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Comparison of Operation Performance of LNG Reliquefaction Process according to Reverse Brayton Cycle and Claude Cycle

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Abstract

A dynamic model to simulate LNG reliquefaction process has been developed. The model was applied to two candidate cycles for LNG reliquefaction process, which are Reverse Brayton and Claude cycles. The simulation was intended to simulate the pilot plant under construction for operation of the two cycles and evaluate their feasibility. According to the simulation results, both satisfy control requirements for safe operation of brazed aluminum plate-fin type heat exchangers. In view of energy consumption, the Reverse Brayton cycle is more efficient than the Claude cycle. The latter has an expansion valve in addition to the common facilities sharing with the Reverse Brayton cycle. The expansion valve is a main cause to the efficiency loss. It generates a significant amount of entropy associated with its throttling and increases circulation flow rates of the refrigerant and power consumption caused by its leaking resulting in lowered pressure ratio. It is concluded that the Reverse Brayton cycle is more efficient and simpler in control and construction than the Claude cycle.

Key words: LNG, reliquefaction, Reverse Brayton cycle, Claude cycle, dynamic model

1. Introduction

It takes approximately 30 days for a carrier to transport LNG (Liquefied Natural Gas) from the Middle East, a place of production, to South Korea, a place of consumption. Despite insulation of heat during the period of transportation, LNG at about -165℃ has heat flowing in and evaporates, increasing pressure within a tank. In order to prevent pressure from increasing, a current LNG carrier uses liquefied natural gas as a heat source of boiler to produce power for motors that propel a ship. In this case, the overall thermal efficiency is about 30%. As the price of natural gas goes up, it is not a good idea to use liquefied gas as a power source. So, a plan to reliquefy and circulate gas to a tank and to use a Diesel engine for ship propelling has been put to practical use these days.(1) It is Hamworthy Ltd. that put such an idea of reliquefying into a commercial use. The company is currently building a LNG carrier.(2)

The reliquefying cycle used by Hamworthy is the one that came from the Reverse Brayton cycle. In this study, in addition to the Reverse Brayton cycle,(3) we will examine and compare the feasibility of the Claude cycle that we developed on our own.(4) In this study, prior to a real operation, we will evaluate the feasibility of process control and performance of each cycle through dynamic simulation.

2. Comparison of process cycles

2.1 Reverse Brayton cycle

Fig. 1 shows the diagram of component devices and valves for cycle configuration and process control. The refrigerant of nitrogen goes through the 3-stage compressor and the intercooler before being compressed in room temperature and high pressure. Then, it is cooled, going through the aluminum plate heat exchangers of HX200A and HX200B within the cold box. In the expander connected to the shaft of the compressor, the cooled nitrogen is expanded in the range of -163℃~-168℃, which is slightly more

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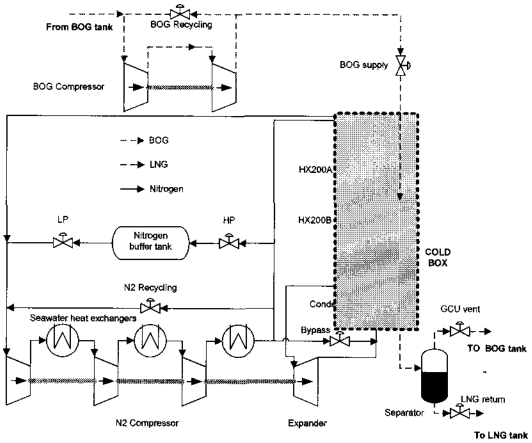

Fig. 1. Reverse Brayton cycle.

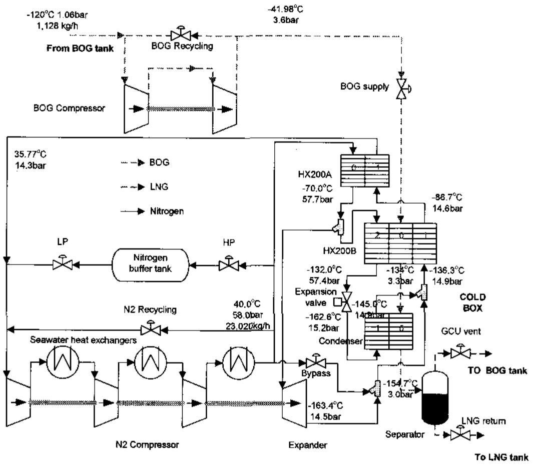

Fig. 2. Claude cycle.

overheated than saturation. The cooled refrigerant is sent to condenser where it cools and liquefies the boil-off gas (BOG) that comes from the LNG tank. In the process of going back to the inlet of the compressor, the refrigerant, which is still in low temperature, exchanges heat with the refrigerant that goes to the inlet of the expander from HX200B and HX200A, ending up with being heated near to a room temperature.

2.2 Claude cycle

Fig. 2 shows the configuration of the Claude cycle. The difference from the Reverse Brayton cycle is that the amount of flow, which is necessary to liquefy the BOG, is diverged to the expansion valve to be expanded and cooled while the rest of the flow is sent to the expander. Since the Reverse Brayton cycle uses only the expander for cooling, it is very sensitive to controlling the degree of superheat at the outlet of the expander in order to secure an adequate mass circulation rate of a refrigerant according to changes in BOG flow. But the Claude cycle is relatively stable.

3. Process control

For process control, an optimal and stable operation should be performed in response to start and stoppage of equipment and changes in BOG load. The purpose of controlling is to liquefy the BOG, consuming the least amount of energy without putting too much load on component devices in the phase of excessive operation. In regard to controlling of reliquefying equipment, some problems to be solved are as follows.

(1) Minimization of thermal stress generation in the plate heat exchangers
(2) Controlling of superheat at the expansion device outlet
(3) Liquefying of BOG with a minimum power

There are specific restraint conditions that are required to solve the problems mentioned above. The plate heat exchanger installed inside the insulated cold box was selected in consideration of a limited space in a ship and high efficiency of the exchanger. But it is a brazed type heat exchanger so that it is vulnerable to thermal stress. Therefore, manufacturers of plate heat exchanger for plant established regulations of the ALPEMA (Brazed Aluminum Plate-Fin Heat Exchanger Manufacturer's Association) to ensure safety of using heat exchanger. Some of the basic regulations to be observed in regard to process control are as follows.(5)

(1) The temperature change rate at heat exchanger should not be more than 2℃ per minute.
(2) The allowable maximum temperature difference between counter flows is less than 50℃.
(3) The temperature difference is less than 20-30℃ between fluids that have two-phase flow or periodic temperature change.

Nitrogen should not be condensed at the outlet of the expander to protect turbine blade so that the degree of superheat should be controlled at a minimum of more than 2-3℃. Since the generation rate of the BOG may change at any given time of operation, the mass circulation rate of a refrigerant should be reduced at an optimal level according to the flow rate of the BOG that is to be cooled with a view to minimizing the consumed power.

3.1 Control algorithm

In the initial stage of starting up, the equipment is probably in a room temperature. Therefore, the precooling section is required for cooling at the gradient of 2℃ per minute according to the ALPEMA regulations. In this section, only the refrigerant cycle is in operation. And for controlling of temperature gradient, it is important to control opening of the bypass valve that mixes the low-temperature refrigerant at the outlet of the expander with the high-temperature refrigerant at the outlet of the compressor as shown in Fig. 1. The precooling comes to an end when the temperature reaches approximately -120℃ that corresponds to the idling section. The idle phase is the minimum temperature section where only the refrigerant cycle can be used to lower temperature without supply of the BOG. In this phase, the temperature of the expander outlet is the allowable minimum temperature of superheat. When the BOG starts to be supplied, load operation begins. According to flow rate of the BOG, the temperature of the heat exchanger should be controlled while the mass circulation rate of a refrigerant should be increased gradually.

Cooling load may increase due to increase in flow rate of the BOG, which may cause increase in temperature of the expander outlet. If that happens, in order to lower the temperature to control range of superheat, the amount of nitrogen that is supplied to a refrigerant circulation loop should be increased by controlling the opening of the high pressure valve (HP) and the low pressure valve (LP) that are installed at the both ends of the buffer tank charged with the refrigerant nitrogen. In the case of the Reverse Brayton cycle, cooling load according to increase in flow rate of the BOG has a direct impact on the superheat at the outlet of the expander. Therefore, if the superheat at the outlet of the expander is kept constant under any BOG load, an optimal mass circulation rate of the refrigerant is found automatically by feedback control. On the contrary, the Claude cycle controls the refrigerant temperature at the inlet of the condenser, instead of the outlet of the expander. The refrigerant that leaves from HX H0heis divided at a certain flow rate ratio by the T-type bifurcation tube. If the opening of the HP and LP valves are controlled according to the BOG load, an amount of flow, necessary to handle the BOG load, is supposed to move to the expansion valve.

4. Process simulation

The major component devices for process simulation include heat exchanger, compressor, expander, valve, and pressure container. The detailed information on the process of the modeling can be found in the study(4) by Shin et al. so that the information will not be included in this study. Since calculation of mechanical properties is important, Refprop libraries(6) by NIST is interfaced for use. For a programming language, we used Visual C++ of Microsoft, a object-oriented language.

5. Results and discussion

5.1 Reverse Brayton cycle

Figs. 3 to 7 show the results of simulation of the Reverse Brayton cycle. In Fig. 3, the target temperature expressed with a dotted line is the setting temperature in consideration of temperature gradient (2℃ per minute) based on the ALPEMA regulations. This is the temperature that the refrigerant of nitrogen at the inlet of the condenser should follow. For about 4,500 seconds, which is a beginning stage of precooling period, the temperatures of refrigerant at the outlet of the expander and inside the condenser followed similar temperature gradients. The part where the temperature was somewhat out of the setting temperature in the beginning is related to discordance between compressor operation and bypass valve opening control. This can be improved for a real pilot operation or enhanced by lowering the gradient of 2℃ per minute. The period from about 4,500 seconds to about 5,000 seconds indicates the idle phase. And the certain setting temperature of approximately -120℃ has been maintained. Afterward, there is a load operation section where the BOG starts to be supplied to reliquefaction equipment.

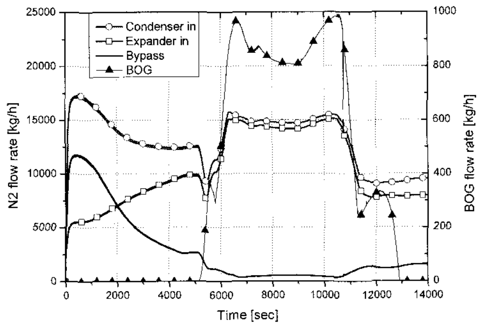

Fig. 3. Temperature control (Reverse Brayton).

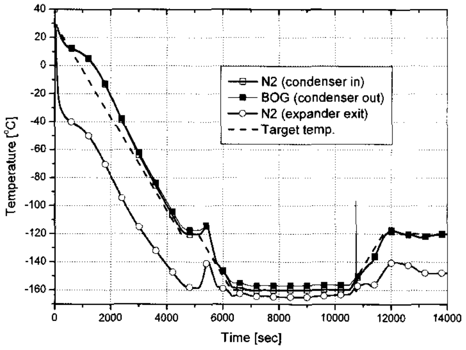

Fig. 4. Mass flowrate (Reverse Brayton).

The BOG mass flow rate is shown in Fig. 4 Some of the refrigerant that leaves from the compressor in Fig. 1 goes through the bypass valve for controlling of the downward gradient of the temperature of the heat exchanger while the rest flows through the heat exchanger into the expander. The diverged refrigerants meet together at the outlet of the expander and reach an optimal temperature before flowing to the condenser. As shown in Fig. 4, in the period of pre-cooling, the amount of bypassing is decreased gradually for controlling of temperature gradient. And the amount becomes almost 0 in the rated load operation section. Since the increase in bypassing amount is a cause for efficiency decrease, it should be reduced as much as possible. In the initial stage of part load operation where the BOG starts to be supplied, the temperatures of fluids tend to be out of the setting temperature due to a dramatic increase in BOG flow rate. To improve this, the BOG should be supplied at a gentler gradient of flow rate. Excluding the initial phase where the flow rate increases dramatically, it can be said that the temperatures of fluids follow the setting temperature well.

Fig. 5 shows superheat at the outlet of the expander and performance of BOG liquefaction at the outlet of the compressor. The vertical axis indicates the quality, which is the ratio of vapor mass to the total mass. This is also the output value from Refprop program.[6] In addition to the ideal value ranging between 0 and 1, the program shows that the value is expressed in negative in proportion to subcooling while the value is larger than 1 in proportion to superheat. As a result, the degree of phase change can be viewed continuously. The refrigerant at the outlet of the expander reaches near the quality of 1.0, which is the most important part and requires monitoring in a real control. As the quality becomes much larger than 1.0, the performance gets deteriorated so that the capacity of equipment should be bigger. Therefore, in order to improve performance, the quality at the outlet of the expander should be controlled near at 1.0 if possible. The quality of the BOG at the outlet of the compressor is maintained at less than 0.0 so that a small amount of the subcooled LNG is emitted.

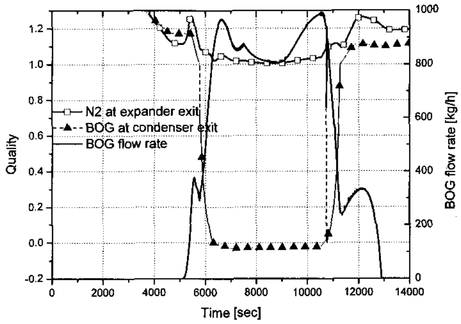

Fig. 5. Vapor quality (Reverse Brayton).

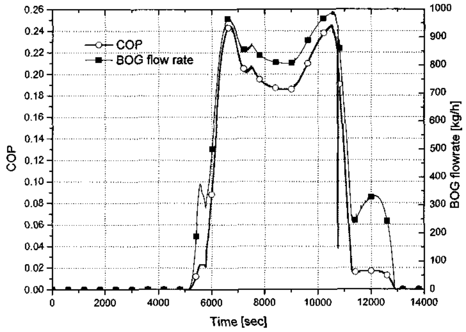

Fig. 6. COP (Reverse Brayton).

Fig. 6 shows the COP (Coefficient of Performance) of the equipment. The definition of the COP is as below.

$$COP = \frac{\text{Heatremoved from BOG}}{\text{Compressorpower} - \text{Expander power}} \quad (1)$$

According to Fig. 6, the COP changes in line with the BOG flow rate and is approximately 0.2. This has something to do with the properties of the cycle where the refrigerant with the low COP changes from the high temperature of about 40℃ to the extremely low temperature of about -170℃ while it maintains the gas state. Similar results can be found in the study conducted by Moon et al. who made an analysis of thermodynamic cycle.

Fig. 7 shows the pressure of the refrigerant at the compressor for the refrigerant and before and after the

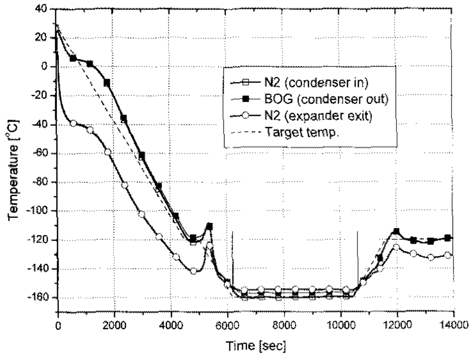

Fig. 7. Pressure (Reverse Brayton).

BOG compressor. In the phase of load operation, the high pressure and low pressure of the refrigerant are approximately 4,800 kPa and 1,250 kPa, respectively.

5.2 Claude cycle

Figs. 8 to 12 show the results of simulation of the Claude cycle. The performance of following temperature inside the heat exchanger is similar to the case with the Reverse Brayton cycle. In the case of BOG liquefaction and the quality at the outlet of the expander, the performance is similar. Conversely, the COP that indicates the performance of the equipment is inferior to that of the Reverse Brayton cycle. In Fig. 11, it is shown that the COP is proportional to the BOG flow rate just as with the case of the Reverse Brayton cycle. This means that the COP is influenced because the mass circulation rate of a refrigerant for nitrogen in Fig. 9 is relatively constant in the load operation section so that the power consumption is also constant while, on the contrary, the BOG flow rate, required for liquefaction, is changing. The BOG flows through the heat exchanger due to the difference between pressure at the BOG outlet and pressure inside the separator. As shown in Fig. 12, the pressure at the BOG outlet is controlled relatively constant. On the contrary, the pressure inside the separator cannot maintain the constant value but keeps changing slightly. As a result, control performance should be improved. In spite of minimal change in process configuration in which only an expansion valve is added to the Claude cycle while the rest of equipment is common to the Reverse Brayton cycle, comparison of mass circulation rate and high pressure of the refrigerant shows significant differences. Those values are 20,000 kg/h and 4,000 kPa with the Claude cycle and 15,000 kg/h and 4,800 kPa with the Reverse Brayton cycle, respectively. This difference is basically attributed to the existence of the expansion valve. In the Claude cycle, about 1/3 of mass circulation rate of a refrigerant is supposed to flow to the expansion valve for expansion cooling. This is similar to the case where refrigerant leaks from a high pressure part to a low pressure part. As a result, the compressor cannot reach to high pressure sufficiently while the turbo compressor, revolving at a constant speed, sheds a great amount of flow due to a low ratio of pressure. This caused excessive loss of power, resulting in the COP being inferior to that of the Reverse Brayton cycle.

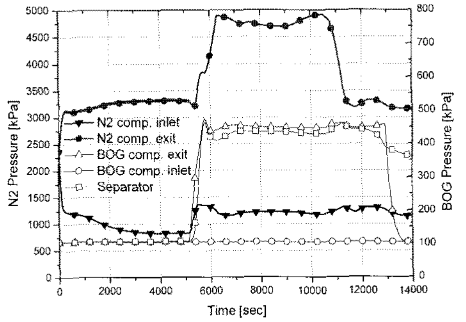

Fig. 8. Temperature control (Claude).

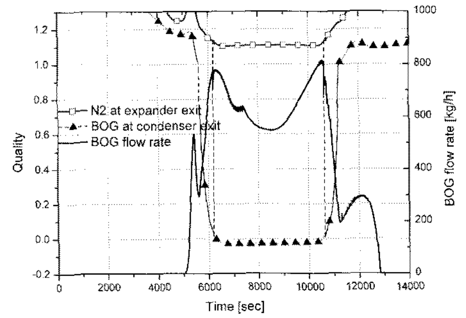

Fig. 9. Mass flow rate (Claude).

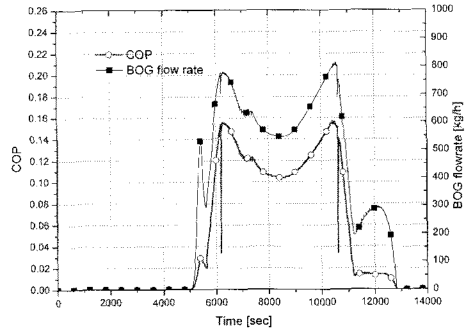

Fig. 10. Vapor quality (Claude).

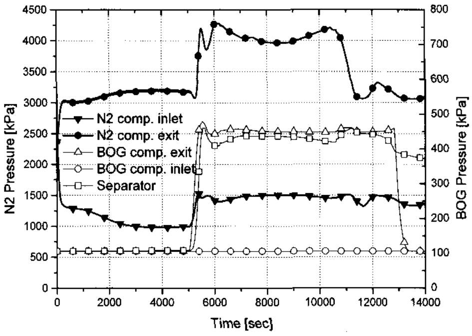

Fig. 11. COP (Claude).

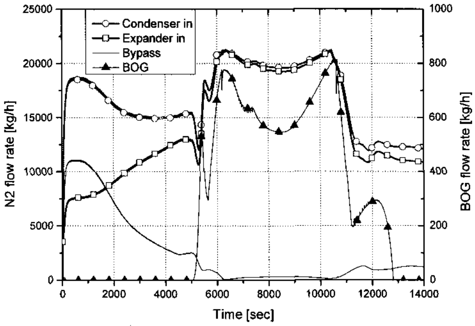

Fig. 12. Pressure (Claude).

6. Conclusion

We developed the process simulation dynamic model to predict operation characteristics according to the process cycle of LNG reliquefaction equipment. The results of simulation produced the conclusion as follows.

Both of the Reverse Brayton cycle and the Claude cycle showed a satisfactory performance that was required for temperature control of aluminum plate heat exchanger and natural gas liquefaction. In terms of the COP, the Reverse Brayton cycle proved to be better than the other. The reason for the performance of the Claude cycle being inferior is that the power consumption of the compressor increases due to exergy and pressure losses associated with the refrigerant flow that was diverged to the expansion valve. In addition, as another expansion valve was added with the refrigerant being diverged, the system got complicated and so did the control algorithm. As a result, it seems that the operation instability increased compared to the Reverse Brayton cycle. In view of equipment for natural gas reliquefaction, the Reverse Brayton cycle seems to be advantageous in that it achieves operation goals in a simpler and stable fashion. However the Claude cycle can also be advantageous to other equipment that should utilize the saturation phase by an expansion device. Therefore, performance of cycles should be evaluated according to the purpose of use.

Acknowledgement

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