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Operational strategy to minimize operating costs in liquefied natural gas receiving terminals using dynamic simulation

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Abstract−Although the operation of an LNG receiving terminal, especially for LNG unloading process, is important in terms of economics and safety, the systematic approach for this process is deficient with regard to operating variables and inherent terminal characteristics. Because the characteristics of each LNG terminal vary according to its individual condition, it is worth to investigate the operational method manipulating operating variables to reduce operating costs regarding terminal characteristics. In this study, we perform a rigorous and extensive dynamic simulation of LNG unloading process to demonstrate the effects of terminal characteristics, including the total length of the pipeline, the number of storage tanks, the ambient temperature, and the operation cycle. Based on simulation results and cost analyses, we can suggest an operational strategy to minimize the operating cost in LNG receiving terminals.

Key words: LNG, LNG Receiving Terminal, Operating Cost, Dynamic Simulation

INTRODUCTION

LNG (liquefied natural gas) demand is continuously increasing due to its cleanness and economic efficiency [1]. Although the energy source produces fewer contaminants during combustion compared to other fossil fuels, such as diesel and kerosene, it has a competitive heating value. Furthermore, since the major consumer countries of LNG (e.g., South Korea, Japan, Taiwan) are usually located far from the main supply source such as the Middle East, LNG is the most economical way of transporting NG over long distances [2]. As the use of LNG expands continuously, the number of LNG receiving terminals, whose role is to store, vaporize LNG and send it to end users, is also increasing [3]. When we consider this trend of increasing demand for LNG receiving terminals, the operation of these terminals is vital in terms of economics.

Although the operation of LNG receiving terminals is complicated from the point of view of safety and economics, there exist few research studies about the operation of LNG receiving terminals. In particular, the research for LNG terminals has mainly focused on BOG (boil-off gas) generation inside the storage tank [4-8]. From an operational standpoint, Shin et al. solved an optimization problem regarding compressor operation using MILP formulation and investigated BOG compressor operation using boil-off rate model [9,10]. Lee et al. suggested a noble LNG unloading procedure for a mixed operation of above-ground and in-ground storage tanks [11]. Park et al. focused their study on the operation of the recirculation stage in the terminal considering the demand variation in LNG supply [12].

In summary, even though some studies of LNG receiving terminals targeting the storage tank and unloading operation have been conducted, a systematic approach to terminal operation considering terminal characteristics is lacking. An operational strategy is needed regarding various characteristics of LNG terminals including the total length of the main pipeline, the number of storage tanks, the timing of the unloading cycle, and the ambient temperature, in order to reduce operating costs. In this study, we performed an operating cost analysis for the LNG unloading process using dynamic simulation and suggest an operational strategy to minimize total operating costs.

THEORETICAL BACKGROUND

1. LNG and LNG Receiving Terminal

The characteristics of LNG are well described in several research works [13,14]. The composition of LNG used in this article mainly consists of methane (89.3 mol%), ethane (8.6 mol%), propane (1.4 mol%), and other heavy hydrocarbons. The normal boiling point of LNG of this composition is around −160 °C. Above this temperature, the LNG is vaporized to NG (natural gas), with a sudden volume expansion of 600 times, which is called BOG (boil-off gas) generation. The generated BOG inside the LNG storage tank is usually withdrawn by the BOG compressor to keep the pressure of the tank stable around 13.73 kPa gauge [9].

The schematic design of LNG receiving terminals is described in Fig. 1. In this study, we are interested in the LNG unloading process, which extends from the LNG carrier, through the main/branch pipeline, to the LNG storage tank, as shown in Fig. 1. The tank in the LNG carrier is designed according to the MAWP (maximum allowable working pressure) criterion of 10-14 atm [2]. Meanwhile, the operating condition for the LNG storage tank is known to be −140 °C for gas temperature and 13.73 kPa gauge [9]. For valve sizing, the C_v value of the unloading valve is much larger than that of the bypass valve (e.g., 40,000 USGPM/40 USGPM) because its role is to allow a large amount of LNG from the carrier to pass through to the unloading stage. The bypass valve, on the other hand, is used

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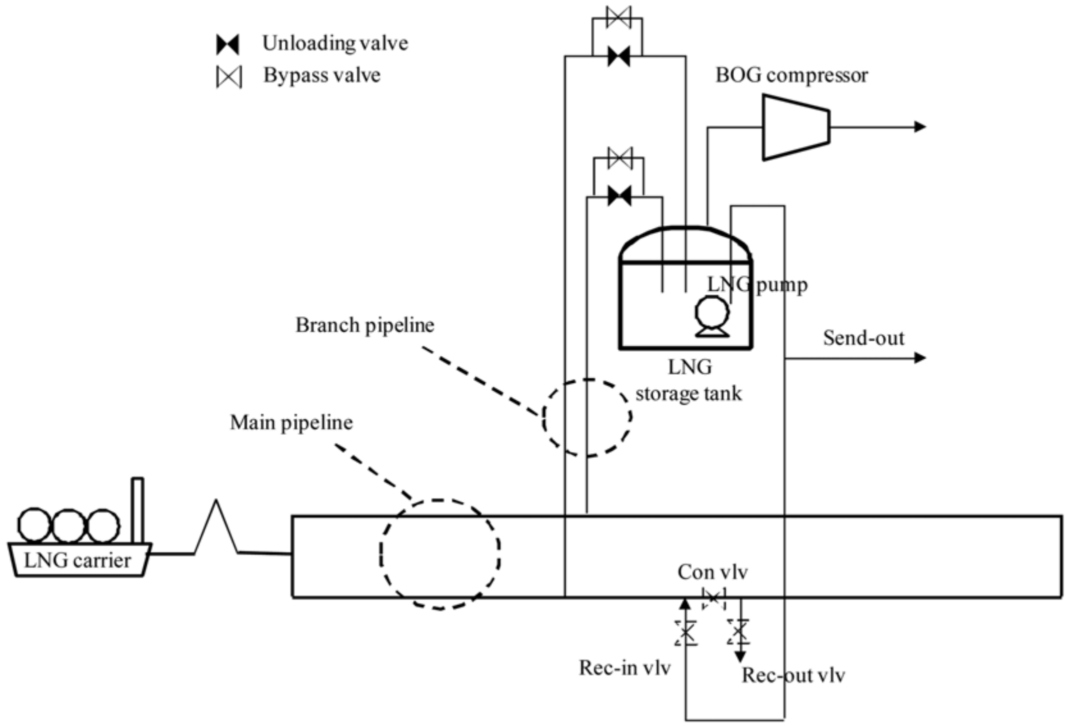

Fig. 1. Schematic design of an LNG receiving terminal.

only for passage of the recirculation flow.

2. LNG Unloading Process

2-1. LNG Unloading Procedure

The LNG unloading procedure consists of three stages: recirculation, depressurization, and unloading [11]. In the recirculation stage, a small amount of LNG flowing from the LNG storage tank is circulated through the main pipeline and branch pipeline in order to cool both pipelines. At this stage, the pressure is maintained at a relatively high level (e.g., 10 bar) to prevent the LNG from vaporizing. The pump inside the storage tank is operated to produce a recirculation flow stream during this stage.

The second stage is depressurization, in which the pressure of a main pipeline is decreased to prepare for the unloading from the LNG carrier ships, since the pressure of the ship is much smaller than that of the main pipelines. To decrease the pressure, the recirculation inlet valve (Rec-in vlv) and outlet valve (Rec-out vlv) are closed, followed by the opening of the connection valve (Con vlv). Then the closed loop is formulated in the terminal, since it is the only outlet flow through the bypass valve, thus decreasing the pressure in the main pipeline.

After the depressurization stage, the LNG is transferred from the carrier ship to the on-shore LNG storage tank. Large amounts of BOG inflow can occur due to the pressure difference across the unloading valve during transfer [11].

2-2. Operating Variables

There are two main operating variables that can be manipulated in the LNG unloading process: recirculation flow rate (F_{rec}), and bypass flow rate (F_{byp}). The purpose of recirculation is to keep the pipeline cold, near −160∼−150 °C. An outlet temperature of the recirculation flow is around −155∼−150 °C, slightly warmer than the main pipeline at the inlet point, −160∼−155 °C, due to recirculation cooling. The recommended temperature difference ($\Delta T_{out\text{-}in}$) between the inlet and outlet points of recirculation flow, as denoted in Fig. 1, is about 3-5 °C. Thus, the temperature difference can be manipulated by changing the recirculation flow rate. That is, when we reduce the recirculation flow rate, the temperature difference increases due to the heat from the outside, and vice versa.

The role of the bypass flow is to keep the branch pipeline cold. The bypass flow rate is usually much smaller than that of the recirculation flow rate. Accordingly, the diameter of the bypass valve is only a few inches (e.g., two inches), compared to that of the unloading valve (e.g., 24 or 32 inches). After cooling in the branch pipeline, the LNG flows into the storage tank. We can manipulate the bypass flow rate in order to control the cool down in the branch pipeline. Likewise, in the case of the recirculation flow rate, we can increase the cool down in the branch pipeline by increasing the bypass flow rate.

2-3. Operating Cost Analysis

The purpose of this research is to suggest an operational strategy

Table 1. Parameters of pump and compressor equation

Parameter	Value	Unit
S	1	
η_{pump}	0.8	
η_{motor}	0.85	
P_{drop}	800	kPa
k	1.52	
PI	111.4	kPa
Pout	990.8	kPa
η_B	0.7	

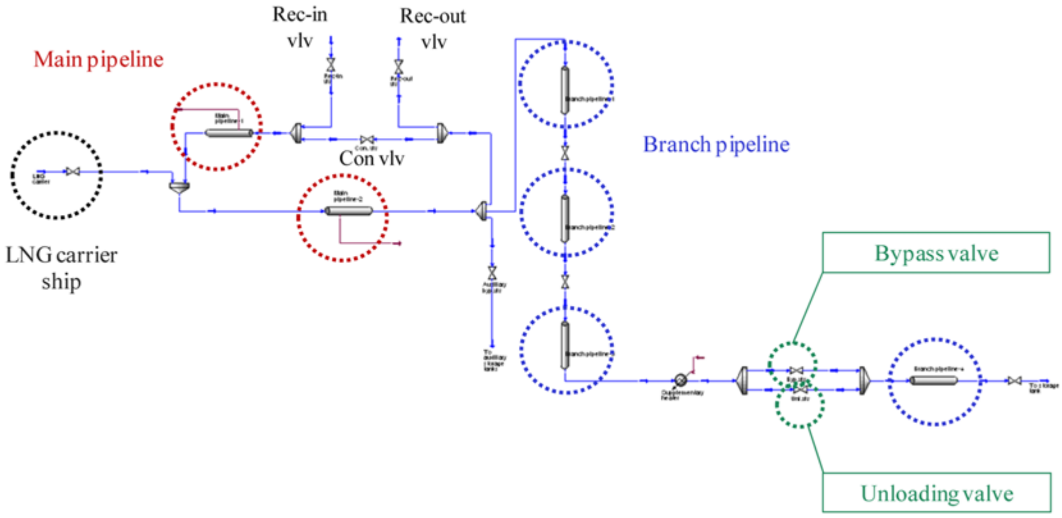

Fig. 2. Constructed dynamic model for LNG receiving terminal using process flow diagram.

for LNG receiving terminal operation to minimize its operating cost. We need first to analyze the operating cost by dividing it into two parts: pump and compressor costs. The cargo pump inside the storage tank produces recirculation flow at the recirculation stage. That is, the pump cost varies according to the recirculation flow rate. As presented in the previous section, it is possible to change the temperature difference between the inlet and outlet points of recirculation from 3 °C to 5 °C. The operating cost of the pump was calculated based on the pump work from Eq. (1) and Table 1 [15].

$$W_{pump} = \frac{\dot{m}}{\rho} P_{drop} \frac{S}{\eta_{pump}\eta_{motor}} \tag{1}$$

The compressor's role is to draw out BOG generated inside the storage tank in order to keep the inner pressure of the tank constant, ensuring its safety. Excessive BOG generation inside the tank or BOG inflow into the tank can increase the inner pressure and cause a critical problem in the storage tank. The main sources of BOG are the recirculation stage and the unloading stage.

At the recirculation stage, the endpoint of the branch pipeline is connected to the upper part of the storage tank. Because the pressure inside the tank is about 115 kPa [9], the endpoint pressure of the branch pipeline is below the bubble point of LNG. Therefore, the BOG inflow is generated in the recirculation stage, during which the compressor needs to draw out the BOG. At the unloading stage, a sudden BOG inflow occurs when the unloading starts. Compared to the recirculation stage, the compressor works much harder in this phase because of the large amount of LNG that is unloaded. During the unloading stage, the compressor also works to draw out the BOG to maintain storage tank safety. The operating cost of the compressor was calculated based on the compressor work from Eq. (2) and Table 1 [16].

$$P_B = 0.00436\left(\frac{k}{k-1}\right)\frac{Q_I P_I}{\eta_B}\left[\left(\frac{P_O}{P_I}\right)^{\frac{k-1}{k}} - 1\right] \tag{2}$$

Energy consumption from the unloading operation, including the pump and compressor uses, can be analyzed for a whole unloading cycle using a dynamic simulation. We first constructed the dynamic model and simulated a whole process from recirculation to unloading. Then, we investigated the operating cost considering the characteristics of the LNG receiving terminal. Finally, we suggested an operational strategy that minimizes the operating costs.

MODELING AND SIMULATION

1. LNG Receiving Terminal Modeling

The constructed dynamic model for LNG receiving terminal is shown in Fig. 2. As we focused on the operating cost for the unloading process, the constructed model was mainly of the main pipeline and branch pipeline. The LNG carrier ship and storage tank could be simply modeled using the pressure specification [2,9]. The height of the storage tank was assumed to be 5 meters as an in-ground type, and the recirculation inlet temperature at the main pipeline was −158.5 °C. Polyurethane was used as an insulation material in the pipe module. We constructed the dynamic model using Aspen HYSYS V7.2 and PRSV (Peng-Robinson Stryjek Vera) for the fluid package.

2. Dynamic Simulation

The purpose of the dynamic simulation in this study is mainly to measure the amount of BOG generated in the transient state, especially for the unloading stage. Since the work of the pump and compressor depends on the operating variables of the recirculation flow rate and bypass flow rate, we simulated all of the segments by manipulating the operating variables for a given range under a variety of terminal characteristics, such as the length of the main pipeline, the number of storage tanks, the ambient temperature, and the unloading operation cycle.

The simulation procedure, described in Fig. 3, is applicable to a variety of scenarios. We first fix the parameter and conditions based on a specific terminal specification. Then, a dynamic simulation with a given F_{rec} and F_{byp} is conducted from the recirculation to unloading stages. When the unloading starts, a large amount of BOG is generated, which results in a two-phase flow and may produce an unstable simulation. After obtaining a stable simulation result for each step including BOG generation, we can estimate the pump and compressor work and the operating cost.

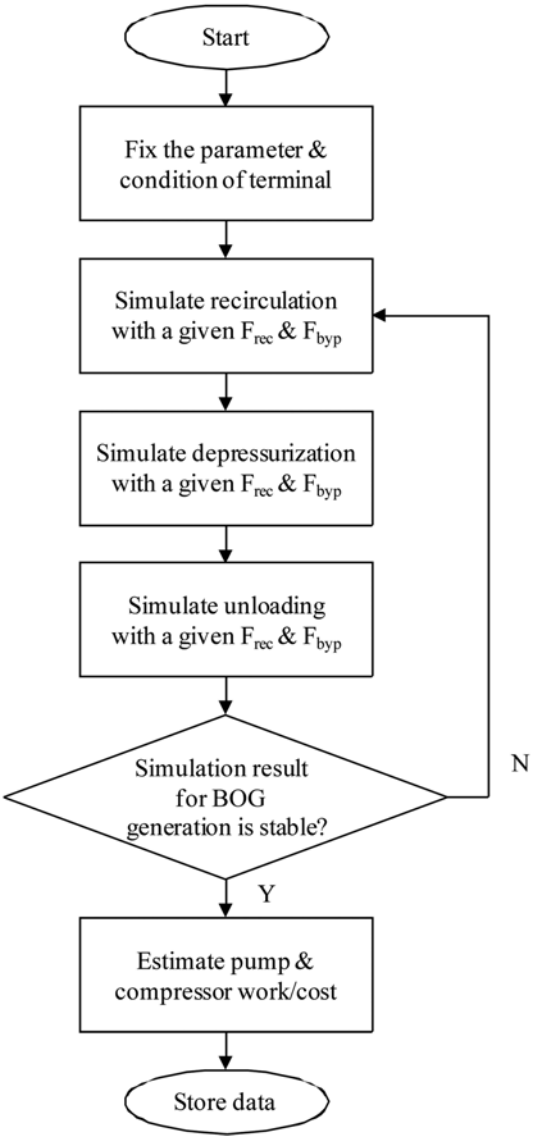

Fig. 3. Flow chart of the dynamic simulation procedure.

2-1. Scenario Generation

Since the purpose of this research is to suggest an operational strategy to minimize the total operation costs for the unloading process, the production of a variety of realistic scenarios is essential. In this study, the operational conditions and characteristics of the terminal were also considered. The operating variables are the recirculation flow rate in the main pipeline (F_{rec}) and the bypass flow rate in the branch pipeline (F_{byp}). The terminal characteristics included the length of the pipeline, the number of storage tanks, the ambient temperature, and the operation cycle.

Because the total length of the pipeline affected the amount of heat leaked to the pipeline, we varied the length of main pipeline as 1 km, 3 km, and 5 km. By the same token, the atmospheric temperature was varied at 0 °C and 25 °C. The number of storage tanks was manipulated according to the total length of the pipeline and could have an effect on the bypass flow rate. We assigned two storage tanks per one kilometer of main pipeline; consequently, the number of tanks in the terminal was varied to 2, 6, and 10. The operation cycle, or how often the whole unloading operation occurs, was varied from one day to five days. When unloading is conducted more frequently, BOG generation is repeated, which leads to increased work for the compressor. Finally, the total operating cost varied according to the operation cycle. The operating variables and terminal characteristics with their notations and manipulated values are summarized in Tables 2 and 3.

Table 3. Terminal characteristics for each scenario

Terminal characteristic	Notation	Value	Unit
Length of main pipeline	L1, L2, L3	1, 3, 5	km
Ambient temperature	T1, T2	25, 0	°C
Operation cycle	C1~C5	1, 2, 3, 4, 5	day(s)

2-2. Simulation Results

Dynamic simulations were conducted by manipulating the operating variables for scenarios that consider the terminal characteristics. Since it is not possible to present all of the feasible scenarios, we show the main effects of each case. It is necessary to cautiously differentiate one scenario from another in order to compare individual effects of the terminal characteristics on the total operating cost.

We first analyzed the operating cost variation by manipulating the recirculation flow rate in the main pipeline (F_{rec}). The bypass flow rate in the branch pipeline was fixed at 2 m^3/h (q1) in order to exclude its effect. This scenario was applied to the terminal case of a 1 km main pipeline (L1) at 25 °C (T1), and a two-day operation cycle (C2), which can be denoted as S-L1-T1-C2.

Fig. 4 shows the inflow rates of BOG and LNG for S-L1-T1-C2 when the unloading started at 10 min. When the unloading valve in the branch pipeline was opened, a large mixture of BOG and LNG entered the storage tank. The peak point of BOG inflow was different in each case because the recirculation flow rate has an effect on the temperature of the pipeline, which determines the vapor fraction. Because the cold LNG at −158.5 °C was transferred from the LNG carrier to the storage tank by the cargo pump inside the ship, the amount of BOG inflow decreased dramatically and arrived at a steady state 20 minutes after the start of unloading. The maximum capacity of the cargo pump in the ship was fixed around 12,000 ton/h for each case.

As presented in previous section, the operating costs consist of the compressor cost and pump cost. The compressor works to withdraw BOG from the storage tank, and the pump cools the main and branch pipelines using recirculation. The simulation result of S-L1-T1-C2 is described in Fig. 5. For this scenario, the annual operat-

Table 2. Operating variable for each scenario

Operating Variable	Notation	Value	Unit
Recirculation flow rate in the main pipeline (F_{rec})	Q1~Q5	ΔT_{out-in}=5, 4.5, 4, 3.5, 3	°C
Bypass flow rate in the branch pipeline (F_{byp})	q1~q5	2, 2.4, 2.8, 3.2, 3.6	m^3/h

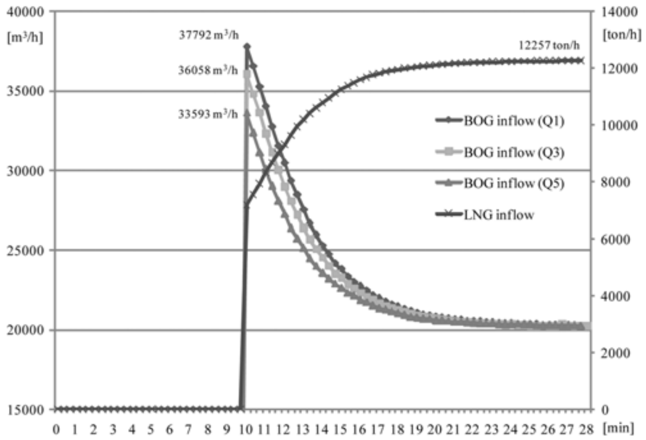

Fig. 4. Inflow rates of BOG (Q1, Q3, Q5) and LNG for S-L1-T1-C2 (pipeline length of 1 km, ambient temperature of 25 °C, operation cycle of two days).

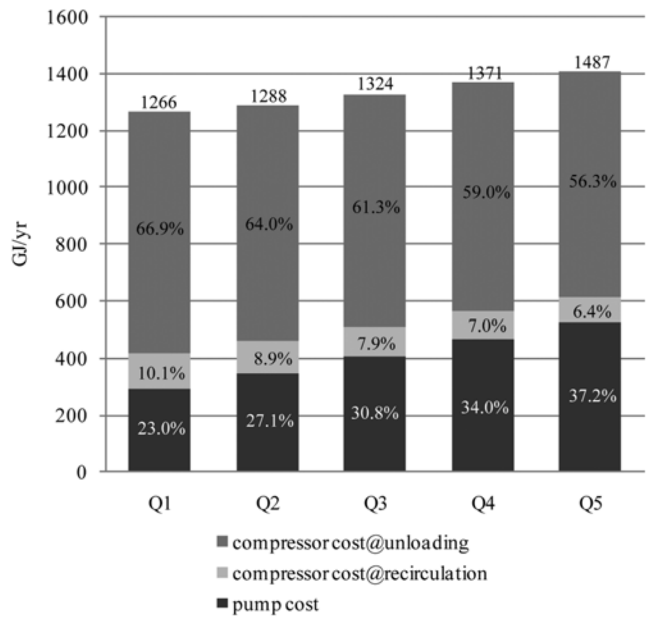

Fig. 5. Operating cost according to F_{rec} variation for S-L1-T1-C2 (pipeline length of 1 km, ambient temperature of 25 °C, operation cycle of two days).

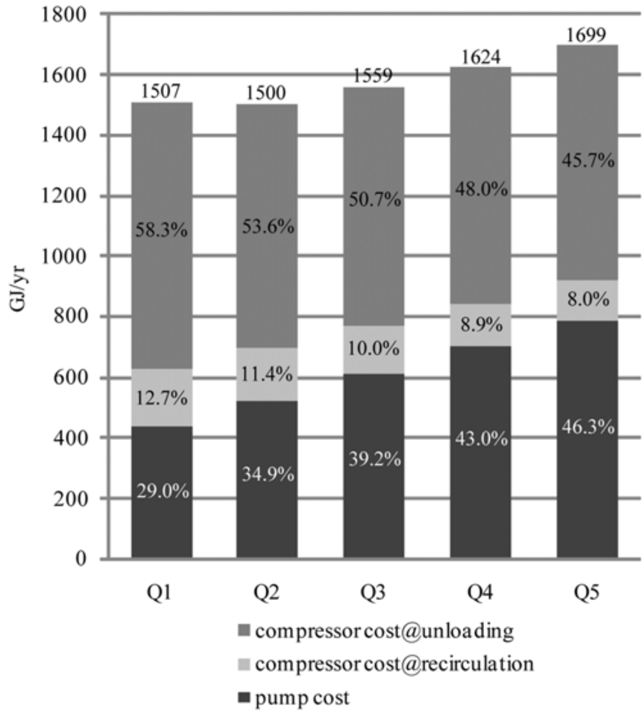

Fig. 6. Operating cost according to F_{rec} variation for S-L3-T1-C2 (pipeline length of 3 km, ambient temperature of 25 °C, operation cycle of two days).

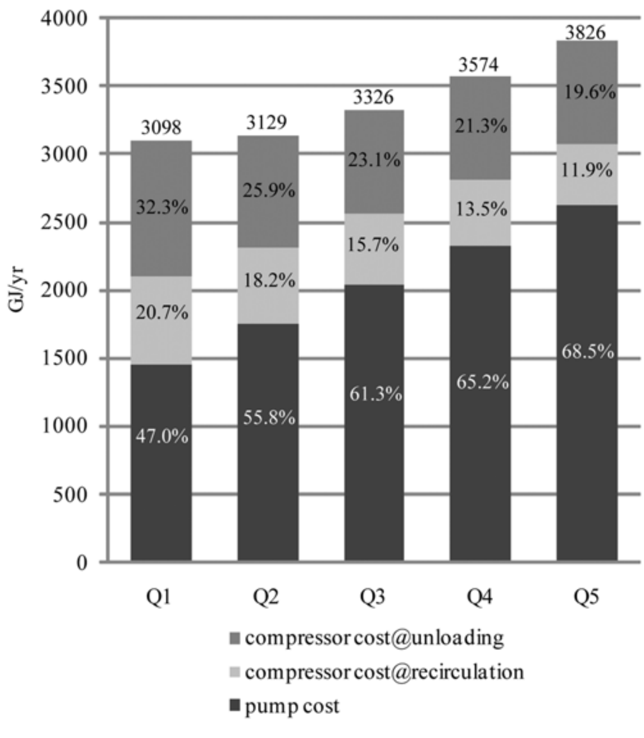

Fig. 7. Operating cost according to F_{rec} variation for S-L5-T1-C2 (pipeline length of 5 km, ambient temperature of 25 °C, operation cycle of two days).

ing cost for the Q1 case ($\Delta T_{out\text{-}in}$=5 °C) was lower than that for the Q5 case ($\Delta T_{out\text{-}in}$=3 °C) by 14.9%. That is, we could reduce the annual operating cost by 14.9% by increasing the recirculation flow rate from Q1 to Q5. The effects of recirculation flow rate on total length of pipeline are also shown in Figs. 6 and 7. As the length of main pipeline was increased from 1 km (S-L1-T1-C2), through 3 km (S-L3-T1-C2), to 5 km (S-L5-T1-C2), the total operating cost also grew. The trend of the cost variation for all cases, however, was the same with the former scenario (S-L1-T1-C2), which means it is profitable to maintain the recirculation flow rate as small as possible within the operating constraint of $\Delta T_{out\text{-}in}$=5 °C.

The reason the operating cost for each case varies can be explained in Fig. 8. First, the pump cost increased as the recirculation flow rate increased from Q1 to Q5 as depicted in Fig. 5. When the recirculation flow rate increased, the pipeline cooling ability also increased, which decreased the vapor fraction at the end of the branch pipe-

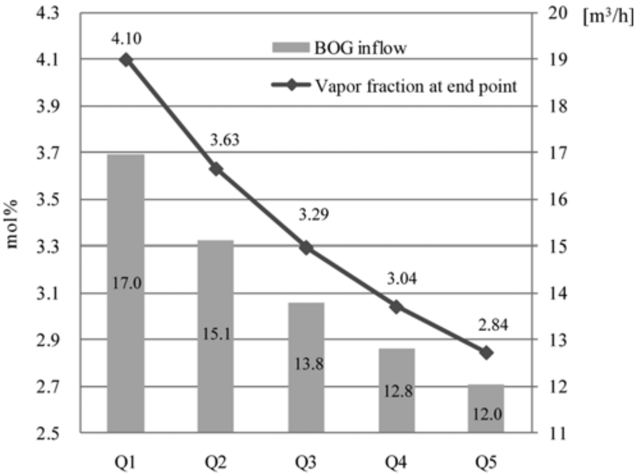

Fig. 8. Vapor fraction and BOG inflow change according to F_{rec} variation for S-L1-T1-C2 (pipeline length of 1 km, ambient temperature of 25 °C, operation cycle of two days).

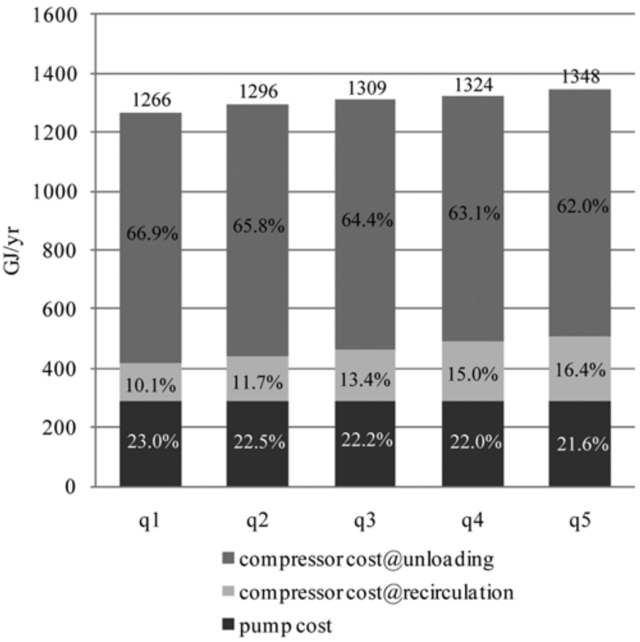

Fig. 9. Operating cost according to F_{byp} variation for S-L1-T1-C2 (pipeline length of 1 km, ambient temperature of 25 °C, operation cycle of two days).

line from 4.10 mol% (Q1) to 2.84 mol% (Q5). This reduction also had an influence on the decrease in the BOG inflow to the storage tank from 17.0 m^3/h (Q1) to 12.0 m^3/h (Q5), as shown in Fig. 8. At the recirculation stage, the amount of BOG inflow did not vary significantly, as depicted in Fig. 8. At the unloading stage, however, the peak points of the BOG inflow were quite different from one other (Fig. 4), which resulted in an operating cost gap for the compressor (Fig. 5).

Secondly, we performed dynamic simulation to test the effect of the bypass flow rate (F_{byp}) on the total operating cost. The trend of the results, as shown in Fig. 9, was similar to that in the previous case of S-L1-T1-C2 in Fig. 5, but the constitutive portions of the

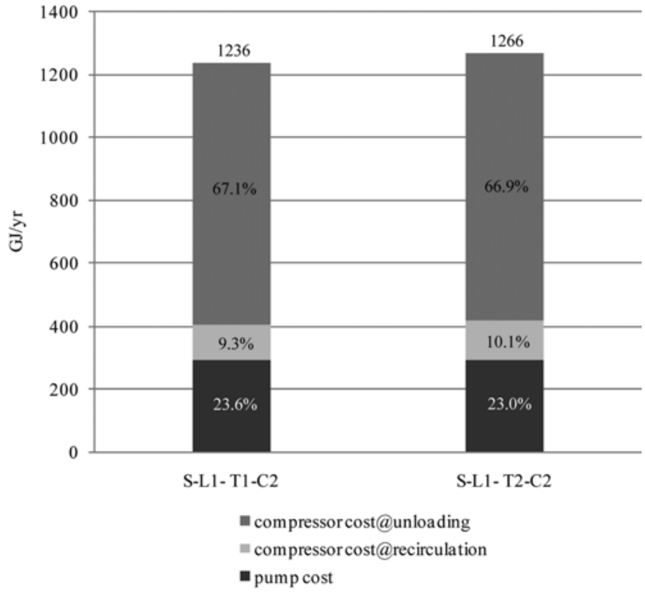

Fig. 10. Operating cost variation according to ambient temperature change between S-L1-T1-C2 (0 °C) and S-L1-T2-C2 (25 °C).

costs were different. The pump cost was fixed because the recirculation flow rate should be constant at the value of Q1. The compressor cost at recirculation continuously increased with the bypass flow rate because it is related to the vapor fraction. While the vapor fraction at the end of the branch pipeline was not much reduced, the bypass flow rate continuously increased, which requires the BOG compressor to work harder at the recirculation stage, as shown in Fig. 9. Consequently, the annual operating cost for the q1 case (F_{byp}= 2 m^3/h) was 6.08% lower than that for the q5 case (F_{byp}=3.6 m^3/h). That is, the annual operating cost could be reduced by 6.08% by decreasing the bypass flow rate from q5 to q1.

Third, the influence of the atmospheric temperature on the operating cost was investigated. Fig. 10 shows the variation in the annual operating cost when the atmospheric temperature was changed from 25 °C to 0 °C, noted as S-L1-T2-C2 (pipeline length of 1 km, ambient temperature of 0 °C, operation cycle of two days). The operating cost could be reduced by 2.35% by varying the recirculation flow rate. This result shows that it is effective to adjust the recirculation flow rate to reduce the operating cost to the region when the atmospheric temperature is varied by up to 50 °C according to season, such as would be the case in South Korea.

Finally, we tested the effect of the operation cycle on the annual operating cost. The "operation cycle" describes how often the whole unloading process, from recirculation to unloading, occurs in the LNG receiving terminal. Fig. 11 shows the constitutive portion of the annual operating cost according to the operation cycle. The more frequently the unloading process occurs, the more the compressor cost increases, and vice versa. This indicates that an individualized operational strategy is needed to minimize the operating cost. For example, we need to focus on reducing the compressor cost by modifying BOG generation, which has a one-day unloading cycle (S-L3-T1-C1). On the other hand, reducing the pump cost can be more effective because it has a long operation cycle (S-L3-T1-C5).

2-3. Operational Strategy

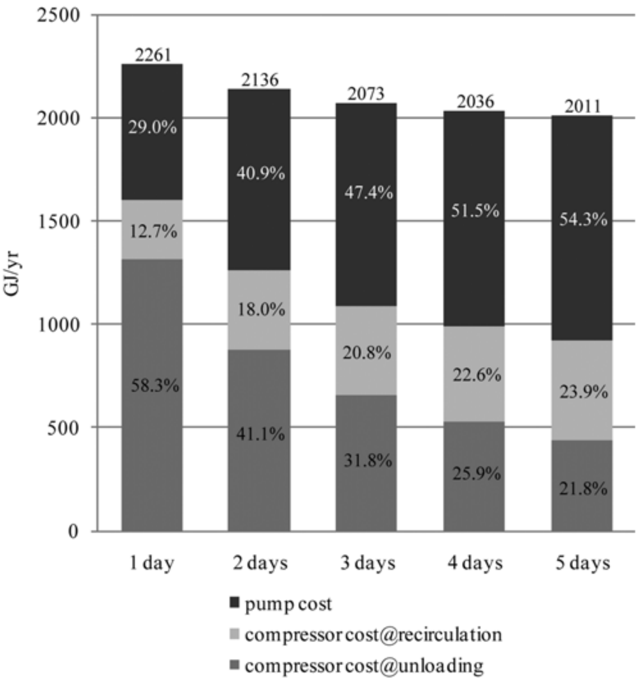

Fig. 11. Annual operating cost variation according to operation cycle for S-L3-T1 (pipeline length of 3 km, ambient temperature of 25 °C).

A careful consideration of the simulation results could demonstrate an operational strategy that minimizes the total operating cost for the LNG receiving terminal based on the trade-off for operating costs between the pump and compressor. When we tried to reduce the pump cost by reducing the recirculation flow rate (F_{rec}), the vapor fraction at the end of the branch pipeline was increased, thus increasing the BOG inflow and causing the BOG compressor to work harder, and vice versa.

To summarize the total effect of each cost variation, we found that it is more efficient to maintain the minimum amount of recirculation flow rate within the range guaranteed from the design basis. For a bypass flow on the branch pipeline, keeping the bypass flow rate as low as possible within the value of the design was cost-effective. Furthermore, if the LNG receiving terminal is located in a region where ambient temperature varies dramatically with season, operating the terminal at the adjusted recirculation flow rate could reduce the annual operating cost compared to that of a fixed operation.

CONCLUSIONS

We performed operating cost analysis for the whole unloading process of an LNG receiving terminal using dynamic simulation and suggested an operational strategy to minimize the total operating cost. We studied the effects of the operating variables of recirculation flow rate (F_{rec}) and bypass flow rate (F_{byp}) on several terminal characteristics, including the length of the main pipeline, the number of storage tanks, the ambient temperature, and the operation cycle. On the basis of our simulation results, the annual operating cost could be reduced by 14.9% by decreasing the recirculation flow rate. Furthermore, we attained a 6.08% annual savings by adjusting the bypass flow rate. This adaptive flow rate strategy can be effective to specific LNG receiving terminal operations where the ambient temperature varies by season. Finally, we explored the possibility of cost reduction by applying this adaptive strategy to the unloading operating cycle. Although all of these cost-effective operating strategies were validated through dynamic simulation, integrating economics with safety issues, such as the impact on terminal internals of urgent BOG inflow, remains as future work.

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NOMENCLATURE

USGPM : US gallon per minute
Rec-in vlv : recirculation inlet valve
Rec-out vlv : recirculation outlet valve
Con vlv : connection valve
ΔT_{out-in} : temperature difference between inlet and out points of main pipeline [°C]
F_{rec} : recirculation flow rate in the main pipeline [m^3/h]
F_{byp} : bypass flow rate in the branch pipeline [m^3/h]
W_{pump} : power required to pump [W]
$\dot{m}$: mass flow rate [kg/s]
ρ : fluid density [kg/m^3]
P_{drop} : pressure drop [Pa]
S : safety factor
η_{pump} : pump efficiency
η_{moter} : motor efficiency
P_B : brake horsepower [BHP]
k : constant specific heat ratio
Q_I : inlet volumetric flow rate [ft^3/min]
P_I : input pressure [psi]
P_O : output pressure [psi]
η_B : typical mechanical efficiency

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