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# A decomposition methodology for dynamic modeling of cold box in offshore natural gas liquefaction process

Chul-Jin Lee[a], Kiwook Song[b], Yongseok Lee[b], Chonghun Han[b,*]

[a] Engineering Development Research Center, Seoul National University, Gwanak-ro, Gwanak-gu, Seoul 151-744, Republic of Korea
[b] School of Chemical and Biological Engineering, Seoul National University, Gwanak-ro, Gwanak-gu, Seoul 151-744, Republic of Korea

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ABSTRACT

Natural gas liquefaction process using mixed and/or cascade refrigerant is popular in onshore LNG (liquefied natural gas) plant. Similar attempt has been adopted for FLNG (floating LNG) but still needed for the improvement of the process to enhance its efficiency as well as reliability. The dynamic modeling of cold box which is a core equipment in LNG/FLNG plant enabling to liquefy natural gas is crucial in order to develop or improve a liquefaction process concerning operability and controllability. A decomposition methodology for dynamic modeling of cold box in the case of lack of internal design data at early design stage is presented. The proposed methodology is validated through the industrial application of offshore natural gas liquefaction process and expected to be extensively applied to the various process designs which require dynamic simulation of cold box unit.

## 1. Introduction

Natural gas is the fastest growing energy source in the world the consumption of which is expected to increase at an average rate of 1.4–1.6% per year from 2008 to 2035, owing to its lower environmental impact compared to other fossil fuels (Gruenspecht, 2010). With this growing demand of natural gas, a number of researches have been investigated on the perspectives of how to reduce the production cost and improve the efficiency of the liquefaction processes which is the core part in the LNG value chain (Kikkawa et al., 1997; Alabdulkarem et al., 2011; Roberts and Brostow, 2014; Minta et al., 2008).

The natural gas liquefaction processes using mixed refrigerants (MR) utilize the plate-fin type heat exchangers (PFHEs), sometimes called the cold box, to associate all the streams in the heat exchange into a single piece of equipment. This greatly improves the efficiency and lowers capital cost, the number of equipment, space requirement, etc.

The greatest usefulness of PFHEs exhibited in handling more than two streams, usually up to 12 streams. Plate-fin, coil-wound, and multi-pass shell-and-tube types are all multi-stream heat exchangers extensively used in cryogenics, gas separation, and liquefaction processes. PFHEs usually have a higher heat transfer area to volume ratio (300–1000 $m^2/m^3$) compared to coil-wound heat exchangers (50–150 $m^2/m^3$). The high degrees of compactness and flexibility in stream arrangements are their main advantages (Pacio and Dorao, 2011).

Most of the research area dealing with LNG liquefaction process and cold box consists of the evaluation of the performance of the process focusing on the thermodynamic efficiency using exergy minimization technologies (Remeljej and Hoadley, 2006; Kanoğlu, 2002), and the optimization of the process design and operation through rigorous simulations and algorithms, and plant performance improvement by process integration and equipment enhancements (Lim et al., 2013; Skaugen et al., 2014).

Despite the existence of prior work, very few studies have focused on the dynamic modeling and simulation of the natural gas liquefaction process. Particularly for offshore plants, the process design has to be performed in a dynamic manner owing to their highly dependent nature on the operational environments like fluctuating disturbances, which are different from those for onshore plants (Song et al., 2012; Peric et al., 2009).

Dynamic modeling and simulation of heat exchangers has been mainly focused in the viewpoint of dynamic behaviors as well as design aspects and. Sharifi et al. (1995) have studied to develop a dynamic simulation of plate fin heat exchangers, but coupling of the flow and temperature which shows the system response to flow rate change still remains. Pingaud et al. (1989) and Averous

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* Corresponding author. Tel.: +82 2 880 1887; fax: +82 2 880 1887.
*E-mail address:* chhan@snu.ac.kr (C. Han).

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**Nomenclature**

| | |
|---|---|
| FLNG | floating LNG |
| JT | Joule–Thomson |
| $k$ | pressure flow coefficient $\left(\text{kg/h}/\sqrt{\text{kg/m}^3\,\text{kPa}}\right)$ |
| LNG | liquefied natural gas |
| MR | mixed refrigerant |
| $m_{\text{ref}}$ | mass, flow of rate of streams in original steady state design (ton/h) |
| $m_{\text{sim}}$ | mass, flow of rate of streams in dynamic simulation (ton/h) |
| PFD | process flow diagram |
| PFHE | plate-fin type heat exchanger |
| PI | proportional-integral |
| PRSV | Peng–Robinson–Stryjek-Vera |
| $T_{\text{ref}}$ | temperature of streams in original steady state design (°C) |
| $T_{\text{sim}}$ | temperature of streams in dynamic simulation (°C) |
| UA | heat transfer coefficient (kg/°C h) |
| $X_{\text{ref}}$ | temperature, flow rate of values of streams in original steady state design |
| $X_{\text{sim}}$ | temperature, flow rate of values of streams in dynamic simulation |
| WEDT | warm end delta temperature |

et al. (1999) emphasized the importance of dynamic studies in complement with steady-state ones for plate fin exchangers. Luo et al. (2003) developed own dynamic simulator for PHTE. Singh and Hovd (2007) studied the effect of the simplification of the heat exchanger model on systematic control structure design in the PRICO process in order to develop a dynamic model, illustrating the effect of the operating strategy (maximum production and given production) on the number of unconstrained degrees of freedom. Michelsen et al. (2010) developed a dynamic, control relevant, and mechanistic model for operability analysis of the TEALARC process. Although the thermodynamics of this model are simplified, it has sufficient complexity for both steady-state and dynamic operability analyses. Applications to other processes for cold box with controllability have been studied (Shin and Lee, 2009; Mandler, 2000; Boehme et al., 2003).

Even though all of these relevant studies deal with the operability and dynamic performance of the liquefaction processes through control modeling based on the structure design procedure, any systematic research on the general methodology of the internal design of the LNG multi-stream heat exchanger is yet to be developed in accordance to the dynamic behavior of a fluid like LNG. Furthermore, the refrigerants participating in the multi-stream heat exchanger have not been obviously interpreted or evaluated.

The internal design of the PFHEs, mightily important for the dynamic modeling of the liquefaction process, has an impact on the thermodynamic and hydrodynamic behavior of the fluids passing through the plate-fins where complicated heat transfer and phase changes occur. It aims to match the results of the dynamic modeling calculated sequentially through several discrete grids of each PFHE to those of the steady-state modeling using an error minimization feedback algorithm. The main advantage of the proposed decomposition methodology is that it can handle the coupling between the flow rate and temperature effectively. When the parameter regarding flow changes to obtain the target flow rate, the temperature also changes due to the flow variation and vice versa. The proposed methodology enables to handle the coupling highly correlated between the flow rate and temperature using the decomposition algorithm.

In this research, the decomposition methodology for dynamic modeling of cold box is suggested. When the basic design in the static mode is completed, an engineering study of the dynamic behavior must be performed to verify that the process and equipment function in accordance to expectations. The noble methodology is validated with the application of offshore natural gas liquefaction process.

## 2. Theory

### 2.1. Dynamic modeling of a PFHE

Proper equipment sizing, specifying the resistance of unit operations, and adding accurate boundary conditions for the entire flowsheet, are critical for the dynamic simulation of the plant. Dynamic behaviors of streams are affected by the volume of the equipment and hence the geometry information is essential. Rating of a multi-stream PFHE (i) the length and the width of the exchanger, (ii) the layer configuration, (iii) fin types and properties, (iv) zone configuration, and (v) the heat transfer configuration.

In many cases, dynamic simulation is used to check on whether the plant is easy, safe, and cost-efficient to operate, and on whether the equipment functions as expected and in accordance to the design phase of the flowsheet. Therefore, it is common that the exact internal design of the equipment is not prepared a priori and is further finalized according to the simulation results. In these cases, one can use simple exchanger rating tools, i.e. ASPEN MUSE, for preliminary assumption of the geometry.

### 2.2. Layer configuration

The arrangement of streams in the exchanger affects the total heat load distribution. A single pattern of layers repeated over the height of the exchanger block is defined as a set. For optimal layer configuration, single banking of cold and hot layers, with a counter-current flow pattern, and with repeated sets, is assumed. For each layer, fin properties, such as the fin height, thickness, density and others, should be specified.

### 2.3. Zone configuration

A zone is a partitioned length of the exchanger. Each zone features a stacking pattern with one feed and one product connected to each representative layer in the pattern. It is recommended to specify 10 or more heat zones to remove the wiggle temperature profiles. Zone metal properties such as thermal conductivity, and specific heat capacity should also be specified.

In a pressure–flow dynamic model solver, the flow rate in the heat exchanger is calculated using resistance equations. The resistance equation modeled based on the equation of turbulent flow is

$$F = k\sqrt{\rho \cdot \Delta p} \tag{1}$$

where $k$ = pressure flow coefficient, kg/h $\sqrt{\text{kg/m}^3\,\text{kPa}}F$ is the flow rate through each zone in the heat exchanger and $\Delta p$ is pressure difference in the same section, which has a role as driving force of flow. With pre-specified $k$ values, the resistance equation calculates the flow rates from the pressure differences of the surrounding nodes.

For a heat exchanger consisting of $n$ layers with $m$ zones in a set, $n \times m$ $k$ values should be specified. However, the temperature and pressure drops for each zone are not known, thus exact $k$ values cannot be specified. For simplification, we propose to fix the $k$ values to a single value for each layer in every zone. This means that a stream in a layer has equal $k$ values for all $m$ zones, i.e.