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Dynamic simulation and optimization of the operation of boil-off gas compressors in a liquefied natural gas gasification plant

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Abstract−We propose an algorithm for the optimal operation schedule of the BOG compression process based on simulation of the dynamic behavior of an LNG tank. The algorithm uses an empirical boil-off rate model to predict the amount of BOG generation, and an MILP formulation to distribute the BOG compressors loads. Finally, a safety analysis is done using a dynamic simulator. To improve the accuracy, Aspen Dynamics with the Peng-Robinson equation of state is used in place of a simplified dynamic model used before. The dynamic simulation of the LNG tank pressure showed the results of oscillation within a safe pressure range while the BOG compressors were operated normally. The performance of the proposed algorithm was found to be superior to the algorithm used in routine processes as well as those from previous works in terms of safety and energy savings.

Key words: Dynamic Simulation, Optimization, Operation, Boil-off Gas, Aspen Dynamics

INTRODUCTION

The changing economic outlook, energy demands, and environmental factors have resulted in increased demand for liquefied natural gas (LNG). Worldwide, LNG trade has increased steadily (over 5% per year) since the industry began. This trend is expected to continue as natural gas becomes more widely used due to increased energy demands from developing countries. Some industry analysts have predicted that demand for LNG will double by the end of the next decade [1].

An LNG gasification plant is mainly composed of LNG storage tanks, pumps, LNG vaporizers, and the gas pipelines. Fig. 1 represents the LNG gasification process. The plant receives LNG from a carrier and stores it in a cryogenic liquid state. The liquid temperature is approximately −160 °C and the pressure is slightly above the atmospheric pressure in the storage tanks [1-3]. Due to heat transfer from the surrounding environment, part of the LNG in the tank is continuously evaporated as boil-off gas (BOG), which should be removed by compressors to maintain the tank pressure within a safe range. An excess amount of evaporated BOG causes safety problems related to the increased pressure of the LNG tanks, but the operation of the compressors requires much more energy than is necessary. Therefore, the correct operation procedure for BOG compressors is essential for the efficiency of the operation and safety of

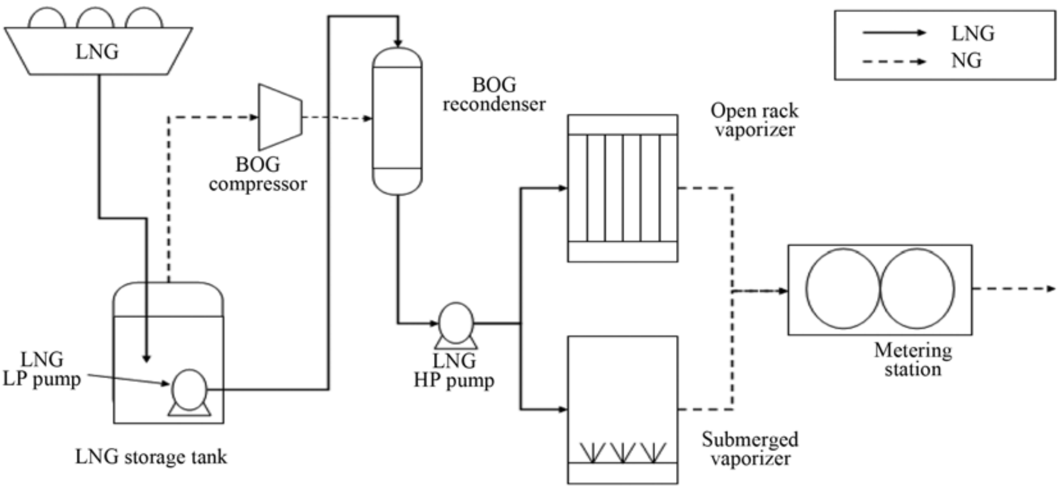

Fig. 1. A typical LNG receiving and gasification process [2].

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an LNG terminal.

Several studies have attempted to solve the trade-off between energy usage and safety assurance associated with this process. One example is the algorithm for the operation of compressors reported by Shin et al., which used an empirical boil-off rate model for the safe and efficient operation of BOG compressors [4]. They proposed a mixed integer linear programming (MILP) formulation to determine the optimal operation policies within the safe operation pressure. The optimal operation policies serve to distribute compressor loads, turn on/off the time fraction of the operation of a BOG compressor, and determine any redundant compressor operations in consideration of safety using a simplified dynamic model [5].

In this paper, we propose an optimal operation scheme for BOG compressors that finds the optimal pressure between the steady state and desired tank pressure using a turn on/off compressor operation. To improve the accuracy of the scheme, a dynamic simulation and a safety analysis are conducted to test the proposed operation procedure using the rigorous model of Aspen Dynamics instead of the simplified dynamic model used in previous works [4,5].

PROPOSED ALGORITHM FOR OPTIMAL OPERATION

The proposed procedure for determining the optimal operation of BOG compressors is illustrated in Fig. 2. The proposed algorithm involves the three steps of load calculation, MILP formulation, and dynamic simulation and safety analysis.

1. Load Calculation

An empirical model is proposed for the estimation of the rate of boil-off gas generation in an LNG storage tank [4].

$$F=\frac{C_R B_S \rho_L V_L}{K_1 K_2 K_3} \quad (1)$$

where C_R is the rollover coefficient (≥1) by LNG circulation. B_S is the boil-off rate from the specifications (h^{-1}) supplied by the tank manufacturer, ρ_L is the LNG density (kg/m^3), and V_L is LNG volume (m^3). K_1, K_2, and K_3 are correction factors for the offset of the tank pressure from the LNG vapor pressure, the LNG temperature, and the ambient temperature, respectively.

Based on this model, the total compressor load can be calculated for the desirable highest tank pressure (P_{hi}). The target compressor load F_0 can be calculated using the empirical model equations, which can be summarized as follows:

$$F_0=F(P_{hi}) \quad (2)$$

where F is a function defined by Eq. (1).

2. MILP Formulation

The MILP formulation is proposed for the optimal distribution of the compressor load, which minimizes the total average power consumption. The details pertaining to this formulation are available in the literature [5].

3. Dynamic Simulation and Safety Analysis

A dynamic simulation and safety analysis were performed to predict the pressure change in the tank. In the dynamic simulation using the proposed algorithm, the pressure of the tank oscillated within a safe pressure range ($P_s \le P \le P_{hi}$) when the BOG compressors were operated normally; here, P_s is the steady state pressure.

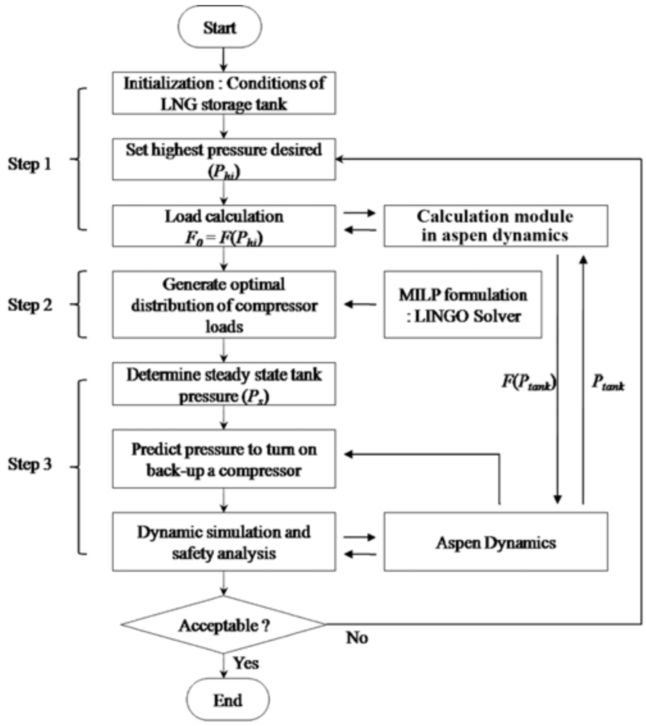

Fig. 2. Flowchart of the proposed algorithm.

The redundant compressors are on standby at idle level in order for safe operation. Also, the operators need to know the time to turn on backup compressors, because the backup compressors need the startup time which is 30 min in the cooling system and the tank pressure will increase in this period. In the previous works, we calculated the turning on time using a simplified dynamic model [5]. In this paper, the safety operation scheme is proposed by using a dynamic simulator. First, initial time and limitation pressure are assumed. Then, the dynamic simulation is performed during startup time. If the pressure is lower or higher than limitation pressure, the initial time will be modified. And then, the procedure is repeated.

The simulation procedure is also shown in Fig. 2 using the rigorous model from Aspen Dynamics. First, the generated BOG is computed by the calculation module. Next, the pressure of the tank (P_{tank}) is changed by the operation of the compressors and updated to the BOG calculation module, and finally the generated BOG is recomputed. The routine of this calculation is repeated.

PROCESS DESCRIPTION OF THE BOG COMPRESSION PROCESS

The Korea Gas Corporation (KOGAS) has three LNG receiving terminals in Korea. The receiving terminal facilities are located in Pyongtaek, Incheon, and Tongyoung. This paper focuses on the Pyongtaek LNG terminal because of the availability of its operation data, process data, and the stabilization of its operation system.

The Pyongtaek LNG terminal operates ten LNG storage tanks with a volume of 100,000 m^3 each and a BOR (boil-off rate) of 0.1%/day according to the specifications. There are six BOG compressors with a maximum capacity of 10 tons/h each. The design pressure of a storage tank at this facility is −2.5~230 g_f/cm^2 gauge. The

Table 1. Operation specifications of BOG compressors

Cooling system	Mixing LNG (in the1st stage)	Air-cooled cooling pen (in the 1st and 2nd stage)
Flow rate [Nm^3/h]	12,000	12,000
P [kg/cm^2]	10.56	10.56
Shaft power [kW]	909	966
Declared power [kW]	1,100	1,100

Table 2. Compositions of LNG and BOG in pyongtaek LNG terminal (mole %)

Composition	LNG1 (Specific Gravity: 0.4746)	LNG2 (Specific Gravity: 0.455)	BOG
Methane	85.11	89.26	99.64
Ethane	9.32	8.64	0.02
Propane	4.58	1.44	-
iso-Butane	0.56	0.27	-
n-Butane	0.42	0.35	-
iso-Pentane	-	-	-
n-Pentane	-	-	-
Nitrogen	0.01	0.04	0.34
Carbon dioxide	-	-	-

BOG compressors require 30 min of idle operation for startup and have load levels 0, 50, 75, and 100%, at which the electric current is 65, 115, 127, and 145 A, respectively, when operated at 6,600 V. The design specifications of the BOG compressors are shown in Table 1. The normal operation range of the tank pressure is between 50 g_f/cm^2 and 170 g_f/cm^2 gauge. If the pressure decreases to 40 g_f/cm^2 gauge, a vacuum breaker is activated, and if it increases to 190 g_f/cm^2 gauge, the BOG is sent to a flare stack. The height and diameter of the LNG storage tank are 55.16 m and 57.04 m, respectively. Manufacturing supports two types of LNG composition in the technical specifications: LNG 1 (Specific Gravity: 0.4746) and LNG 2 (Specific Gravity: 0.455) in the LNG storage tanks, as shown in Table 2. The composition of the BOG is also presented [6].

PERFORMANCE EVALUATION

A simplified model is often used for the initial step of the process simulation to lower the computation time; however, the obtained solution may not be accurate. Therefore, a rigorous model is usually considered to improve the simulation performance and increase the accuracy of the results despite the longer computation time. In this paper, an equation of state model is used to predict the pressure changes in an LNG tank for accuracy. Among the various equations available, those generally used are the Peng-Robinson equation of state and the Soave-Redlich-Kwong equation of state. The Peng-Robinson equation of state is commonly used as the equation of state to predict the pressure behavior of BOG. Using the Peng-Robinson equation of state, the *K*-value and vapor density values can be predicted quite accurately. Several studies have reported the predicted thermodynamic data for an LNG mixture, specifically the bubble point pressure and the liquid density, compared with experimental data using the Peng-Robinson equation of state. However, predictions of the saturated liquid density are inaccurate using this equation, with an average error of approximately 10% due to nitrogen interactions with methane, ethane, or other gases in the LNG mixture [7,8]. The nitrogen interaction effect, however, is disregarded in this study.

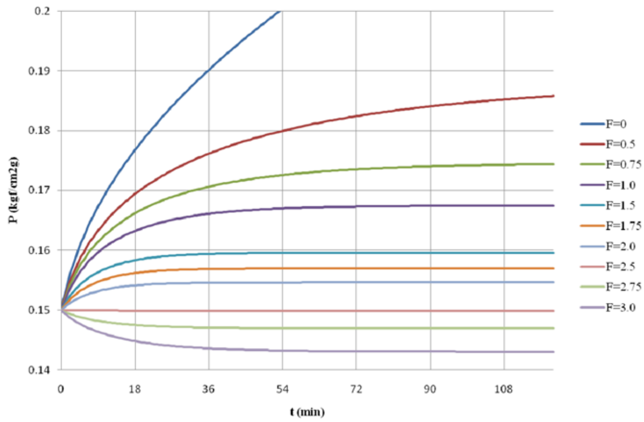

Fig. 3. Pressure changes for the various compressor operation options using the Peng-Robinson EOS of Aspen Dynamics.

Shin et al. [4] reported changes in the pressure in an LNG tank for compressor flow rates from 0 to 30 tons/h. In this paper, the change in the pressure with various compressor operation options is predicted, as represented in Fig. 3, using the Peng-Robinson equation of state of Aspen Dynamics. The results show some differences in the rate of the pressure change. For example, the simulation results of the tank pressure reach 190 g_f/cm^2g within 36 min when the compressor loads are not operated (F=0 tons/h) as compared to the simplified dynamic model based on the ideal gas law, which requires 40 min.

To test the operation procedure generated by the proposed algorithm, the situation for a high boil-off rate is considered. LNG storage tanks are filled 90% in this case; thus, the total LNG volume is 900,000 m^3. The LNG temperature is −159 °C, and the density is 459.7 kg/m^3. The temperature of the gas phase 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. To maintain the initial tank pressure, two-and-a-half loads of compressors are necessary.

The proposed method starts from a target steady state tank pressure P_{hi}≤170 g_f/cm^2 gauge. The steady state tank pressure (P_s) is 167.9 g_f/cm^2 gauge when the compressor is operated under a full load. Let P_{hi}=170 g_f/cm^2 gauge. Thus, F_o=8.978 tons/h. Optimization for this load results in the use of one compressor at full level for 0.8978 and 0.1022 at the idle level.

The dynamic simulation was performed using a general LNG composition and the Peng-Robinson equation of state. The literature reports that the composition of methane in LNG varies from 80 to 97% [9-11]. In addition, the boil-off gas at 150 g_f/cm^2 gauge in the tank is mainly composed of methane and ethane, as shown in Table 3. This is calculated using the flash model in Aspen Plus. The composition of the BOG supported by the manufacturer, shown in Table 2, was not used in the dynamic simulation, as the composition of the BOG in the technical specifications applies to the general condition of the design specifications for the LNG storage tank at

Table 3. Compositions of the LNG and BOG as an example

Component	LNG (mol%)	BOG at 150 g_f/cm^2 g (mol%)
N_2	0.04	0
C1	89.26	98.84
C2	8.64	1.16
C3	1.44	0
n-C4	0	0
i-C4	0.27	0
n-C5	0	0
i-C5	0.35	0

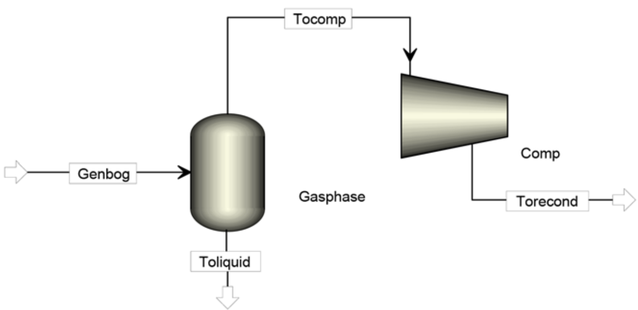

Fig. 4. Simplified BOG compression process.

the Pyongtaek terminal facility.

A simplified depiction of the BOG compression process is shown in Fig. 4. It is composed of the gas phase of an LNG storage tank and a compressor. For the simulation, the storage tank is divided into the two phases (liquid and gas), of which the gas phase has been modeled. Some features of the process were removed to keep it simple.

The results of dynamic simulation are shown in Fig. 5. At startup, compressor 1 is operated under a full load until the pressure reaches 166.5 g_f/cm^2 g, which requires 36.5 min. Compressor 1 is then operated idle for 3.6 min until the pressure reaches 170 g_f/cm^2 g. Next, compressor 1 runs for 42.6 min under a full load and then idles for 2.4 min. The operation procedure is repeated, and the pressure oscillates within a safe range. The backup compressor 2 is turned on at a pressure of 163 g_f/cm^2 g 16.8 min after the startup and remains on standby. The pressure reaches at 190 g_f/cm^2 g within 30 min when a compressor fails without a backup compressor, as shown in Fig. 6. This is earlier than the time predicted according to the ideal gas law. This procedure is represented in Fig. 7, where compressor 1 is the working compressor and compressor 2 is the backup compressor. Additionally, the power consumption of this method is compared with that of a conventional method in Table 4. The results from the power consumption are lower than in a previous paper [4] because the compressors are operated in a high-pressure range. In addition, the safety of the LNG tank when operating the backup compressor is guaranteed through the use of a rigorous dynamic simulation.

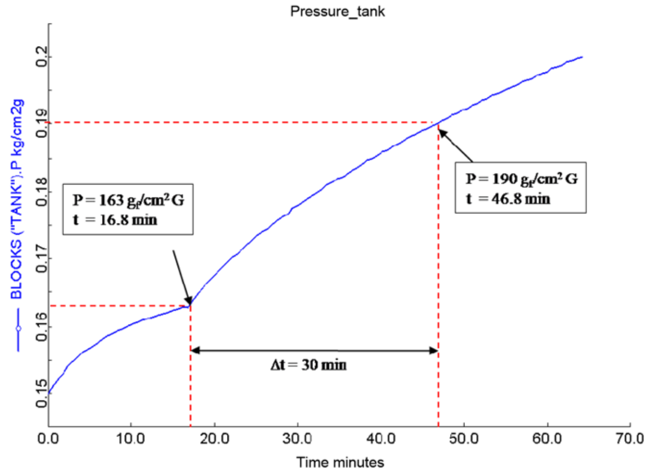

Fig. 6. Dynamic simulation results to predict the pressure to turn on a backup compressor.

CONCLUSION

An algorithm was proposed for the optimal operation of a BOG compressor at an LNG gasification plant. Based on an empirical boil-off rate model, the total compressor load can be calculated for a given target tank pressure. Next, an MILP formulation was applied for the optimal distribution of the compressor load and for the operation schedule. Finally, dynamic simulation and safety analysis were performed to predict the pressure change using a rigorous model

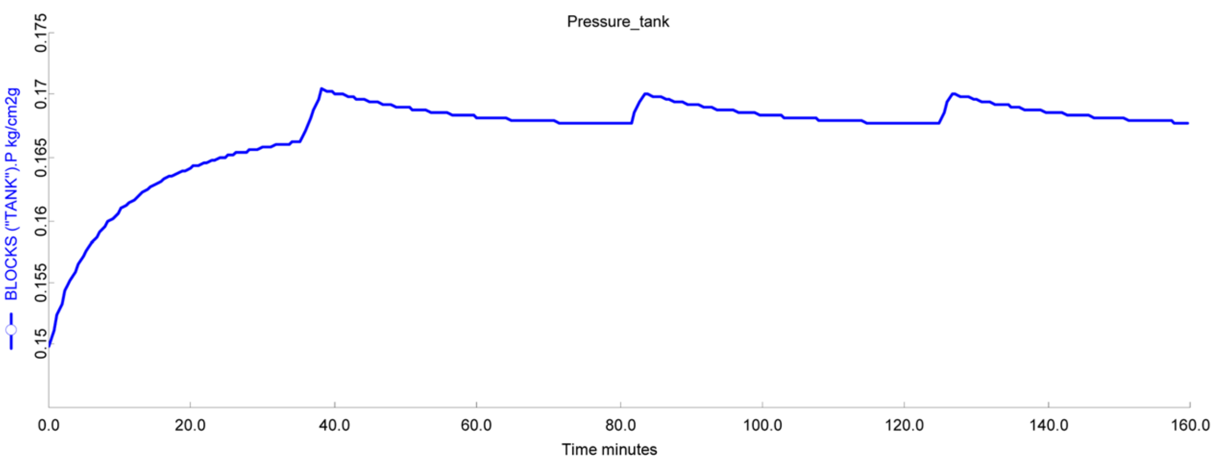

Fig. 5. Dynamic simulation result for the LNG storage tank pressure.

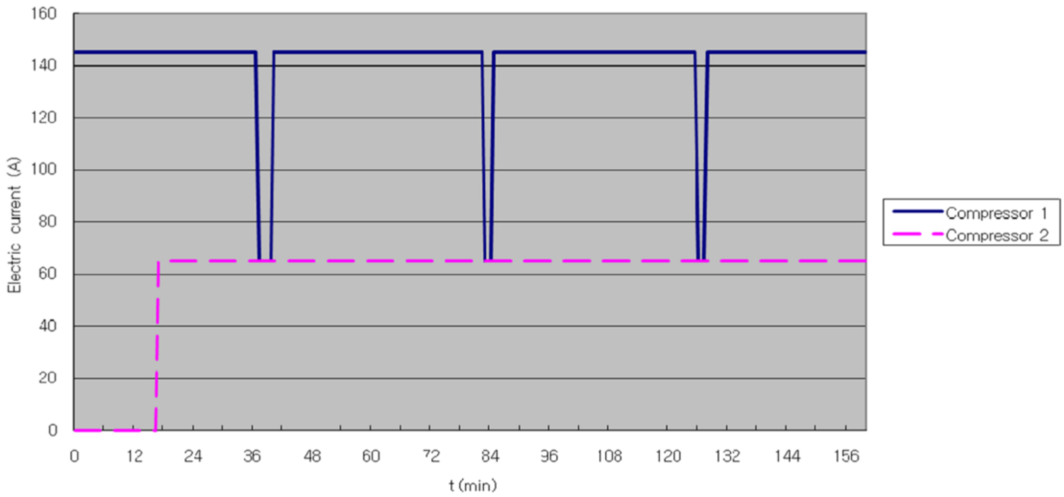

Fig. 7. Operation schedule for a BOG compressor.

Table 4. Comparison of operation methods

Method	Compressor loads (tons/h)	Target pressure (g_f/cm^2g)	Power consumption (kW)	Energy save (%)
Conventional	10, 10, 5, 0	150	3,102	-
Proposed by shin et al. [4]	10, 0	167.5	1,386	55.3
Optimal	10/0, 0	170	1,358	56.22

in the dynamic simulator of Aspen Dynamics. A case study was conducted at the Pyongtaek LNG terminal. The dynamic simulation was done to test the generated procedure and predict the pressure change using the Peng-Robinson equation of state of Aspen Dynamics. To apply various concentrations of LNG, the concentration of the BOG was calculated using the flash module in Aspen Plus. The results of the pressure change for the LNG storage tank were similar to those of a simplified dynamic model within a safe range. However, the safety-limit pressure and time to turn on a backup compressor both differed from these values in the simplified dynamic model. The performance of the proposed algorithm is superior to that of both the routine process and the results of previous work in terms of safety and energy savings. The proposed algorithm can increase the efficiency when operating and controlling the LNG gasification process. The dynamics of an LNG storage tank using the rigorous model can be adopted for all LNG terminals, piping networks and LNG industries.

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NOMENCLATURE

F : predicted boil off rate [tons/hr]
F_0 : total output compressor rate [tons/hr]
C_R : rollover coefficient by LNG circulation
B_S : boil off rate from the specification [h^{-1}]
ρ_L : LNG density [kg/m^3]
V_L : LNG volume [m^3]
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
P_S : steady state tank pressure [kg_f/cm^2g]
P_{hi} : desired highest tank pressure [kg_f/cm^2g]
P_{tank} : pressure of LNG tank [kg_f/cm^2g]
COMP : BOG compressors
GASPHASE : gas phase in the LNG tank
GENBOG : generated BOG
TOLIQUID : material stream to liquid phase
TOCOMP : material stream linking LNG tank to BOG compressors
TORECOND : material stream linking BOG compressors to recondenser

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