for NG rapidly increases as a source of clean energy, especially in power generation industries. Worldwide, the NG demand is expected to increase by nearly 70% during the period from 2002 to 2025 (International Energy Outlook, 2005).

Huge NG reservoirs have been found in many regions of the world, but they are frequently located in remote places far from the consumption areas (Park et al., 2016). NG can be transported either through pipelines or by liquefied natural gas (LNG) carriers. For long-distance overseas delivery, transporting LNG by ships is preferred (Won et al., 2014). The liquefaction of NG can reduce the volume by a factor of 600, which greatly facilitates shipment (Wang et al., 2011).

Liquefaction of NG is an energy-intensive process. The required temperature is approximately −160 °C at atmospheric pressure (Mortazavi et al., 2012). Thus, enhancing operational energy efficiency is an important issue for LNG suppliers to secure competitiveness (Won and Kim, 2017). However, although the economy of LNG production can be significantly improved by an optimal operation system, published works on this issue seem to be limited. The majority of the papers are focused on design issues, including exergy analysis (Tsatsaronis and Morosuk, 2010a,b; Morosuk et al., 2015; Remeljej and Hoadley, 2006; Morosuk and

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Tsatsaronis, 2011; Morosuk and Tsatsaronis, 2008), new process configuration (Mortazavi et al., 2012; Wang et al., 2012; Chang et al., 2011; Kikkawa et al., 1997; Lee et al., 2012), heat exchanger design with refrigerant optimization (Khan et al., 2013; Xu et al., 2013; Aspelund et al., 2010; Khan and Lee, 2013; He and Ju, 2014; Nogal et al., 2008; Hatcher et al., 2012; Hwang et al., 2013), and steady-state and dynamic modeling (He and Ju, 2016; Singh and Hovd, 2007; Son et al., 2016; Rodríguez and Diaz, 2007). Only few groups have aimed at developing an operation system for a simple refrigeration cycle (Jensen and Skogestad, 2007a, b) and a simplified commercial LNG process (Michelsen et al., 2010; Husnil et al., 2014; Mandler, 2000; Khan et al., 2010; Husnil and Lee, 2014). No published works have been reported regarding an optimizing control system for a real-scale industrial LNG plant.

Similarly to other processes, such as distillation (Lewis et al., 1991; Qin and Badgwell, 2003; Tatulea-Codrean et al., 2016; Yang and Biegler, 2013), crystallization (Kwon et al., 2014; Mesbah et al., 2011; Nagy et al., 2013), and chemical reactor (Maner et al., 1996; Özkan and Kothare, 2006; Saade et al., 2014; Won et al., 2010), the LNG process is a good target where the operation can be improved by a model predictive controller (MPC). Refrigerants circulate continuously in a closed-loop cycle by varying pressures and exchanging energy with NG in a multi-tubular heat exchanger. Due to this, a severe interaction exists between manipulated and controlled variables. However, the previous reports mentioned above (Jensen and Skogestad, 2007a,b; Michelsen et al., 2010; Husnil et al., 2014; Mandler, 2000; Khan et al., 2010; Husnil and Lee, 2014) were all focused only on the decentralized control technique, and no studies have investigated the potential of the MPC or operational optimization of the LNG process.

The performance of the MPC strongly depends on the accuracy of the process model (Ljung, 1999). However, the following characteristics of the LNG process add challenges to the task of model identification. First, the process is composed of delicate pieces of equipment, such as compressors and a cold box; thus, the stability of the process operation is the highest priority. Identification experiments in a real process would be difficult to perform because the arbitrary perturbation of the process may cause instability and damage to the equipment. Second, the LNG process has a wide range of dynamics, represented by a time constant. Because the sampling rate is generally determined by the shortest time constant in a multiple-input multiple-output (MIMO) system, the discrete-time model for a subsystem with a large time constant becomes vulnerable to truncation error due to finite-bit data representation, which is crucial for real-time applications (Goodwin et al., 2008).

Based on the above considerations, the objective of this study is to propose a novel energy optimizing control system for an LNG process. The optimizing control system consists of two tiers, a MPC cascaded by an online optimizer. The optimizer calculates the optimum operating conditions, and the designed MPC is put into an action to steer the process toward the target conditions. To accommodate industrial practice, where operational stability is the highest priority, the model for the controller design is derived from a rigorous LNG process simulator constructed in this study. To cope with the model discrepancy from a true system, an adaptation mechanism is added to the MPC technique. A small number of tunable parameters that can modify the major characteristics of the process model are incorporated into the state-space model and updated online during operation by a model parameter estimator. The process model and MPC algorithm are developed in the delta-form so that the effect of truncation error

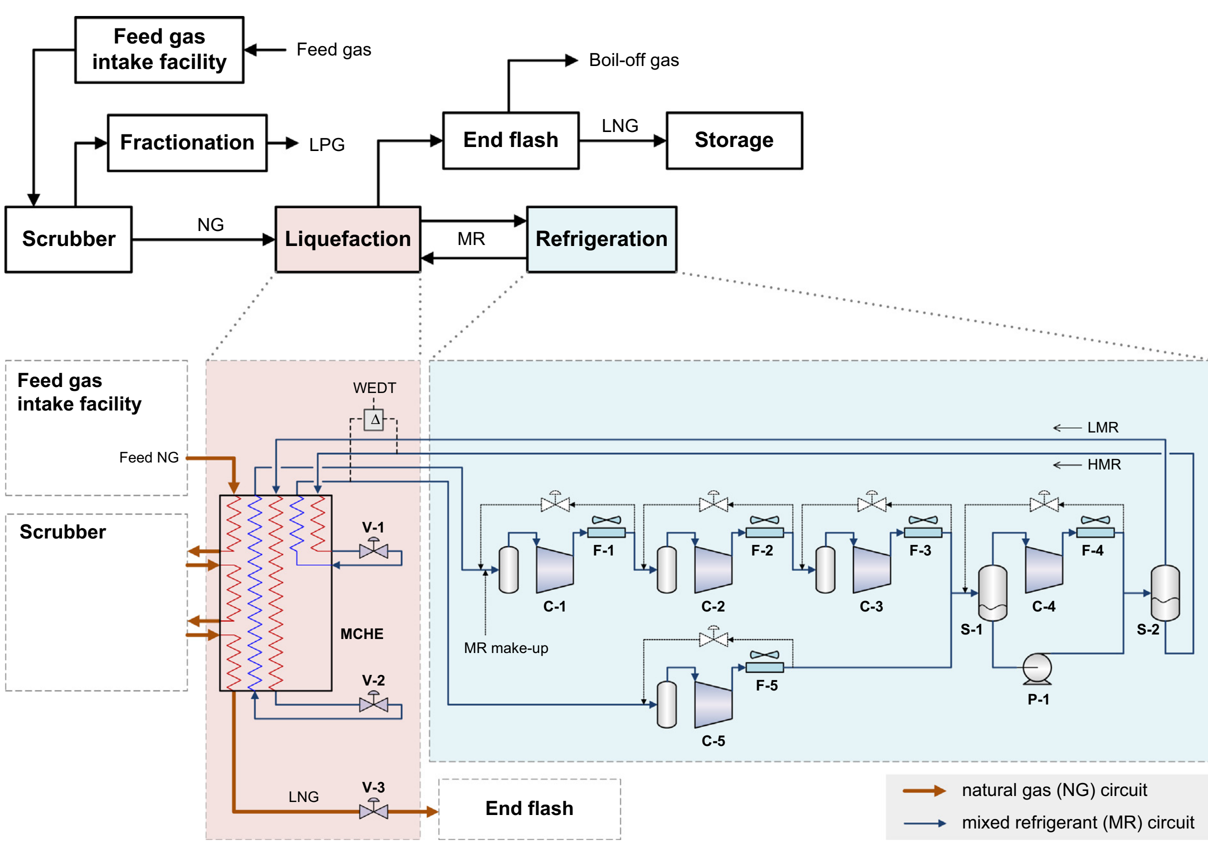

Fig. 1. Overall process flow diagram of the 100 ton-per-day LNG plant being constructed in Incheon, Korea. MCHE: main cryogenic heat exchanger, LMR: light-component mixed refrigerant, HMR: heavy-component mixed refrigerant.