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Synthesis of Unloading Operation Procedure for a Mixed Operation of Above-Ground and In-Ground Liquefied Natural Gas Storage Tanks Using Dynamic Simulation

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Because of increased liquefied natural gas (LNG) demand, operation of LNG receiving terminals having both above-ground and in-ground LNG storage tanks will soon be required. In such cases, there exists a pressure head difference between the two types of tanks. As such, during the depressurization step of LNG unloading, vapor can be generated at the top of the unloading pipeline of the above-ground tank due to pressure head. Vapor produced in a branch pipeline of the above-ground tank can thereby cause congestion during depressurization, resulting in a pressure difference across the unloading valve. This can, in turn, cause excessive boil off gas inflow into the storage tank. In this paper, we suggest a reliable unloading operation procedure for a mixed operation of above-ground and in-ground storage tanks using dynamic simulation.

1. Introduction

Natural gas is widely used as a heating fuel as well as a raw material for various chemical processes, and its usage has been continuously increasing due to the fact that it is a clean burning fuel.[1] At liquefied natural gas (LNG) production sites, such as in the Middle East, natural gas is usually liquefied to LNG to decrease its volume by 1/600. It is then transported to the demand region by LNG carrier ship. LNG in a carrier ship is usually transferred onshore to a LNG receiving terminal via an LNG unloading process.

In general, LNG receiving terminals are composed of a single type of LNG storage tank, i.e., above-ground tanks or in-ground tanks. Above-ground tank receiving terminals represent about 59% of all terminals, while the rest are in-ground, thus it is currently more common for LNG terminals to operate using above-ground type storage tanks.[2]

However, since LNG demand is continuously increasing, terminal capacity must be extended. In that case, it is preferable to choose in-ground tanks as this requires a smaller safety exclusion zone and less chance for public complaint as the tanks will be buried.[3,4] Also, as terminal expansion occurs to meet the increasing demand of LNG usage, the operation of LNG terminals composed of both types of storage tanks will be required. When such operation is required, terminal operation must account for the difference in head pressure caused by the height difference between the two kinds of tanks.

On unloading LNG, abrupt temperature increases by heat input or pressure decreases due to pipeline height can make LNG vaporize, resulting in sudden volume expansion by 600 times, which could cause damage to terminal facilities such as pipelines and storage tank internals. Therefore, it is important to examine potential factors which may bring about sudden expansion and prepare a safe and reliable unloading operating procedure.

Studies related to the prevention of sudden volume expansion of LNG have usually focused on the inside of the tank. Shi et al., Germeles et al., and Sarsten et al. performed numerical modeling related to stratified layers in LNG tanks, which can cause large volumes of BOG (boil off gas) called rollover.[5−7] Also, Bates et al. constructed a mathematical model of stratified LNG to compare with experimental data.[8] Heestand et al. and Hashemi et al. suggested a predictive model for rollover and a BOR (boil off rate) model to calculate the quantity of generated BOG, respectively.[9,10] Kim et al. and Shin et al. studied the economic aspects of handling BOG.[11,12] Park et al. investigated how to minimize the cost in terminal operation according to the variation of LNG demand.[13] To address the comprehensive process reliability in LNG terminals, Jung et al. investigated BOG treatment from the viewpoint of operator practices.[14]

Besides the BOG generation occurring inside of the tank, inflow of BOG into the tank can also cause critical problems in terminal operation. Therefore, it is necessary to prepare a reliable operation procedure to minimize BOG inflow. However, there is little research about reliable operation in LNG terminals considering mixed operation of above-ground and in-ground tanks.[15] For mixed operation, there exists a height difference between the two kinds of tanks. Since a large quantity of BOG can flow into a storage tank during unloading, which can have a critical impact on the LNG facility, it is necessary to investigate the root causes for BOG generation and suggest a reliable unloading procedure for a mixed operation.

In this study, we performed modeling and dynamic simulation related LNG unloading processes in an LNG receiving terminal which contains two kinds of storage tanks. Further, we analyze causal factors related to the risk of large BOG inflow and suggest a safe and reliable unloading operation procedure for a mixed operation.

2. Theoretical Background

2.1. LNG and LNG Receiving Terminal. LNG is mainly composed of methane and ethane. The composition of LNG varies based on the source. In this study, LNG composed of 90 mol % methane, 8 mol % ethane, and other components was used for modeling and simulation.

Natural gas is liquefied to LNG at cryogenic temperatures near −160 °C at atmospheric pressure and is then transported by the LNG carrier to be stored in an LNG tank. An LNG receiving terminal, as depicted in Figure 1, refers to equipment

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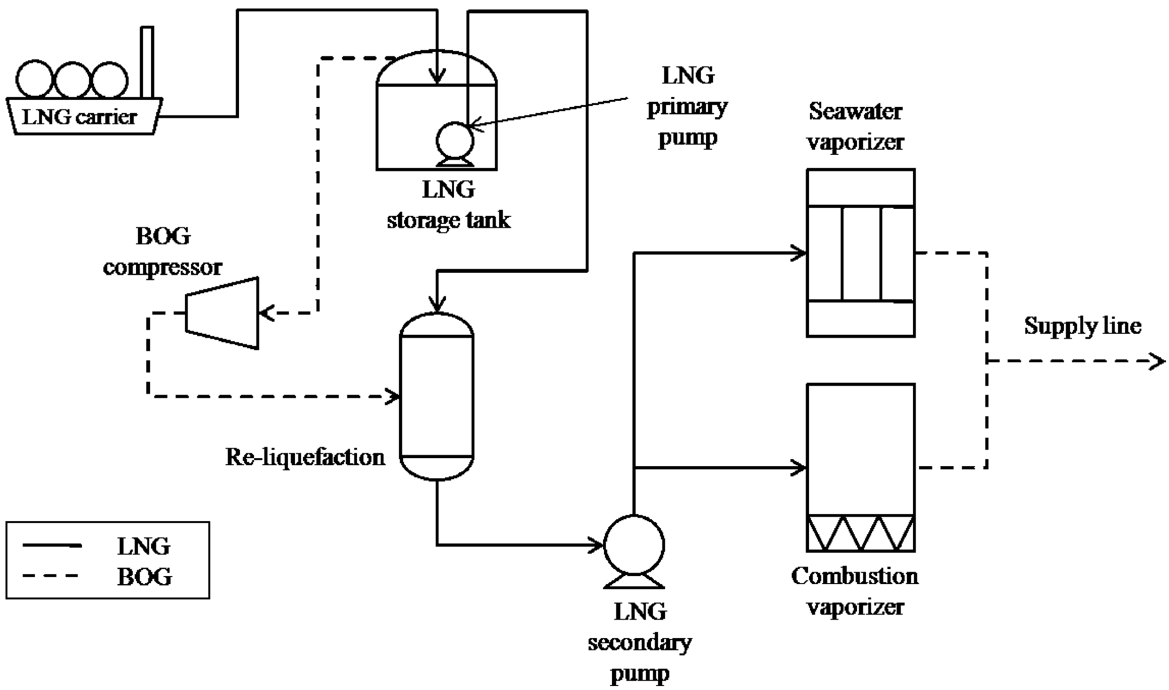

Figure 1. Schematic diagram of LNG receiving terminal.

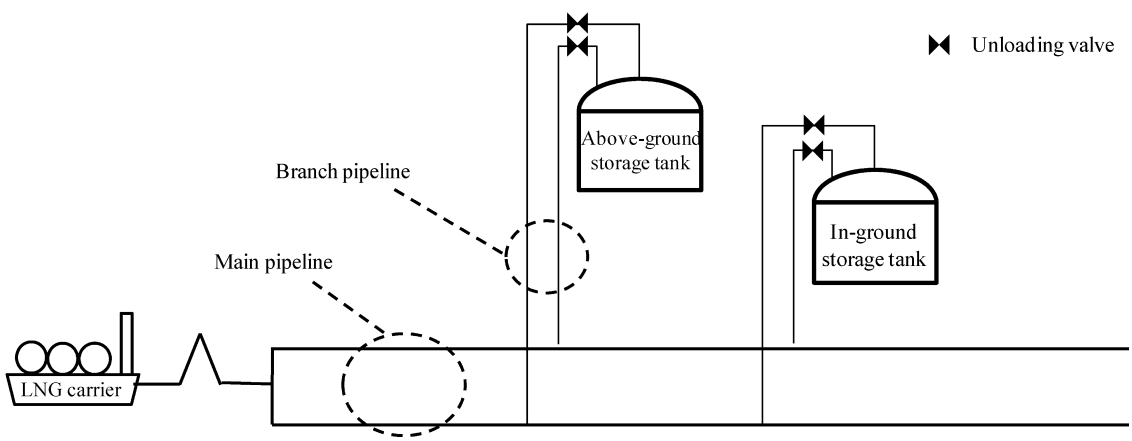

Figure 2. Unloading pipeline to LNG storage tank.

required for LNG storage and sending natural gas to end users.[13] It generally includes a pipeline, branch pipelines, LNG storage tanks, compressors, vaporizers, sending pump, and so on.

LNG is transferred to the storage tank through the main pipeline and branch pipeline from the LNG carrier ship. There are two kinds of storage tanks: above-ground tanks and in-ground tanks. In the former case LNG is transferred via a vertical unloading pipeline which is several tens of meters above the main pipeline. In the latter case, the vertical pipeline is only a few meters high (Figure 2).[13] Because of the height difference between the two kinds of tanks, care must be taken in determining an unloading operation procedure.

2.2. LNG Unloading Process. 2.2.1. LNG Unloading Procedure. The LNG unloading process consists of three stages: recirculation, depressurization, and unloading. Before LNG unloading, the main pipeline and unloading pipeline need to be kept cold to prevent warming of the pipeline from external heat transfer. To keep the pipeline cool, a small amount of LNG from the storage tank circulates continuously through the main pipeline and branch pipeline; this is called the recirculation stage. In the depressurization step, the pressure of the main pipeline and branch pipeline need to be lowered to the appropriate pressure in order to transfer LNG from the carrier ship to the storage tank. The general operating pressures of LNG carrier ship and storage tank are slightly above the atmospheric pressure.[12,16] Then, the pressure decrease is retarded when vapor is generated at the highest point of the branch pipeline, i.e., where the bubble point of LNG is reached. At the final point of depressurization, the unloading valve is opened to equalize the pressure between the main pipeline and branch pipeline; this step is called pressure equalization. At this point, some BOG can flow into the storage tanks. After pressure equalization, unloading starts via operation of the cargo pump in into LNG carrier, which transfers LNG from the carrier ship to the storage tank. When an unloading is finished, the process returns to the first stage of recirculation.[17] As for a pressure effect on the whole LNG unloading process, the pressure of the main pipeline has to be adjusted for two objectives: (1) prevent vaporization of LNG in the main pipeline at the recirculation step and (2) enable the transfer of LNG from the ship to the storage tank in the unloading step. Further details of the pressure effect will be discussed in section 3.2.1.

2.2.2. BOG Generation Mechanism. BOG is produced as the operating condition of LNG ascends above its bubble point resulting in vaporization. There are two main causes which bring about BOG generation: temperature increase and pressure decrease. At first, the temperature can increase due to the heat leak of the pipeline. The pipeline is modeled using a layered composite pipe module which consists of stainless steel and polyurethane for pipe material and insulation, respectively. During the whole steps from recirculation to unloading, heat from the surroundings indispensably permeate into the pipeline due to the temperature difference. The quantity of heat leak is calculated using eq 1 for dynamic simulation.[18] On the other hand, the pressure around the unloading valve is lower than that of the main pipeline because it is located higher than the main pipeline. Also the pressure at the end of the branch pipeline is specified by the inner pressure of the storage tank in our model. As a result, the BOG always exists about 3−5 wt % in the branch pipeline behind the unloading valve to the end of the pipeline during the whole process. The BOG generated in the recirculation step does not have much influence on operation due to its small volumetric flow rate, whereas it can cause a critical impact on the storage tank and terminal operation at the pressure equalization step. The details of BOG inflow are discussed with the simulation results in section 4.

$$Q_0 = \frac{2\pi L(T_a - T_b)}{\left(\frac{1}{r_0 h_0} + \frac{\ln(r_1/r_0)}{k_{01}} + \frac{\ln(r_2/r_1)}{k_{12}} + \frac{1}{r_2 h_2}\right)} \qquad (1)$$

2.2.3. BOG Inflow in Pressure Equalization Step. As mentioned in section 2.2.1, the pressure between the main pipeline and the branch pipeline must be equalized by opening the unloading valve. During this pressure equalization step, a large amount of BOG can flow into the storage tank due to the pressure difference across the unloading valve of the branch pipeline when this valve is opened. Sudden inflow of BOG could damage the storage tank and its internals. Thus, we should prevent BOG inflow as much as possible and minimize the possible quantity of BOG produced.

3. Modeling and Simulation

We simulated the LNG unloading process for a mixed operation of the above-ground and in-ground storage tanks using Aspen HYSYS Dynamics. Peng−Robinson−Stryjek−Vera (PRSV) was used for a property method, which is suitable for a cryogenic hydrocarbon process.

3.1. Pipeline Modeling. We constructed two kinds of models for the main pipeline and branch pipeline. A dynamic model for the main pipeline was used for the unloading process from recirculation to depressurization. A separate dynamic model for the above-ground and in-ground branch pipeline was used to obtain a volumetric quantity of BOG inflow during the pressure equalization step. As we focused on the amount of BOG inflow, the models cover from the main pipeline to the end of the branch pipeline, not including the storage tank. Although the rear end of the storage tank is connected to the inlet of the main pipeline for recirculation in the real situation, the process models do not include any physical connection for a recycle flow. Instead, we made the recirculation flow by imposing a pressure difference on the main pipeline in our model. Such a modification makes our model describe the real situation with increased stability.

The heights of the above-ground and in-ground tank were assumed to be 30 and 5 m, respectively, to reflect the height difference. This difference results in a pressure head, and the pressure at the highest point of the branch pipeline is smaller

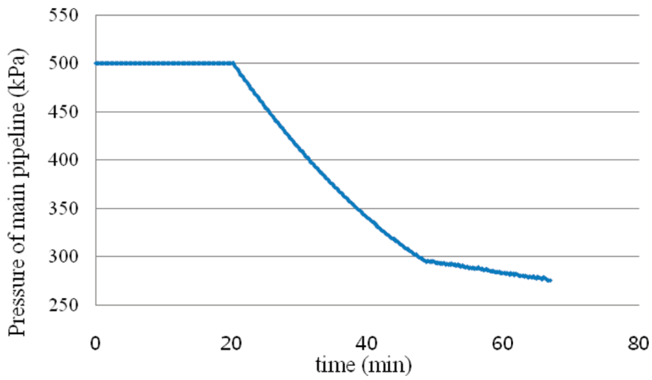

Figure 3. Pressure decrease through the whole unloading process.

than the main pipeline by this pressure head. There also exists a pressure difference across the unloading valve. Consequently, a large amount of BOG can be generated on top of the branch pipeline and flows to the LNG storage tank when we open the unloading valve for pressure equalization. Stainless steel was used as a pipe material, and polyurethane was used for insulation.

3.2. Dynamic Simulation. The inner pressure for both tanks is assumed to be 116.3 kPa, and this was the pressure boundary condition specified in the dynamic model.[8]

3.2.1. Operating Procedure for Unloading Process. As we mentioned in section 2.2, the LNG unloading process consists of three stages: recirculation, depressurization, and unloading. In this paper we concentrate on the depressurization step, especially the pressure equalization stage, which can cause a large amount of BOG inflow. In Figure 3, the pressure change in the main pipeline is obtained by dynamic simulation. For a recirculation step (0−20 min in Figure 3), a high pressure of 500 kPa is maintained on the main pipeline to keep the fluid as a liquid. Then, the pressure is decreased to prepare for unloading to adjust the pressure of the main pipeline to be similar to the pressure of the LNG ship (20−47 min in Figure 3). At the end of the depressurization step, we reach the stage in which depressurization is congested due to the vapor generated at the top of the branch pipeline (after 47 min in Figure 3). To complete the pressure equalization between the main line and the branch pipeline, we open the unloading valve, resulting in an influx of BOG into the tank.

We performed a dynamic simulation in order to calculate the quantity of BOG produced when the unloading valve is opened to equalize the pressure between the main and unloading pipeline during the depressurization step. Because a large volume of BOG can critically damage internals of the tank, we studied the unloading operation procedure to minimize the amount of BOG produced using dynamic simulation.

3.2.2. Dynamic Simulation of Pressure Equalization for a Single Operation of an Above-Ground Tank. We first configured a dynamic model, which consisted of a single kind of storage tank. As mentioned in section 3.2.1, a small amount of LNG is circulated through the main pipeline and unloading pipeline via the bypass valve (In-Byp-VLV in Figure 4, Ab-Byp-VLV in Figure 5) to cool down the pipeline. Then, as the input feed is blocked, depressurization begins. At the end of depressurization, vapor is produced at the top of the unloading pipeline (In-TK-05, 06 in Figure 4, Ab-TK-05, 06 in Figure 5) resulting in congested depressurization. Then, the unloading valve is opened (In-Unl-VLV in Figure 4, Ab-Unl-VLV in Figure 5) to equalize the pressure through the

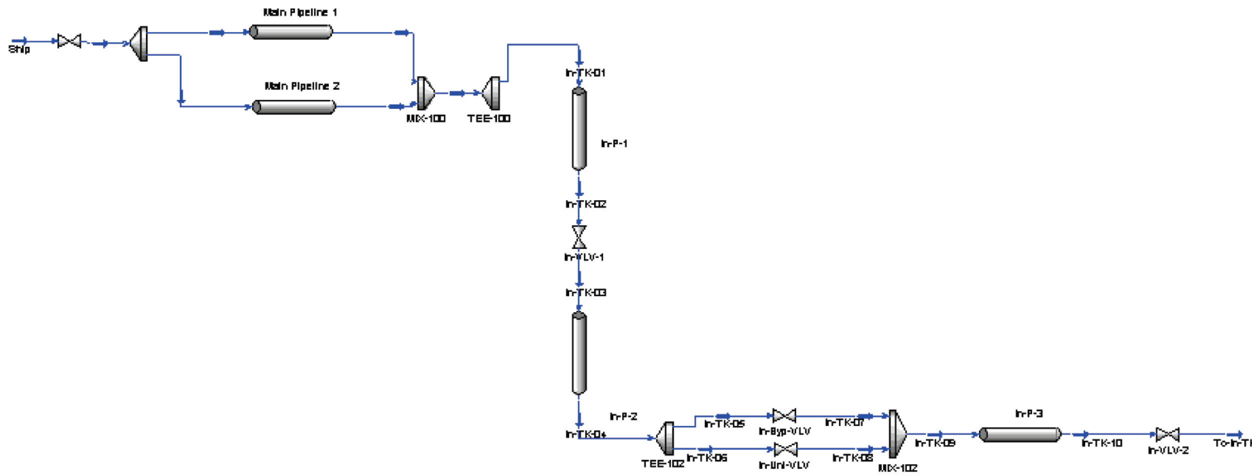

Figure 4. Dynamic model for in-ground unloading connected to a main pipeline.

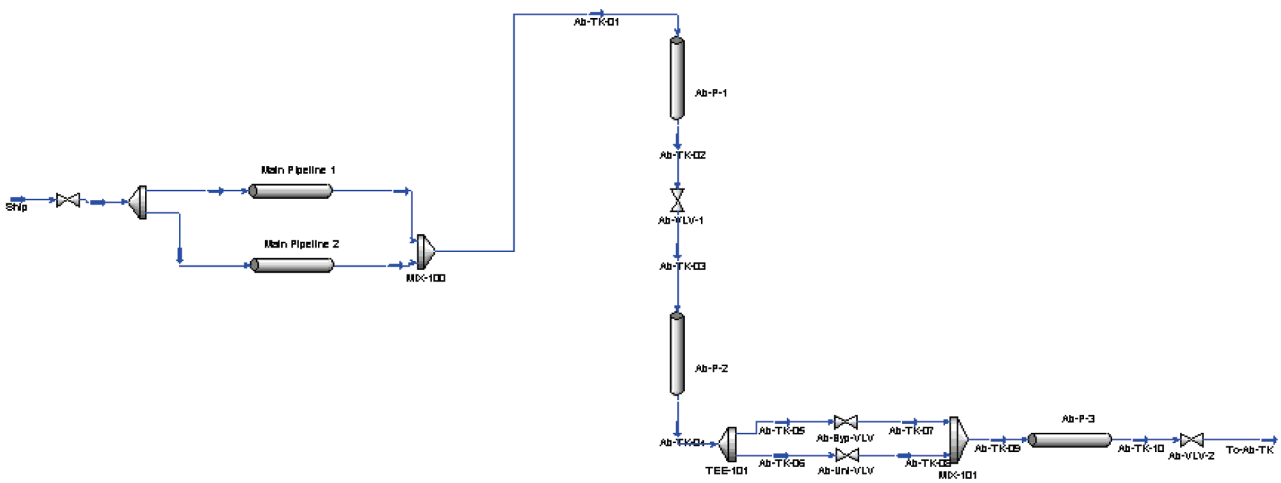

Figure 5. Dynamic model for above-ground unloading connected to a main pipeline.

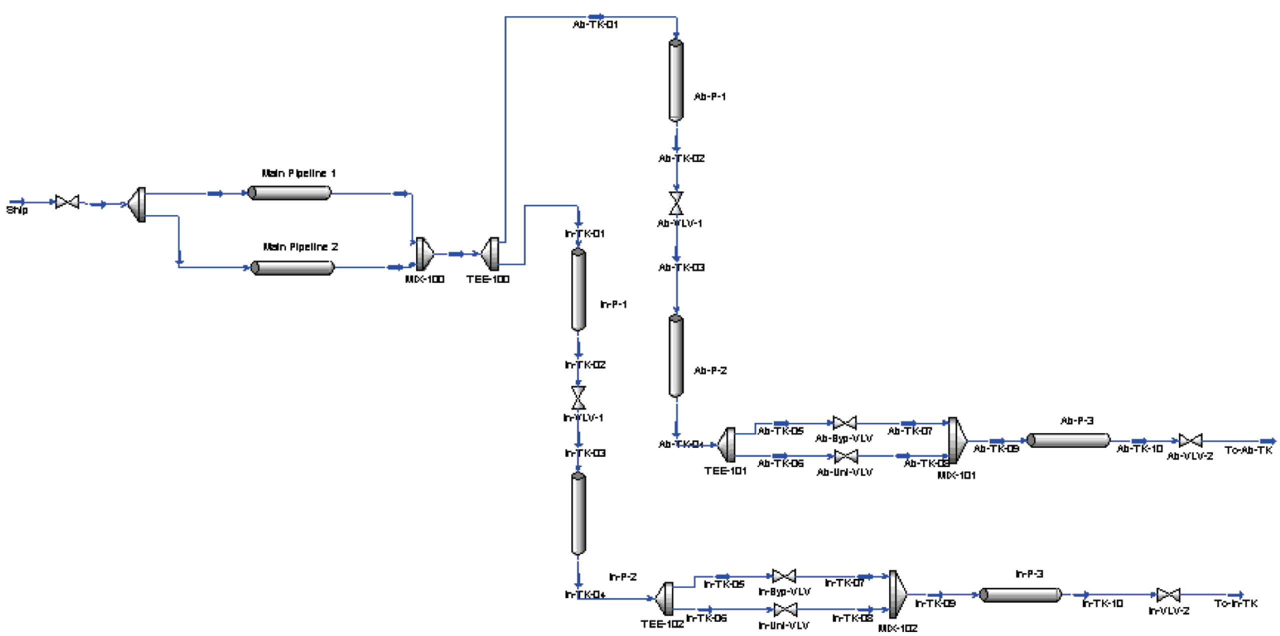

Figure 6. Dynamic model for an above-ground and in-ground unloading pipeline connected to a main pipeline.

whole pipeline including the main pipeline (main pipeline 1-1, 1-2, 2-1, 2-2 in Figures 4 and 5) and the unloading pipeline (units from In-TK-01 to To-In-TK in Figure 4 and Ab-TK-01 to Ab-In-TK in Figure 5). Such an unloading valve opening can equalize the pressure through the whole pipeline to make it ready for the next unloading action. We can obtain the quantity of BOG inflow when we open the unloading valve at pressure equalization via dynamic simulation.

Table 1. BOG Inflow at Pressure Equalization Step According to Single Type Operation

single type operation	unit	above-ground tank
maximum height	m	30
final pressure of depressurization step	kPa	243
ΔP between unloading valve	kPa	3
BOG inflow	m^3/h	7 015

Table 2. BOG Inflow at Pressure Equalization Step According to Unloading Priority for Mixed Operation

		prior unloading tank	
mixed type operation	unit	above-ground tank	in-ground tank
maximum height	m	30	5
final pressure of depressurization step	kPa	243	243
ΔP between unloading valve	kPa	3	110
BOG inflow	m^3/h	7 004	62 842

3.2.3. Dynamic Simulation of Pressure Equalization for a Mixed Operation of In-Ground and Above-Ground Tank. Mixed operation was modeled in a manner similar to the unloading process with a single tank operation, as depicted in section 3.2.2, except that the unloading priority was decided. For a receiving terminal composed of a mixture of above-ground and in-ground tanks, the depressurization process is finally stagnated due to the vaporization on top of the branch pipeline of the above-ground tank. That is, as the pressure on the top of branch of the pipeline of the above-ground tank is much lower than that of the in-ground tank due to its height, vapor is produced first for the former case during depressurization. At this point, if we open the unloading valve of the in-ground tank first to equalize the pressure, excessive BOG flows to the in-ground tank due to the pressure difference. A large volume of BOG can flow to the tank due to the pressure difference across the unloading valve (In-Unl-VLV in Figure 6).

Table 3. BOG Inflow to Above-Ground Tank with Variation in Pressure Difference Across Bypass Valve

unit	ΔP across unloading valve (kPa)	final pressure at the end of depressurization stage of main pipeline (kPa)	BOG inflow (m^3/h)
case 1	1	241.86	4 571
case 2	3	243.86	8 392
case 3	5	245.86	11 060
case 4	7	247.86	13 260
case 5	9	249.86	15 190
case 6	11	251.86	16 930
case 7	13	253.86	18 110

4. Results and Discussion

Simulation results of a single type operation and mixed operation are summarized in Tables 1 and 2, respectively. In the case of the single type operation, there is a small BOG inflow of about 7 015 m^3/h when we open the unloading valve for the pressure equalization step. The amount of BOG inflow is similar to mixed operation when we choose an above-ground tank to be unloaded first. When the above-ground tank is selected to be unloaded prior to the in-ground tank, we conduct pressure equalization first for the above-ground tank. In that case, there is only 7 004 m^3/h BOG inflow, as depicted in Table 2. On the contrary, when LNG is to be transferred to the in-ground tank first, a BOG rate as much as 9 times higher, i.e., about 62 842 m^3/h, suddenly flows to the tank during the pressure equalization step. Thus, for a hybrid unloading system, LNG should be unloaded to the above-ground tanks first to reduce the BOG inflow to minimize damage to the storage tanks.

We can also decrease the quantity of BOG inflow by minimizing the pressure difference across the unloading valve on a branch pipeline. The quantity of BOG can be calculated by eq 2, thus, we can reduce BOG inflow by minimizing the pressure difference between the front and rear point of the unloading valve.[19]

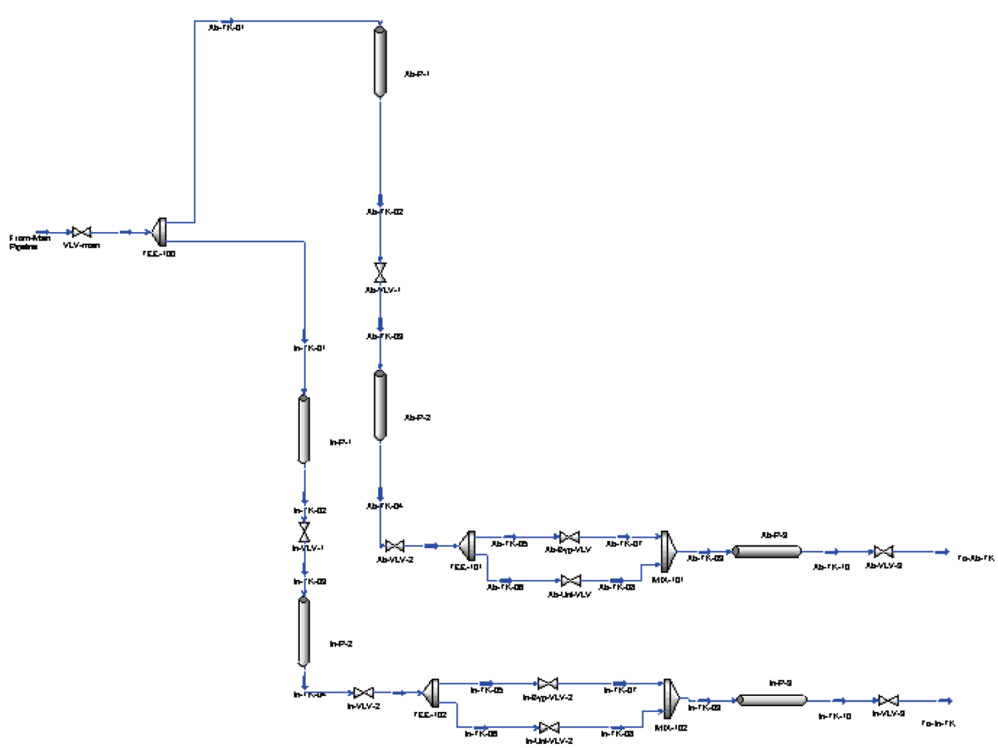

Figure 7. Dynamic model for investigating the effect of the degree of depressurization.

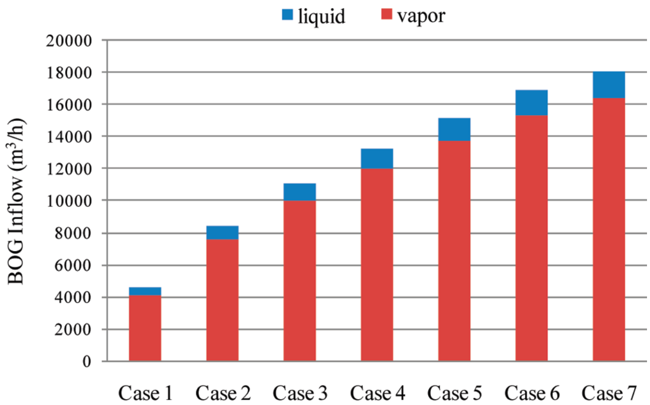

Figure 8. BOG inflow according to the pressure difference across the unloading valve.

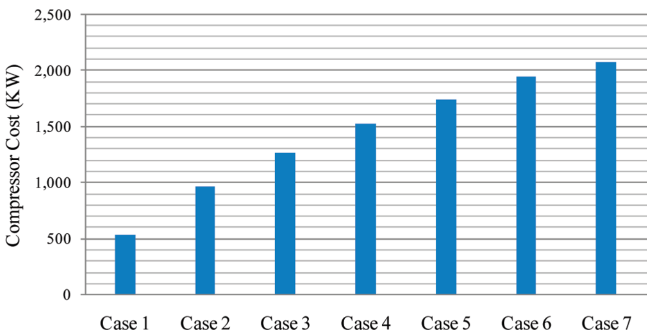

Figure 9. Compressor cost according to the pressure difference across the unloading valve.

$$Q_{\text{gpm}} = C_{\text{v}}\sqrt{(\Delta P/G)} \tag{2}$$

where Q_{gpm} is the liquid flow in GPM, C_{v} is the valve sizing coefficient, ΔP is the pressure drop across the valve, and G is the liquid specific gravity.

In order to investigate the effect of pressure difference on BOG inflow, we constructed a modified dynamic model focused on the unloading pipeline excluding the main pipeline, as shown in Figure 6. Using the modified model, we can control the pressure difference across the unloading valve by manipulating the input pressure (from main pipeline in Figure 6). Hence, we obtained simulation results for BOG inflows when the pressure difference across the bypass valve varies. We set up seven cases for different pressures across the unloading valve, and each value pressure difference is noted in Table 3. The pressure of the main pipeline is decreased until the pressure difference across the bypass valve becomes 1, 3, 5, 7, 9, 11, and 13 kPa, respectively. Then, by opening the unloading valve to equalize the pressure between the main and unloading pipeline, we obtained the amount of LNG inflow.

As shown in Table 3, the quantity of LNG inflow is increased in proportion to the pressure difference. So, as much as possible, the pressure difference across the unloading valve should be minimized during depressurization (see Figure 7). There are two ways to minimize this pressure difference. One is to extend the depressurization period as long as possible. As shown in Figure 3, although the slope of depressurization curve is changed to be smaller after 47 min than 20−47 min, the pressure of the main pipeline decreases continuously. Hence, we can reduce the pressure difference across the unloading valve by making the depressurization stage as long as possible. The other option is to keep the unloading pipeline sufficiently cold to minimize vaporization. The pressure congestion at the final point of depressurization stage is caused by the vaporization of LNG at the outlet of the unloading valve. Therefore, keeping the unloading pipeline as cold as possible may defer vaporization of LNG.

As shown in Figure 8, BOG is mostly composed of vapor rather than liquid. Large amounts of BOG inflow can increase the inner pressure of the storage tank, which can have a critical impact on tank operation. To maintain the inner pressure of the tank reliably and safely, there is generally a BOG compressor which allows the operator to pump out the BOG generated. We compared the operating costs of the BOG compressor for each case by eqs A1−A4 in the Appendix, Figure 9, and the operating conditions shown in Table A1 in the Appendix.

Hitherto we analyzed a methodology using dynamic simulation to minimize BOG inflow during pressure equalization. We may now draw the whole unloading operation procedure for a mixed operation of the above-ground and the in-ground storage tank, as shown in Figures 10 and 11. The valve operation and operation logic are explained in the procedure.

5. Conclusions

In this study, we suggest a reliable LNG unloading operation procedure for a mixed operation of above-ground and in-ground storage tanks using dynamic simulation. To minimize the BOG inflow during the pressure equalization stage, unloading should be conducted first for an above-ground tank to reduce BOG

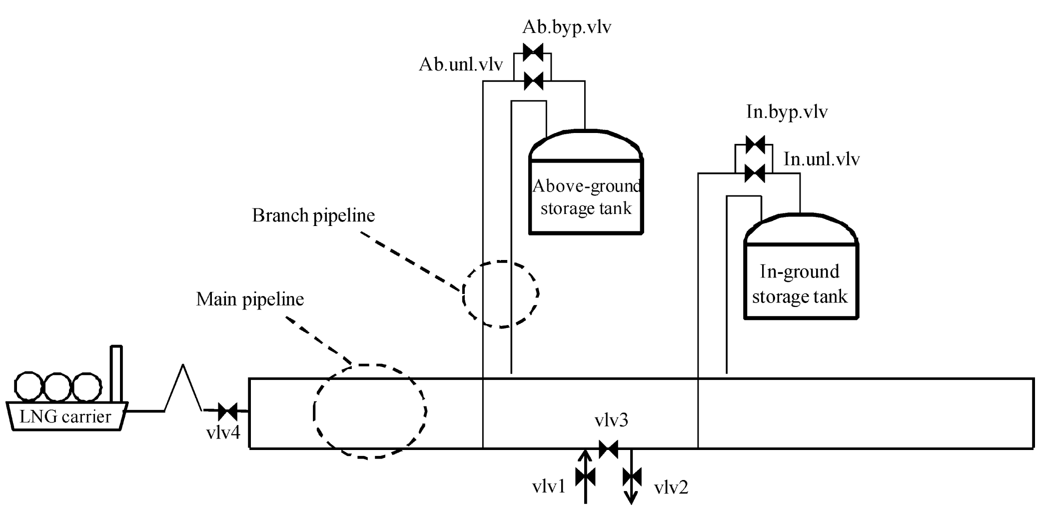

Figure 10. Schematic of the unloading pipeline to the LNG storage tank including valves.

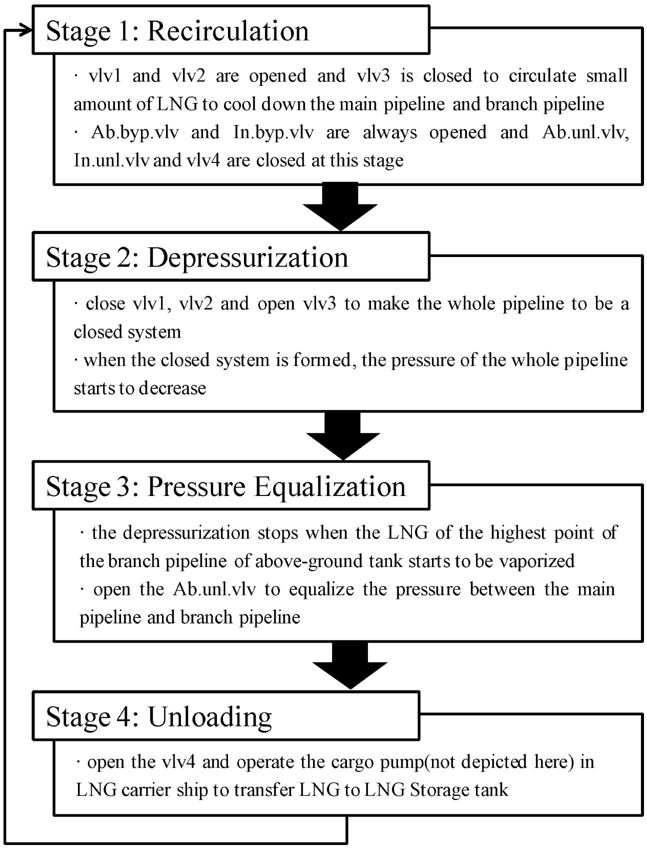

Figure 11. Suggested unloading operation procedure for a mixed operation of the above-ground and the in-ground storage tank.

generation and inflow to the tank. Furthermore, to reduce BOG generation and inflow, we should minimize the pressure difference across the unloading valve on the unloading pipeline by lengthening the time for depressurization. With the use of the suggested unloading operation procedure and methodology, BOG inflow can be minimized, resulting in a safer, more reliable LNG unloading process.

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Nomenclature

Q_0 = heat flow into the pipe
L = length of pipe
T_a = temperature in pipe
T_b = ambient temperature out of pipe
r_0 = inner radius of pipe
r_1 = radius of pipe including inner wall
r_2 = radius of pipe including outer wall
k_{01} = conductive coefficient of material 1
k_{12} = conductive coefficient of material 2
h_0 = convective coefficient at the inner surface
h_2 = convective coefficient at the outer surface
Q_{gpm} = liquid flow in GPM
C_v = valve sizing coefficient
P = pressure drop across valve
G = liquid specific gravity
P_B = break horse power
k = constant specific heat ratio
Q_I = inlet volumetric flow rate
P_I = input pressure
P_O = output pressure
η_B = typical mechanical efficiency
η_M = motor efficiency
P_C = horse power
F_D = equipment design factor
F_M = material factor
C_B = base f.o.b. purchase costs

Appendix

Calculation of Figure 9[20]

$$P_B = 0.00436\left(\frac{k}{k-1}\right)\frac{Q_I P_I}{\eta_B}\left[\left(\frac{P_O}{P_I}\right)^{k-1/k} - 1\right] \quad (A1)$$

$$C_P = F_D F_M C_B \quad (A2)$$

$$C_B = \exp\{7.2223 + 0.80[\ln(P_C)]\} \quad (A3)$$

$$\eta_M = 0.80 + 0.0319(\ln P_B) - 0.00182(\ln P_B)^2 \quad (A4)$$

Table A1. Compressor Cost According to an Amount of BOG Inflow

	BOG inflow (m^3/h)	compressor cost (KW)
case 1	4 116	527.39
case 2	7 572	965.68
case 3	9 983	1271.08
case 4	11 980	1523.94
case 5	13 730	1745.50
case 6	15 300	1944.27
case 7	16 380	2081.00

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