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Optimization of Operating Procedure of LNG Storage Facilities Using Rigorous BOR Model

Hosoo Kim*, Myung-Wook Shin, En Sup Yoon***

*Department of Chemical and Biological Engineering, Seoul National University,
Seoul, Korea (e-mail: lake@pslab.snu.ac.kr)
**Korea Gas Corporation, Seoul, Korea
(e-mail: author@snu.ac.kr)

Abstract: In this study, in order to improve the efficiency and the safety of the LNG storage facilities, the rigorous hybrid dynamical model is proposed. This model is composed of continuous state dynamics which estimate the boil-off rate (BOR) based on understanding of the energy and mass transfer between the stratified cells of LNG storage tanks and discrete state dynamics which describe the operational procedure of the boil-off gas (BOG) compressors. By using this model, an optimal operational procedure can be obtained as a dynamic optimization problem with considering the discrete nature of compressors.

1. INTRODUCTION

1.1 Overview

During normal operation, boil-off gas (BOG) is produced in the tanks and liquid-filled lines by heat transfer from the surroundings. Proper handling of BOG during normal operations as well as ship unloading significantly affects the efficiency of the operation and the safety of the whole gasification plant.

Too much BOG inside a storage tank brings about safety issues, and too little BOG caused by overrunning of the BOG compressors may mean unnecessary waste of energy. Hence, optimal operations of BOG compressors need to consider multiple aspects of plant safety and reduced power consumption, simultaneously satisfying all process requirements and constraints. However, due to the not-well known characteristics of the involved dynamics, it is suspected that the BOG compressors are being operated in too much capacity, especially before the ship unloading, and thus unnecessarily consuming too much energy.

1.2 Conventional Method

Conventional methods are summarized in Table 1, where method 1 for a load of 1.1, for example, is to run one compressor at 100% load level continuously and another compressor at 50% for 20% and at 0% for 80% of the operation period, after which the same operation is repeated. Note that a backup compressor is operated idle in any case in order to cover potential failure of a compressor. Failure in the BOG compressor may lead to opening of pressure relief valves, and various studies through dynamic simulations have been reported.

Table 1. Conventional operational methods of BOG compression

Load	Method	No. of compressors operational on each mode			
		100%	75%	50%	0%
1.1~1.5	1	1	-	1	1
	2	-	2	-	1
	3	-	-	3	1
1.6~2.0	1	2	-	-	1
	2	1	-	2	1
	3	-	2	1	1
	4	-	-	4	1
		…			
3.6~4.0	1	4	-	-	1
	2	3	-	2	1
	3	2	2	1	1
	4	1	4	-	1

2. MODELLING OF LNG STORAGE TANKS

For the LNG storage tanks, the experimental approach is very difficult. Because liquefied natural gas is mixture which are composed of nitrogen, methane, ethane, propane and higher molecular weight hydrocarbons and there is complex relationship equation of multicomponent diffusion. Practically, the relationship equation often don't match with the operating commercial tanks, even through the equation is obtained by the pilot-scaled experiment.

In order to appropriately predict vapor evolution rates as well as compositional change of the LNG (i.e., ageing properties), we suppose that a state of thermodynamic equilibrium is imposed on an arbitrarily interfacial film where a convective circulation flow enters and evaporation takes place. The physical picture is shown schematically in Figure 1.

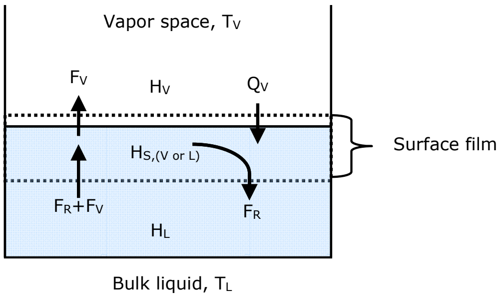


Fig 1. An interfacial film showing Rayleigh flow and the evaporation

Based on the interfacial film model, stratification in a LNG storage tank can give rise to the situation shown schematically in Figure 2. The model is based on material and energy balances on the N cells (liquid stratification) and vapor space. These balances include cargo transfer and liquid recirculation.

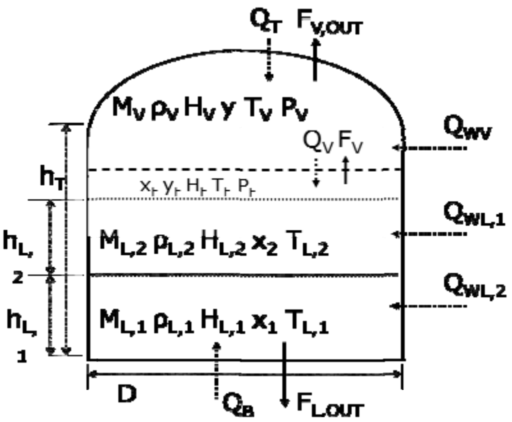


Fig 2. Stratified LNG tank showing the liquid cells.

The following equations describe the cell1 of stratified LNG tank model. In cell1, there are inlet or outlet flows by loading or unloading of LNG. T he component mass and energy balance equation is given in equation 1 and 2. Heestand, et al.(1983) describe the transport phenomena between the stratified cells and heat transfer coefficient can be obtained by the turbulent convective equations 3. Assuming the fully turbulent condition, mass transfer coefficient is defined as equation 4.

$$\frac{dx_1M_{L,1}}{dt} = x_{in}F_{in} - x_1F_{L,OUT} + k_1A(x_2 - x_1) \quad (1)$$

$$\frac{dH_{L,1}M_{L,1}}{dt} = H_{in}F_{in} - H_{L,1}F_{L,OUT} + h_1A(T_{L,2} - T_{L,1}) + Q_B + Q_{WL,1} \quad (2)$$

$$h_i = (\text{constant})k\left(\frac{g\Delta\rho}{\nu^2\overline{\rho}}\right)^{1/3} \quad (3)$$

$$k_1 = \frac{h_1}{C_L} \quad (4)$$

Equation 5, 6 and 7 are the dimensional relations of stratified cells. The rest equations about heat capacity, density and enthalpy of LNG which are functions of temperature, pressure and composition are obtained by Aspen properties of AspenTech, Inc.

$$V_{L,1} = \frac{M_{L,1}MW_{L,1}}{\rho_{L,1}} \quad (5)$$

$$h_{L,1} = \frac{V_{L,1}}{\pi R^2} \quad (6)$$

$$P_{L,1} = P_{L,2} + \rho_{L,2}gh_{L,2} \quad (7)$$

The component mass and energy balance equation of cell2 are given in equation 8 and 9.The rest equations except for equation 10 are same as cell1.

$$\frac{dx_2M_{L,2}}{dt} = -y_FF_V - k_1A(x_2 - x_1) \quad (8)$$

$$\frac{dH_{L,2}M_{L,2}}{dt} = -H_{V,F}F_V - h_1A(T_{L,2} - T_{L,1}) + Q_{WL,2} + Q_V \quad (9)$$

$$P_F = P_2 \quad (10)$$

Heestand, et al.(1983) lay emphasis on necessity of film layer in advanced Hashemi-Wesson model. They assumed the theoretically thin film in vapour-liquid equilibrium state. And, if the film is in the steady-state, the following mass and energy balance equation is obtained.

$$(F_R + F_V)x_L = F_Rx_S + F_Vy_S \quad (11)$$

$$(F_R + F_V)H_L + Q_V = F_RH_{S,L} + F_VH_{S,V} \quad (12)$$

In the above equations, F_R is rayleigh flow representing the convection to liquid phase by density difference.

$$F_R = 0.3276\frac{kA}{C_{L,2}}\left(\frac{g\Delta\rho_{2F}}{\kappa Nu\overline{\rho_{2F}}}\right)^{1/3} \quad (13)$$

$$\Delta\rho_{2F} = |\rho_2 - \rho_F| \quad (14)$$

$$\overline{\rho_{2F}} = (\rho_2 + \rho_F)/2 \quad (15)$$

The equations about vapor-liquid equilibrium and additional properties are obtained by Aspen properties of AspenTech, Inc.

The holdup in vapor phase is calculated from total mass balance equations. Since the important variables, tank pressure, is calculated by vapor holdup, boil-off rate and outlet flow rate by compressor should be obtained exactly.

$$\frac{dM_V}{dt} = F_V - F_{V,OUT} \quad (16)$$

$$\frac{dyM_V}{dt} = y_FF_V - yF_{V,OUT} \quad (17)$$

$$\frac{dH_VM_V}{dt} = H_{V,F}F_V - H_VF_{V,OUT} + Q_{WV} + Q_T - Q_V \quad (18)$$

$$Q_V = (Q_T + Q_{WV})Q_{ratio} \quad (19)$$

The following mathematical program determines an optimal operation strategy for multiple compressors in parallel, which minimizes the total average power consumption. The objective function has two terms. The first one represents the total power consumption, and the second one is a summation of outlet BOG flow.

$$\min \int_{t=1}^{t_f} \sum_{i=1}^{n} W_{i,t} + \sum_{i=1}^{n} F_{comp,i,t} \quad (20)$$

$$\sum_{i=1}^{n} F_{comp,i,t} - F_{v,out} = 0 \quad (21)$$

The power consumption and outlet flow rate by compressor are function of operating mode of compressor. According to operating mode, they have discrete values as shown equations 22, 23. And, the constraints about operating mode are given in equations 24, 25.

$$F_{comp,i,t} = f(mode_{i,t-1}, mode_{i,t}) \quad (22)$$

$$W_{i,t} = f(mode_{i,t-1}, mode_{i,t}) \quad (23)$$

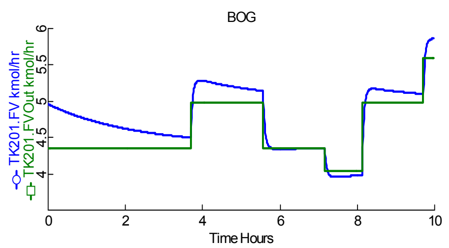
$$mode_{i,t-1} - mode_{i,t} \geq 0 \quad (24)$$

$$\sum_{i=1}^{n} mode_{i,t} - 1 > 0 \quad (25)$$

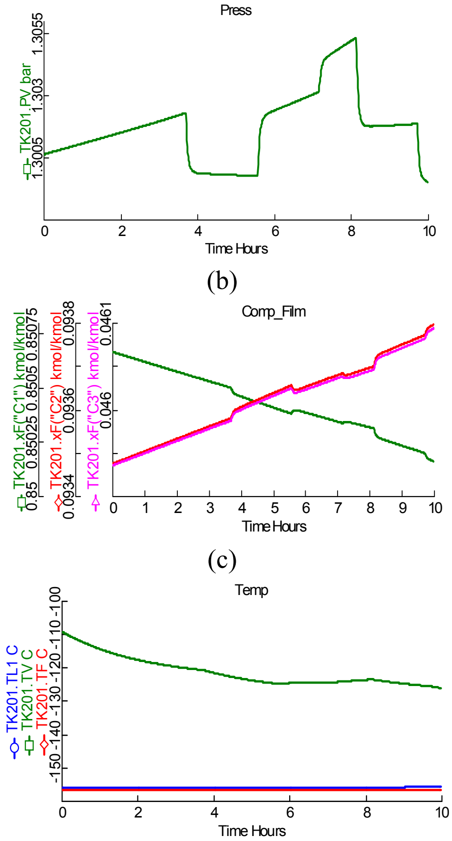
3. SIMULATION RESULT

The following figures are simulation results which is the one case of conventional tank operations. In figure 3(a), the folded straight line indicates the BOG outlet flow by the conventional operation of compressors. Another line indicates the BOG generation at the interfacial film. The pressure of LNG tank in figure 3(b) varies directly as the compressed BOG outlet and has a effect on the BOG generation.

As the BOG generated, for the relative volatility, the composition of methane and ethane at the film increases and the heavy component like propane, butane, etc. relatively decreases. (Figure 3(c)).



(a)

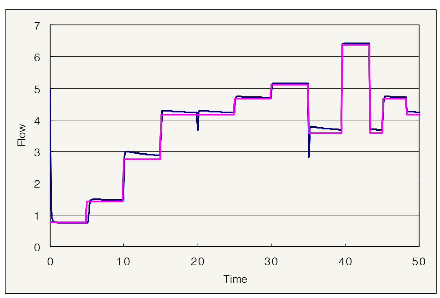


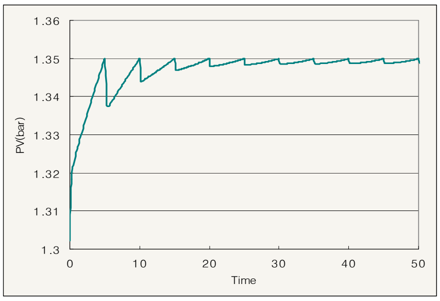
(d)

Fig 3. Simulation of the conventional tank operation

And, the dynamic model is applied to the BOG compressor optimization problem which has the discrete state dynamics describing the operational procedure of the boil-off gas (BOG) compressors. The hybrid dynamical model for solving the optimization problem determines the mode transition sequence of compressors. This optimization problem is solved by iterative dynamic optimization method. The method solve the original optimization problem by iterating the MILP which determine the mode transition sequence of compressors and the relaxed dynamic optimization which calculate the optimal outlet BOG flow rate.

The result of optimization is shown in the following figure 4. In figure 4(a), the folded straight line indicates the BOG outlet flow determined by the optimization. The figure 4(b) showed that safety constraints are satisfied.





(a)/(b)

Fig 4. Simulation of the conventional tank operation.

4. CONCLUSION

A rigorous dynamic model is proposed for estimation of the boil off rate in a LNG storage tank which can well express concrete calculation of heat ingress and behavior in tank affected from various. Model can obtain real-time calculation and control of BOG generation from manipulating pressure, temperature, initial conditions. It has been observed in this study that the BOR is greatly influenced by the difference between the tank pressure and the LNG vapor pressure. This model will help valve and compressor and tank designing to reduce BOG generation and the prediction of the pressure change in the tank using the dynamic model can be effectively applied to safety analysis.

And, the dynamic model is applied to the BOG compressor optimization problem which has the discrete state dynamics describing the operational procedure of the boil-off gas (BOG) compressors. As the result of optimization, the optimal operation procedure is proposed for a safe and energy saving BOG compressor operation, which minimizes the power consumption while preparing against the potential failure of one of the operating compressors. The result of a case study indicates that the energy consumption could be reduced by 10% compared with the conventional method by increasing the tank pressure while the safety is maintained.

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