Design and simulation optimization of cold storage and air conditioning system in LNG powered carrier by using cold energy of LNG based on HYSYS

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Abstract. In order to solve the problem that the LNG (Liquefied Natural Gas) cold energy in LNG powered carrier is not used sufficiently, a set of system is designed. This cold storage and air conditioning system is used in LNG powered carrier. At the same time, the refrigerant required by the system is selected and simulate the process of the system by HYSYS. This paper describes the specific process and gives the simulation parameters of each node. The simulation results meet the expected requirements and accord with the actual situation. The main purpose of this system is to reduce energy consumption by using LNG cold energy as a cold source of cold storage and room air conditioning.

1. Development status
In recent years, with the new requirements of the international regulations on ship emissions having been published, more and more carriers use LNG as fuel. LNG powered carrier has been widely concerned because of LNG’s small pollution and low price [1]. Many international ship enterprises tend to focus on the research, development and production of LNG powered carrier, which makes the number of LNG powered carrier increase rapidly [2].

Taking 300,000-ton VLCC (Very Large Crude Carrier) as an example, shown in Figure 1, the ship can consume more than 100 cubic meters of LNG every day, and a large amount of cold energy will be released in the process of LNG gasification, one kilogram of LNG can be released about 860 ~ 830 kJ by gasification [3, 4]. If these cold energy is not used sufficiently, it will cause a huge waste of cold energy.

At present, LNG cold energy utilization technology develops well in developed countries such as Japan and America, which is mainly used for power generation, air separation, low temperature cold storage, light hydrocarbon separation, cryogenic comminution and other aspects [5, 6].

At present, the domestic ship cold storage and air conditioning basically adopt compression refrigeration, which consumes electric energy. Using LNG cold energy for reducing the temperature of cold storage and air conditioning can achieve the purpose of energy conservation and consumption reduction [7, 8]. In this paper, a set of LNG cold energy utilization system in LNG powered carrier is designed, the LNG cold energy is used as the cold source of the ship's air conditioning and cold storage. The main heat exchangers in the system are also designed in this paper.
2. Design of cold storage and air conditioning system in LNG powered carrier by using cold energy of LNG

2.1. Main parameters of carrier cold storage and air conditioning

The 300,000-ton VLCC is used as a mother ship. The fuel used by the ship is LNG, ME-GI is selected as the type of marine main engine. The parameters considered by the system equipment are designed according to the maximum load (in summer).

This system is able to use LNG cold energy as a cold source of cold storage and room air conditioning. Ship cold storage is divided into low temperature cold storage (to store fish and meat, -22℃~ -18℃) and high temperature cold storage (to store vegetables and dry goods, 0℃~5℃) [7, 8]. Between two kinds of cold storage, there is a buffer room (0℃~5℃) to separate cold storage from external environment. The main parameters of cold storage, buffer room and air conditioning are shown in Table.1 after considering different kinds of heat transfer. In Table 1, the parameters related ship come from the relevant data, and the average load of each system is calculated according to the cabin size and working conditions.

| Content                        | Numerical value |
|--------------------------------|-----------------|
| VLCC                           |                 |
| Length (m)                     | 330             |
| Beam (m)                       | 60              |
| Main engine power (kW)         | 25480           |
| Fuel flow (kg/h)               | 3000            |
| LTCS system a Average load of fish bank (kW) | 1.5              |
| Average load of meat bank (kW) | 1.5             |
| Buffer room Average load (kW)  | 1               |
| HTCS system b Average load of vegetable bank (kW) | 2.5            |
| Average load of dry goods bank (kW) | 2             |
| ACS system c Average load (kW)  | 100             |

a low temperature cold storage system  b high temperature cold storage system  c air conditioning system

2.2. The general plan in system

The main idea of the LNG cold energy utilization system in LNG powered carrier is that to make the refrigerant to absorb the cold energy of LNG, and then the cold energy is transferred to the cold storage system and the air conditioning system through the refrigerant, to meet the requirements of LNG powered carrier for cold energy.

The designed system is shown in Figure 2. In the whole operation process, the phase change of LNG only occurs when it is heated in the LNG heater, while the phase change of refrigerant in the low temperature cold storage system only occurs when it is in the cold storage refrigerant heat exchanger EX-1, air conditioning refrigerant heat exchanger EX-2 and anti-solidification heat exchanger EX-3. The main flow of the system is as follows:
Figure 2. The cold energy of LNG utilization system.

The LNG from the fuel tank is pressurized by the pressure pump P-1, then enters the LNG heat exchanger LNG-1 to transfer the cold energy to refrigerant in the low temperature cold storage, because the cold energy contained in LNG isn’t fully utilized, the LNG will enter the LNG heater LNG-2 to use the heat of the jacket water from diesel engine cooling system to heat up and gasify, and then enter the main engine system for combustion.

In the low temperature cold storage system, the refrigerant obtained the cold energy is pressurized by the circulating pump P-2, and then it enters into heat exchangers (E-1, E-2, E-3) respectively in the cold storage to cool the fish storage, meat storage and buffer room down, while the other two parts of refrigerant respectively enter into the refrigerant heat exchanger EX-1 located in the cold storage and the refrigerant heat exchanger EX-2 located in the air conditioning system, and it will transfer the cold energy to the high temperature cold storage system and the air conditioning system; in the high temperature cold storage system, the refrigerant obtained the cold energy is pressurized by the circulating pump P-3 and respectively enters heat exchanger (E-4, E-5) to cool the vegetable storage and the dry goods storage; in the air conditioning system, after obtaining the cold energy, the refrigerant will enter the evaporator E-6 to release the cold energy which is transmitted to the air through the fan to cool the air.

3. Simulation of the system

3.1. Determine the simulation parameters
The system is simulated by Aspen HYSYS [9, 10]. In response to the call of national environmental protection, R134a, which is more environmentally friendly, is selected as the refrigerant in the low temperature cold storage system, while glycol solution with a concentration of 40% is selected as the refrigerant in the high temperature cold storage system and air conditioning system. Peng-Robinson equation is selected as the property method of the above refrigerant and LNG, and NBS Steam equation is selected as the property method of the jacket water.

When LNG in the system passes through LNG-1 heat exchanger, the cold energy will be transferred to the refrigerant in the low temperature cold storage system, and then it will enter the power system for combustion after being gasified by LNG heater LNG-2. The cold energy utilization system is divided into low temperature cold storage system, high temperature cold storage system and
air conditioning system. Firstly, LNG will transfer the cold energy to the low temperature cold storage system through R134a. Then through exchange the energy between 40% glycol solution in the high temperature cold storage system and air conditioning system and R134a in the low temperature cold storage system. The part of the remaining cold energy is to cool the high temperature cold storage and the air conditioning. Finally, the remaining cold energy is consumed by the heat of the jacket water. In order to ensure that the low temperature cold storage, the buffer room, the high temperature cold storage and air conditioning meet the requirements of temperature, the temperature of the refrigerant in the low temperature cold storage system, high temperature cold storage system and the air conditioning system after releasing the cooling energy shall be lower than the lowest temperature of the low temperature cold storage, the buffer room, the high temperature cold storage and the air conditioning. According to the requirements of the ship working conditions, the main parameters of different modules in the system are shown in Table 2.

### Table 2. Main parameters settings of different modules.

| Modules         | Medium     | Import pressure (MPa) | Inlet temperature (℃) | outlet temperature (℃) | LNG flow (kg/h) |
|-----------------|------------|-----------------------|------------------------|-------------------------|-----------------|
| LNG             | R134a      | 0.3                   | -162                   | 3000                    |
| LTCS system     | R134a      | 0.2                   | -40                    | 25                      |
| E-3             | R134a      |                        |                        |                          |
| EX-1            | R134a      | -20                   |                        |                          |
| EX-2            | R134a      | -20                   |                        |                          |
| HTCS system     | 40% GS     | 0.2                   | -10                    | 0                       |
| AC system       | 40% GS     | 0.2                   | 2                      | 10                      |
| LNGG system d   | Jacket water | 0.2                 | 80                     | 60                      |
| LNGG system e   | R134a      |                       |                        |                          |

| d LNG gasification system |
| e 40% glycol solution |

3.2. Simulation results

After simulation with HYAYS, the main parameters of each node, including gas phase fraction, temperature, pressure, flow and so on, are obtained in the system. According known heat load, the passing weight per hour of refrigerant in the cold storage and air conditioning system have been calculated. The simulation results of the main nodes in the system are shown in Table 3.

It is acquired by calculation that the total release of cold energy of LNG in LNG-1 heat exchanger is 144 kW, and Table 4 shows the consumption of cold energy in high and low temperature cold storage system and air conditioning system.

3.3. Analysis of simulation results

According to the simulation results in Table 3 and Table 4:

1. When LNG passes through LNG-1 heat exchanger, the temperature will rise, which will release a large amount of cold energy. Because the pressure is 30MPa after through pressure pump P-1, LNG does not occur phase change after heat exchange. After in the cold storage system being pressurized to 200KPa by centrifugal pump P-2, R134a will not occur phase change when it through the cold storage heat exchanger (E-1, EX-2, E-3), but after passing through the refrigerant heat exchanger (EX-1, EX-2), the vapor fraction is greater than 0 in Table 4, it will occur phase change, The data shows that the heat transfer here is very large and it will achieve a better refrigeration effect. In addition, after the phase change, the flux of refrigerant will be greatly decreased when required to produce the same
amount of cold energy. This means that the consumption rate of refrigerant is reduced, so the pipe diameter of refrigerant may be reduced properly during the operation of the system to save the investment of the equipment. However, it also increases the design difficulty of the refrigerant heat exchanger EX-1 in the high temperature cold storage and EX-2 in the air conditioning, and it is difficult to control the flow when the phase change of refrigerant occurs.

2. The outlet flow of the heat exchanger (E-1, E-2, E-3) and the heat exchanger (EX-1, EX-2) of the cold storage meet the actual requirements of the ship.

3. The cold energy consumption of each module of cold energy utilization system in VLCC is 108 kW, the numerical value is less than 144 kW, it shows that the cold energy of LNG can meet the demand of cooling each module, the heat exchangers (E-1, E-2, E-3, E-4, E-5, E-6, EX-1, EX-2) are able to achieve the desired cooling effect.

4. In the air conditioning system, the simulation results of C-2, C-4 also reach the expected temperature which is above 0°C. The reason to control their temperature above 0°C is to void small drops of water in the air frosting on the wall surface of exchanger (E-6) when the air passes, so as to void blocking.

### Table 3. Simulated parameters of main nodes based on HYSYS

| Nodes  | Temperature (°C) | Pressure (MPa) | Rate of flow (kg/h) | Vapor fraction |
|--------|------------------|----------------|--------------------|----------------|
| L-1    | -162             | 0.3            | 3000               | 0              |
| L-2    | -153.3           | 30             | 3000               | 0              |
| L-3    | -105.5           | 30             | 3000               | 0              |
| L-4    | 25               | 30             | 3000               | 1              |
| R-2    | -40              | 0.3            | 2356               | 0              |
| R-5    | -25              | 0.27           | 345.3              | 0              |
| R-8    | -25              | 0.27           | 345.3              | 0              |
| R-11   | -20              | 0.27           | 171.3              | 0              |
| R-13   | -39.7            | 0.28           | 66.75              | 0              |
| R-14   | -15              | 0.27           | 66.75              | 1              |
| Y-9    | -5               | 0.27           | 1091               | 0              |
| Y-1    | -10              | 0.27           | 1091               | 0              |
| Y-2    | -9.92            | 0.3            | 1091               | 0              |
| Y-5    | 0                | 0.27           | 606.1              | 0              |
| Y-8    | 0                | 0.27           | 484.5              | 0              |
| R-16   | -40              | 0.28           | 1428               | 0              |
| R-17   | -15              | 0.28           | 1428               | 1              |
| C-4    | 10               | 0.21           | 14440              | 0              |
| C-2    | 2                | 0.3            | 14440              | 0              |
| R-18   | -17.75           | 0.27           | 2356               | 0.63           |
| H-3    | 60               | 0.27           | 1.31×10^4          | 0              |
| H-4    | 80               | 0.26           | 1.31×10^4          | 0              |

### Table 4. Cold energy consumption of VLCC.

| Position of energy consumption | Cold energy consumption (kW) |
|--------------------------------|------------------------------|
| Low temperature cold storage   | 2.8                          |
| Buffer room                    | 0.9                          |
| High temperature cold storage  | 4.3                          |
| Air conditioning               | 100                          |
| Total                          | 108                          |
3.4. Economic analysis
Taking the route from China to the Middle East as an example, the power consumption of the traditional electric refrigeration method is very high, it is shown in Table 5.

Table 5 shows the energy consumption and costs in the first month of each quarter, according to the data, it is estimated that the average annual energy consumption is 260400 kWh and the costs are 390.4 thousand yuan. If this mother ship uses this system, it will save a lot of electricity and achieve substantial savings.

Table 5. Power consumption and cost of each system block

|               | AC system | HTCS system | LTCS system |
|---------------|-----------|-------------|-------------|
| Power         |           |             |             |
| Consumption   | 9900      | 1500        | 2500        |
| Costs         | 1.48      | 0.23        | 0.37        |
| April         | 10800     | 2100        | 2900        |
| Power         |           |             |             |
| Consumption   | 2100      | 0.31        | 0.43        |
| Costs         | 2.61      | 0.35        | 0.47        |
| July          | 13700     | 2400        | 3100        |
| Power         |           |             |             |
| Consumption   | 2400      | 0.35        | 0.47        |
| Costs         | 2.06      | 0.34        | 0.47        |
| October       | 11000     | 2200        | 3000        |
| Power         |           |             |             |
| Consumption   | 2200      | 0.34        | 0.45        |
| Costs         | 1.66      | 0.34        | 0.45        |

The unit of energy consumption in the table is kWh, the unit of costs is ten thousand yuan.

4. Conclusions
1) Take the 300,000-ton VLCC as a mother ship, a carrier cold storage and air conditioning system is designed to utilize LNG cold energy, the cold energy of LNG is transferred to the cold storage and air conditioning through the refrigerant to reduce their temperature.

2) The cold energy utilization process of LNG is simulated by Aspen HYSYS, and the parameters of main simulation nodes have been given. At the same time, these parameters also have proved the rationality of the system, the release of LNG meets the needs of the cold storage and air conditioning in LNG powered carrier.

3) This system can replace the traditional method of using electric energy to refrigerate, so it is able to reduce fuel consumption, save cost and reduce emission.

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