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Optimal operation of the boil-off gas compression process using a boil-off rate model for LNG storage tanks

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Abstract−Proper handling of boil-off gas (BOG) significantly affects the operational efficiency as well as the safety of the whole LNG gasification plant. Due to the not well-known inherent dynamics, it has been suspected that the BOG compressors are being operated at too much capacity, unnecessarily consuming too much energy. An empirical model is proposed for the estimation of the boil-off rate (BOR) in an LNG storage tank, based on the specification supplied by the LNG storage tank manufacturer. By using the BOR model, an optimal operation algorithm 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. Case study results indicate that the energy consumption could be reduced by a half of the conventional method, by increasing the tank pressure while the safety is maintained. The proposed method is expected to be able to contribute to improving the efficiency of the whole gasification plant operation and control without tempering the safety requirements.

Key words: LNG Gasification Process, Boil-off Gas, Compressors, Dynamic Modeling and Optimization, Energy-saving Operation

INTRODUCTION

The ever increasing trend of worldwide liquefied natural gas (LNG) trade is expected to continue as natural gas becomes the fuel of choice for electric power providers and as developing countries increase their energy demands. LNG is natural gas that has been processed and condensed into a liquid at almost atmospheric pressure by cooling it to ~−163 °C. LNG is about 1/614th the volume of natural gas at standard temperature and pressure, making it much more cost-efficient to transport over long distances where pipelines do not exist. An LNG gasification plant is mainly composed of LNG storage tanks, LNG pumps, LNG vaporizers, and gas pipeline [1-6].

During normal operation, ~0.1 vol% of the LNG in the tank is evaporated daily as boil-off gas (BOG) by heat transfer from the surroundings. Thus, 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. Fig. 1 shows the flowsheet of a BOG compression process, where evaporated BOG is chilled by mixing with a portion of LNG, and compressed, and sent to downstream units.

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. If the tank pressure goes too low, a vacuum breaker is activated, and if it goes too high, the BOG is sent to the flare stack. 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.

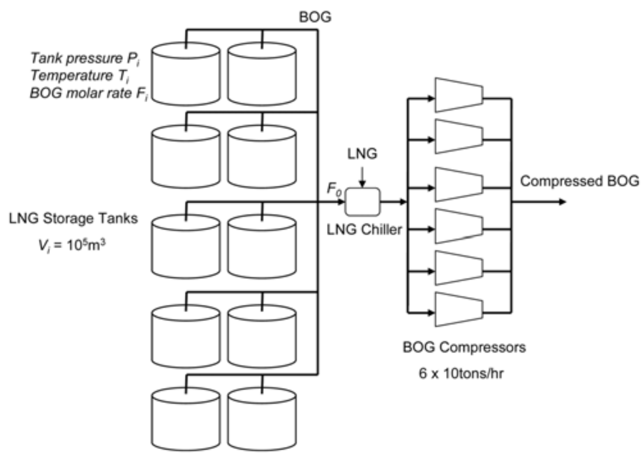

Fig. 1. Flowsheet of a BOG compression process [7] (More than the necessary number of compressors are operated).

Conventional methods of BOG compression operations are summarized in Table 1. For example, method 1 for a load of 1.1 is to run one compressor at 100% load level continuously and another compressor at 50% for 20% and at 0% for 80% of the operational period, after which the same operation is repeated. Note that a back-up compressor is operated idle, in any case, in order to cover potential failure of a compressor. Failure in the BOG compressors may lead to the opening of pressure relief valves if the mitigation action does not retain the tank pressure in an immediate fashion. Various

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Table 1. Conventional operational methods of BOG compression [7]

Load†	Operation 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
2.1-2.5	1	2		1	1
	2	1	2		1
	3		2	2	1
2.6-3.0	1	3			1
	2	2		2	1
	3	1	2	1	1
	4		4		1
	5		2	3	1
3.1-3.5	(Detailed information for these cases is omitted)				
3.6-4.0					
4.1-4.5	1	4		1	1
	2	3	2		1

†Load 1 is equal to the amount that one compressor on full operation can process.
‡BOG compressors were constructed to be operated only on 4 modes: 100, 75, 50 and 0% load levels.

studies through dynamic simulations have been reported [8-13].

As discussed above, the BOG generated in the LNG storage tanks should be removed by compressors in order to maintain the tank pressure within a safe range. Data obtained from an LNG gasification plant indicate that the rate of BOG generation is greatly influenced by the difference between the vapor pressure of the LNG and the pressure of the gas phase in the tank. Therefore, in order to minimize the energy consumption of the BOG compressors, the tank pressure should be maintained as high as possible, as long as the safety is guaranteed. An optimal operation algorithm is proposed in this paper, which uses an empirical BOR (boil-off rate) model and a simplified dynamic tank model. Given the values for a set of process state variables, the proposed algorithm generates an optimal compressor operation schedule, which minimizes the power consumption, without neglecting the preparation against the potential failure of one of the operating compressors.

MODELING OF THE BOG GENERATION AND TANK PRESSURE CHANGE

1. A Boil-Off Rate Model

The LNG storage tank manufacturers submit an experimental report after construction that shows that their tanks satisfy the design specification on the boil-off rate. The BOR on specification (B_s) of the plant of this study is defined as the BOR when the tank pressure equals the LNG vapor pressure, the LNG temperature is −162 °C, and the ambient temperature is 35.3 °C. This is calculated from a measured BOR as follows:

$$B_s = K_1 K_2 K_3 B \quad (1)$$

where
B=measured boil-off rate (%/day)
K_1=correction factor for the offset of the tank pressure from the LNG vapor pressure
K_2=correction factor for the LNG temperature
K_3=correction factor for the ambient temperature

The correction factors are obtained from the graphs provided by the LNG storage tank manufacturer, which are discussed later in this paper.

Based on the above formulation, the following empirical equation is proposed in order to estimate the boil-off rate in a LNG storage tank:

$$F = \frac{C_R B_S \rho_L V_L}{K_1 K_2 K_3} \quad (2)$$

where
C_R=rollover coefficient (≥1)
B_S=boil-off rate on specification (h^{-1})
ρ_L=LNG density (kg/m^3)
V_L=LNG volume (m^3)

The coefficient C_R represents the rollover effect by the LNG circulation, which mainly depends on the LNG feed flowrate, the LNG volume in the tank, and the ambient temperature. In normal operations, the LNG is sent out by the primary pumps in the tank, and a portion is recycled into the tank. The rest of the LNG is transported to evaporators by the secondary pumps, and a portion is also recycled into the tank. Therefore, a large amount of heat is introduced into the tank through this LNG circulation process. The operation data obtained from the plant of this study indicate that the value of C_R varies between 1 and 1.5.

The BOR is considered to be roughly inverse proportional to the offset of the tank pressure from the LNG vapor pressure. It is assumed, in this study, that the correction factor for the pressure offset linearly increases for positive large offsets, and approaches a constant for negative large offsets. Therefore, the following model equation is proposed.

$$[K_1 - a(P-P_v) - b](K_1 - c) = (1-b)(1-c) \quad (3)$$

where
P=tank pressure (g_f/cm^2)
P_v=LNG vapor pressure (g_f/cm^2)

The positive solution to this equation is as follows:

$$K_1 = \frac{1}{2}[a(P-P_v)+b+c + \sqrt{a^2(P-P_v)^2 + 2a(b-c)(P-P_v) + (b+c-2)^2}] \quad (4)$$

Data have been sampled from the graph of K_1 vs. $P-P_v$ furnished by the tank manufacturer, which is considered quadratic. The least square method has been applied to determine the parameters to get a=0.09781, b=0.6090, and c=0.4999. As a result, the following regression equation is obtained:

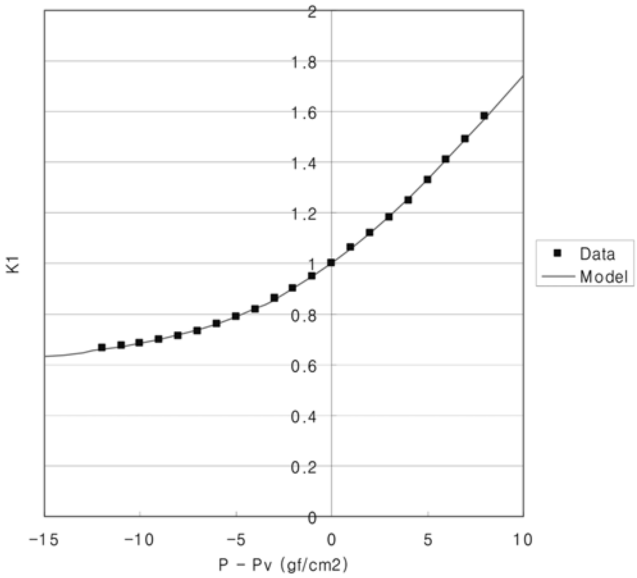

Fig. 2. Correction factor for the offset of the tank pressure from the LNG vapor pressure.

$$K_1=\frac{1}{2}[0.09781(P-P_v)+1.1089 + \sqrt{0.009568(P-P_v)^2+0.02135(P-P_v)+0.7941}],$$
$$-12\le P-P_v\le 8\ g_f/cm^2 \quad (5)$$

The regression errors are small as shown in Fig. 2. Furthermore, this model equation has asymptotic behaviors, and thus can be applied to extrapolation out of the range of the sampled data.

The LNG temperature mainly depends on its composition, which determines its volatility. Therefore, the higher the LNG temperature is, the lower the BOR is. A linear model is proposed for this correction factor. The result of regression is as shown in Fig. 3, and the model equation is as follows:

$$K_2=0.004542[T_L+162]+1,\ -162\le T_L\le -157\ ^{\circ}C \quad (6)$$

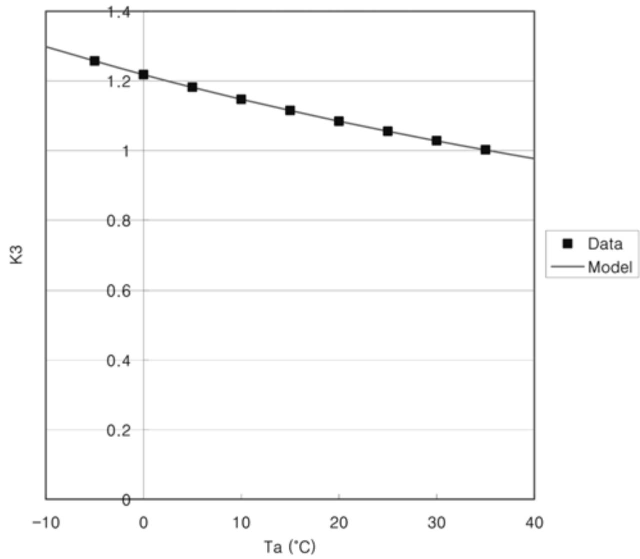

Fig. 4. Correction factor for the ambient temperature.

where

T_L=LNG temperature (°C)

The BOR is roughly considered to be proportional to the temperature offset of the ambient temperature from the LNG temperature. Therefore, an inverse linear model is proposed for this correction factor. The result of regression is as shown in Fig. 4, and the model equation is as follows:

$$K_3=\frac{197.1}{T_a+161.8},\quad -5\le T_a\le 35.3\ ^{\circ}C \quad (7)$$

where

T_a=ambient temperature (°C)

The LNG vapor pressure correlation is based on the Antoine equa-

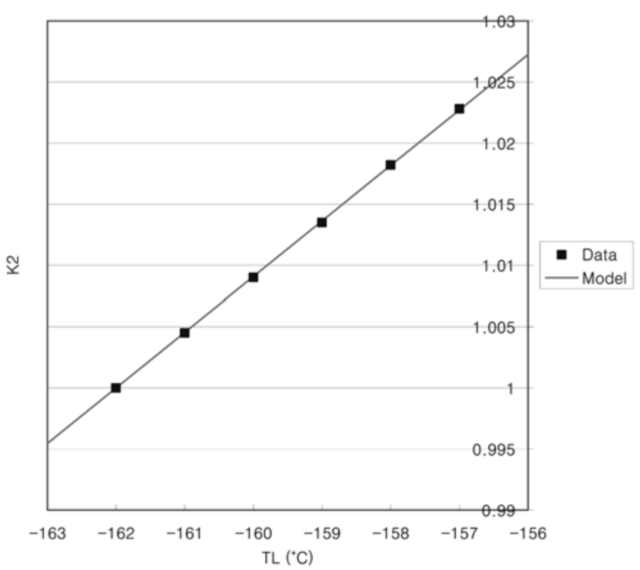

Fig. 3. Correction factor for the LNG temperature.

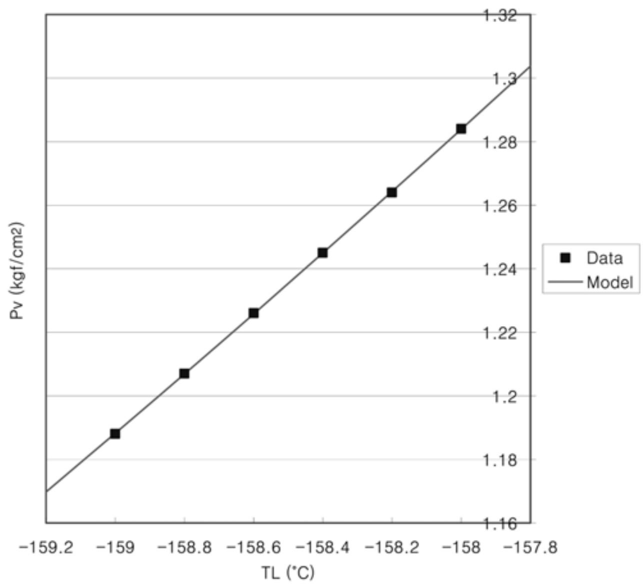

Fig. 5. LNG vapor pressure vs. temperature.

tion. The result of regression is as shown in Fig. 5, and the model equation is as follows:

$$P_v(kg_f/cm^2) = \exp\left(9.0934 - \frac{1018.3}{T_L + 273.15}\right), \quad -158 \le T_L \le -159\,^{\circ}C$$
(8)

where

T_L=LNG temperature (°C)

Note that the data represented by squares in Figs. 2 to 5 are not experimental raw data, but sampled data read from the graphs provided by the LNG storage tank manufacturer.

2. A Simplified Dynamic Tank Model

Let us apply the ideal gas law to the gas phase in the tank. As the tank is large, the gas volume and temperature change slowly. Therefore, the rate of tank pressure change can be expressed as follows:

$$\frac{dP}{dt} \approx \frac{(F - F_o)RT}{V} \tag{9}$$

where F is the BOG molar rate, F_o is the compressor molar flowrate, R is the gas constant, T is the gas temperature, and V is the gas volume in the tank.

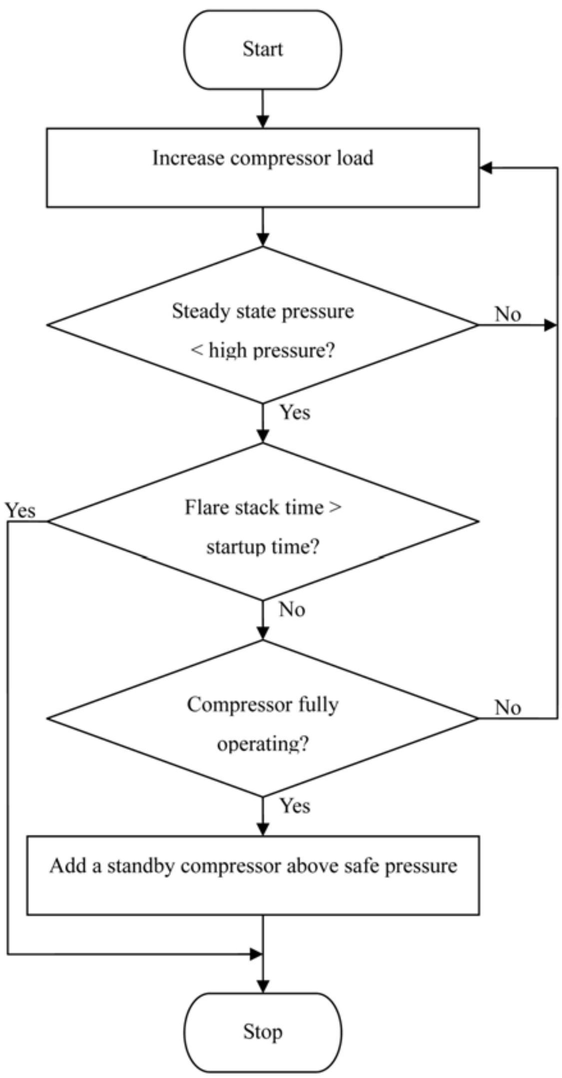

Fig. 6. Flowchart of the proposed algorithm.

AN OPTIMAL OPERATION ALGORITHM

Let us define n as the number of operating compressors, l as the load level of the n-th compressor (n−1 compressors are operated at the full load level L), and $F_o(n, l)$ as the total compressor flowrate. Let P_0 denote the initial tank pressure, P_s the steady state tank pressure, and P_{hi} the highest operating pressure desired. Let $\Delta t_{startup}$ represent the compressor startup time, and Δt_{flare} the time to reach the upper limit pressure P_{flare} when one of the operating compressors fails. The following algorithm is proposed for a safe and energy saving operation of BOG compressors, and summarized as a flowchart in Fig. 6.

1. Start from minimum compressor load:
   Set n=1 and l=1.
2. Determine steady state tank pressure:
   For $F_o = F_o(n, l)$, solve $F(P_s) = F_o$.
3. Increase load to lower a normal steady state tank pressure, if necessary:
   If $P_s > P_{hi}$ {Set $l \leftarrow l+1$; If l>L, set n←n+1 and l=1; Go to step 2}.
4. Predict time to flare stack when one compressor fails:
   For $F_o = F_o(n-1, L)$, determine Δt_{flare} such that $P(0) = \max(P_0, P_s)$ and $P(\Delta t_{flare}) = P_{flare}$.
5. Operate the compressors if time is enough:
   If $\Delta t_{flare} > \Delta t_{startup}$, return $F_o(n, l)$.
6. Increase load, and try again:
   If l<L, set $l \leftarrow l+1$, and go to step 2.
7. Calculate safe pressure:
   Back calculate $P_{safe} = P(0)$ such that $P(\Delta t_{startup}) = P_{flare}$.
8. Operate a standby compressor above safe pressure:
   Return $F_o(n, L)$ while $P(t) < P_{safe}$ and $F_o(n+1, 0)$ while $P(t) > P_{safe}$.

CASE STUDY

Consider a plant with ten LNG storage tanks with a volume of 100,000 m^3 each and six BOG compressors with a maximum capacity of 10 tons/h each, as shown in Fig. 1. The compressors require 30 min idle operation for start-up, and have load levels of 0, 50, 75, and 100%, at which the electric currents are 65, 115, 127, and 145 A, respectively, when operated at 6,600 V. The normal operation range of tank pressure is between 50 g_f/cm^2 and 170 g_f/cm^2 gauge. If the pressure goes down to 40 g_f/cm^2 gauge, a vacuum breaker is activated, and if it goes up to 190 g_f/cm^2 gauge, the BOG is sent to a flare stack.

Let us consider a high boil off rate situation. All the tanks are 90% filled, and thus the total LNG volume is 900,000 m^3. All 10 tanks are at the same condition: The LNG temperature is −159 °C, the gas temperature is −140 °C, and the ambient temperature is 30 °C. The LNG is pumped out, and 20% is recycled into the tanks. The initial tank pressure is 150 g_f/cm^2 gauge. The operation history indicates that two and a half compressors are necessary in order to maintain the tank pressure in this situation, as shown in Table 2. Note that while the total power consumption should be minimized,

Table 2. Comparison of operation methods

Method	Compressor loads (tons/h)	Steady state tank pressure (g_f/cm^2g)	Power consumption (kW)†	Energy save (%)
Conventional	10, 10, 5, 0	149.9	3,102	-
Conservative	10, 5	159.7	1,716	44.7
Optimal	10, 0	167.5	1,386‡	55.3

†Power consumption=(6,600 V)$\sum_i$(Current(Compressor load$_i$)A)

‡No power consumption of the standby compressor during the turn-off period has been neglected because its turn-off period could be negligible compared to the whole period of operation. If that turn-off period is considered, the energy consumption becomes even lower than the calculated value.

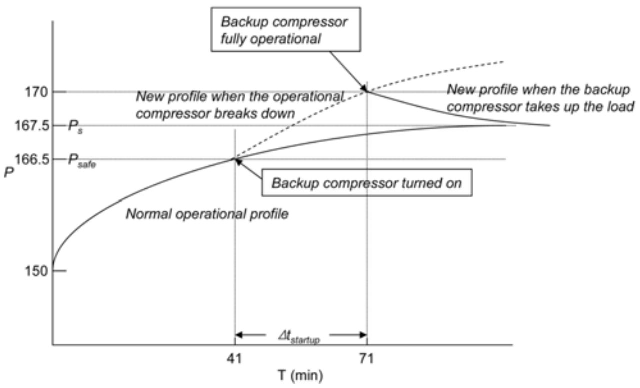

Fig. 7. Pressure changes as the operational compressor breaks down and a backup takes up the load.

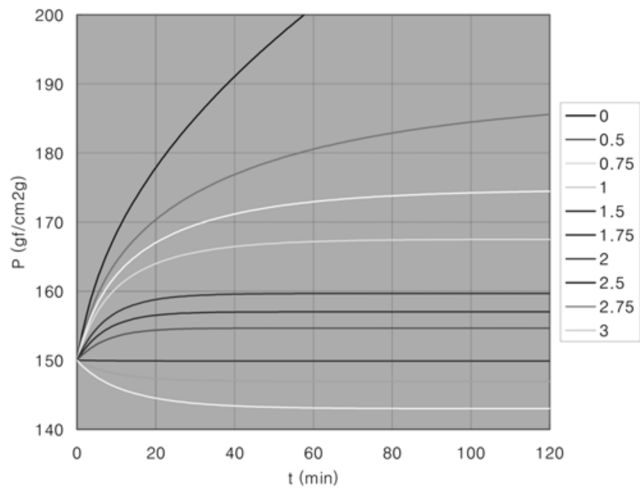

Fig. 8. Simulation results of changes in the tank pressure for the load amount of compressors.

a backup compressor is to be on standby, if necessary, in order to avoid a flare stack discharge even if one of the compressors fails. Determine an optimal operation method.

Let us determine the value of the rollover coefficient first. Assume C_R=1, then the initial BOR estimated by the proposed model is 20,750 kg/h. Therefore, C_R=25,000/20,750≈1.2 is to be used. Changes in the tank pressure for compressor flowrates from 0 to 30 tons/h have been simulated by using the proposed model, and the results are presented in Fig. 8.

The proposed algorithm starts from F_o=5 tons/h, and P_s=188.6 g_f/cm^2 gauge is obtained in step 2. As $P_s>P_{hi}$=170 g_f/cm^2 gauge in step 3, F_o=7.5 tons/h is tried, and P_s=174.7 g_f/cm^2 gauge $>P_{hi}$ is obtained. For F_o=10 tons/h, P_s=167.5 g_f/cm^2 gauge is obtained (see Fig. 8 for the load amount=1). As $P_s<P_{hi}$, step 4 calculates Δt_{flare}= 29 min. As $\Delta t_{flare}<\Delta t_{startup}$=30 min in step 5, step 6 tries to increase the load level, but is skipped because the compressor is fully operating. Step 7 calculates P_{safe}=166.5 g_f/cm^2 gauge. This pressure is expected to be reached at t=41 min in step 8. Therefore, the optimal operation schedule is as follows (As shown in Fig. 7, even when the operational compressor breaks down right at P_{safe}, a standby compressor turns on exactly that time can become fully operational in $\Delta t_{startup}$, and the pressure is surely lowered down from the upper operational limit as the load is taken over by the standby compressor.).

1. Operate one compressor at full load level F_o=10 tons/h.
2. Turn on another compressor after t=41 min, and keep on standby.

Suppose P_{hi}=160 g_f/cm^2 gauge is preferred as a conservative operation, where the operation is kept far from the constraints to reduce the danger of violating them, F_o=15 tons/h can be used. Two compressors are to be operated, and a standby compressor is unnecessary in this case (As shown in Fig. 8, the pressure is always maintained under its steady-state value, 159.7, which is quite a bit lower than P_{safe}. Even when both compressors break down together, a backup compressor turns on at that time becomes fully operational in $\Delta t_{startup}$, and the tank pressure never reaches the upper operational limit.).

Note that the conventional operation method is to use four compressors, in this situation, in order to maintain the tank pressure and guarantee the safety. Three compressors are to be operated for F_o= 25 tons/h, and one compressor is to be on standby. The power consumptions of these three methods are compared in Table 2. As expected, operating closer to the constraints shows more potential for performance improvement.

CONCLUSION

An empirical model has been proposed for estimation of the boil off rate in an LNG storage tank, in which a rollover coefficient and correction factors are applied to the boil off rate on specification supplied by the LNG storage tank manufacturer. 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. A simple dynamic model based on the ideal gas law was also proposed for prediction of the pressure change in the tank, which could be effectively applied to safety analysis. Finally, an optimal operation algorithm was 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 the case study indicates that the energy consumption could be reduced by half as compared with the conventional method by increasing the tank pressure while the required safety is maintained.

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