The thermodynamic analysis and adjusting methods for reliquefaction plant on board LEG carriers

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The real capacity of the reliquefaction plant on board the ethylene carrier depends on the knowledge and skills of the ship cargo engineer to a great extent. Aimed at optimum operation, thermodynamic analyses are made on refrigerating cycles of the plant. The maximum cooling rate mode and the optimum energy-conservation mode are brought forward. Ethylene tank temperature is forecasted; optimum-operating mode is chosen and the division point is determined. Meanwhile, various influencing factors and working parameters of the plant are discussed in the paper.

INTRODUCTION

LEG (liquefied ethylene gas) carrier is a semi-pressurized ship for loading and transporting the cargo of ethylene. Normally, the storing temperature of ethylene is within 169.5-175 K on board. The daily ethylene evaporation rate is about 0.2% - 0.3% of their weight in sailing. The vapor not only causes the tank pressure rise, but also discharge problems because most of the terminals demand the ethylene discharge temperature (T_D) to be kept below 170.5 K. So the reliquefaction plant onboard should run at good performance and in correct operation to maintain the T_D as required.

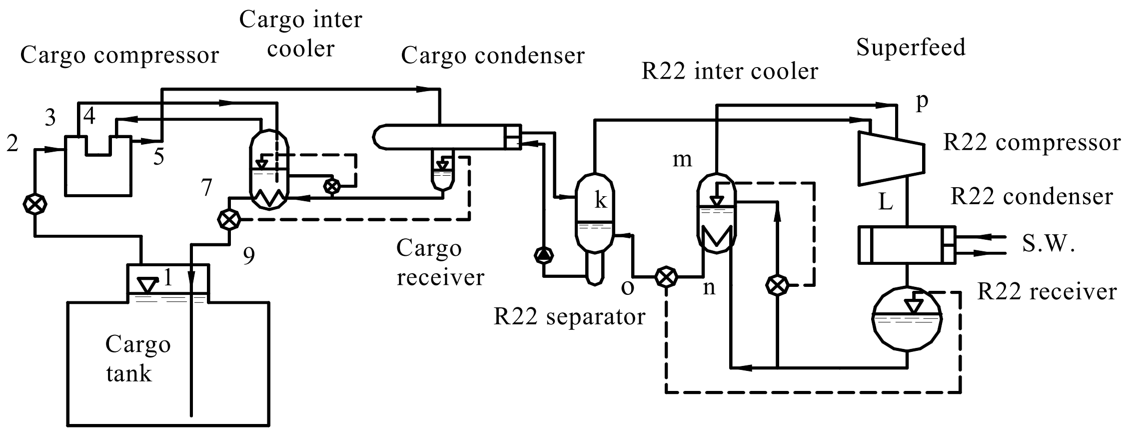

Figure 1 LEG reliquefaction plant system

The system on board MV Norgas Energy is shown in Figure 1. A LEG carrier has three sets of the plant (3 units), whose total power is about 1000 kW. There are two working cycles in each plant, their cooling processes are plotted into a Mollier diagram (see Figure 2).

If ethylene temperature is not low enough when carrier arrives at a terminal, the carrier has to anchor for cargo cooling down; as a result, the ship owner will lose about 10,000-14,000 dollars a day. In order to avoid this, the plant should run at the maximum cooling rate mode (MCRM). But if there is a long voyage or a very low cargo-loading temperature (T_c), the only needs are to keep the tank temperature constant and make the plant run at minimum energy consumption, here termed as optimum energy-conservation mode (OECM). Until now, no LEG carrier has distinguished the above two different operating modes, and a lot of energy has been wasted.

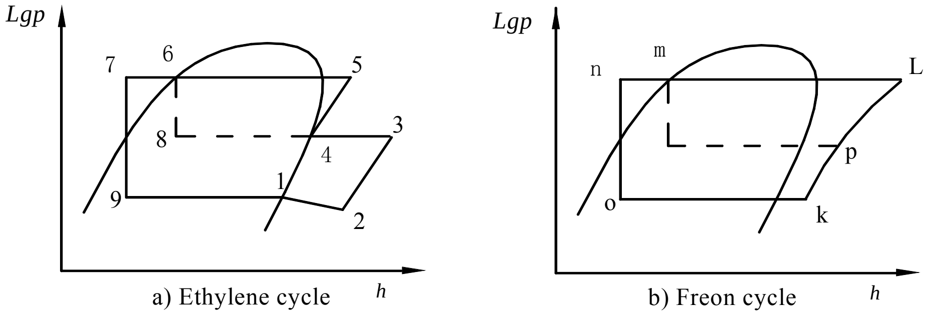

Figure 2 Refrigeration cycles

THERMODYNAMIC ANALYSIS OF THE PLANT

The working parameters of the plant

The key thermodynamic parameters of liquid & vapor include saturation pressure and temperature, specific volume, enthalpy, entropy, exergy, available energy, etc.. Taking the system in Fig.1 for an example, and from the running data of the plant onboard during its 158th voyage, ethylene property table and the data calculated, the parameters of each point in Fig.2 have been derived, and some of them are shown in Table 1.

Table 1 Working parameters of the plant

Running time	T_1 (K)	P_1 (Mpa)	T_2 (K)	P_2 (Mpa)	$Enthapy_2$ (KJ/kg)	$Entropy_2$ (KJ/kg·K)	T_7 (K)	P_7 (Mpa)	$Enthalpy_7$ (KJ/kg)	$Entropy_7$ (KJ/kg·K)
1st day	172.1	0.1185	172.186	0.118	507.922	3.349	205.495	20.195	109.963	0.628
2nd day	171.4	0.115	171.594	0.114	507.423	3.361	203.147	20.02	104.251	0.613
3rd day	170.8	0.112	171.019	0.111	506.937	3.347	201.101	19.51	99.235	0.598

Note: 1. The data are based on seawater temperature 301 K and ambient temperature 306 K.

2. Subscripts are consistent with points in Fig. 1 & 2.

Thermodynamic analysis

Tab.1 shows that tank pressure (P_1) and tank temperature (T_1) obviously change with the plant running. That is to say, the plant working condition varies all the time. According to Mollier diagram and regarding refrigeration coefficient (ε) as goal function, the thermodynamic calculation has been carried out (computational process omitted). When three sets of plant cool down three tanks filled with a total of 3000 tons of ethylene, the ethylene cooling curve in tank and instantaneous ε of the plant are shown in Figure 3. In the Fig., the ε value is relatively low when T_1 is

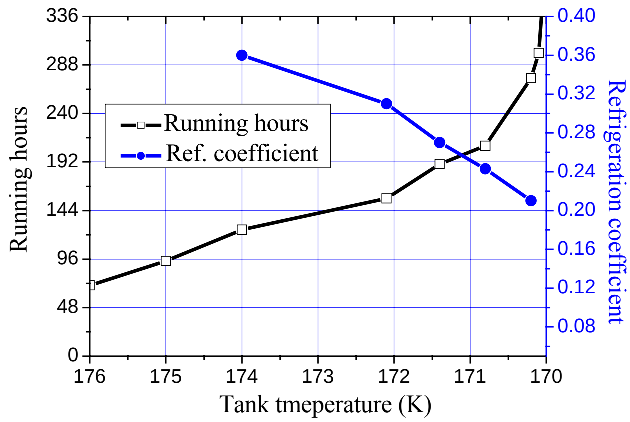

Figure 3 Cooling curve & refrigeration coefficient

below 172 K. It shows OECM should be used after the running hours corresponding to 172 K.

In Fig.3, both the ε and temperature drop per day in tank descend with T_1 decreasing. That means from the beginning, MCRM should be used and then followed with OECM. For a whole voyage, one or both of the operating modes may be adopted according to different sailing conditions. So there are three different operating modes for the plant, i.e. MCRM, OECM, and the combination of MCRM and OECM.

TEMPERATURE FORECAST AND DIVISION POINT DETERMINATION

Operating mode and T_1 forecast

In order to choose the best one of the three operating modes, T_1 should be forecasted. The forecast model in the grey system theory can be used here. A simple program for T_1 forecast has been developed [1]. The basic equation of GM (1,1) used is as follows:

$$\hat{x}^{(1)}(k+1) = \left(x^{(1)}(0) - \frac{u}{a} \right) e^{-ak} + \frac{u}{a} \qquad (1)$$

Table 2 Forecast temperature & real temperature

Running hours	3 units T'_1 (K)	3 units T_1 (K)	2 units T''_1 (K)	1 unit $T^o{}_1$ (K)
0	174.25	174.25	174.25	174.25
24	173.18	173.01	174.16	174.51
48	172.04	172.10	174.08	174.80
72	171.36	171.40	173.96	175.11
96	170.72	170.80	173.89	175.43
120	170.12	170.14	173.83	175.80

Where $\hat{x}$ means T_1 sequence and a & u are endogenous variable.

The computed results of GM (1,1) for above system are shown in Table 2 (computational process omitted). According to the table, the forecasted tank temperature (T'_1) is very close to real T_1. So the varying tendency of T_1 can be determined after a short period of the plant running.

If only two sets of plant (2 units) are used, the tank temperature (T''_1) will descend slowly, which may rise when ambient temperature (T_a) and cargo amount increase or no boost compressor is used. If only one set of plant (1unit) is used, the temperature ($T^o{}_1$) will rise obviously (the heat leakage from ambience into the tank is more than the capacity of a plant). When one or two sets of plant are used, it is usually run at OECM.

After forecasting T_1, the enthalpy, entropy, exergy and system power consumption in each point can be pre-calculated. As a result, the best one among the 3 operating modes can be chosen.

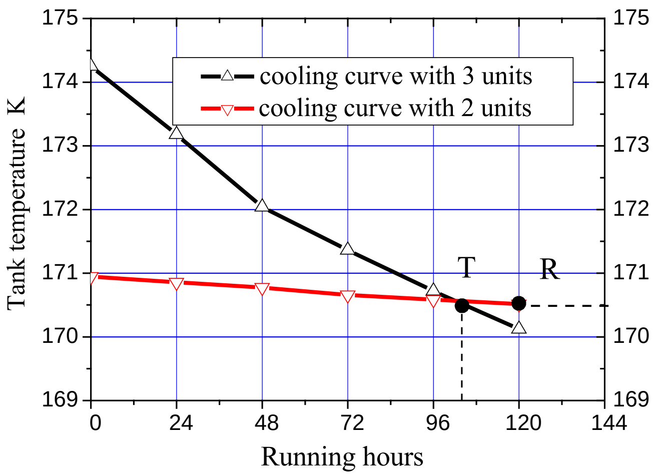

Figure 4 Division point determine

Determination of the division point

The number of the plant to be used depends on T_c, T_a, capacity of cooling plant, length of voyage and insulation of cargo tanks. Normally, three sets of plant at MCRM should be given to the highest priority.

If the combination of MCRM with 3 units and OECM with 2 units is used for a voyage, the transfer time should be at a properly moment (termed as division point). The division point can be determined as follows (see figure 4): By T_c, the cooling curve in tank with 3 units is first forecasted. By considering both the T_D and sailing days of a voyage (point R), the curve of T_1 with 2 units can also be forecasted. Their intersection point (T) will be an optimum division point.

REGULATING METHODS AT DIFFERENT OPERATING MODES

Regulating methods of condenser

There are two condensers in one set of plant (Fig.1), i.e. cargo condenser and R22 condenser. According to Lu Xuesheng's calculation [2], the available energy loss in a condenser is relatively large. For reducing the energy loss, the T_6, T_m and ΔT (difference in temperature) between hot and cold liquids should be reduced. The basic equation for condenser heat transference is as follows:

$$Q = KA(t_k - t_w) = KA[t_k - (t_{w1} + \frac{1}{2}\Delta t_w)] \quad (2)$$

In Eq. 2, increasing of condensation temperature (t_k) and decreasing of average seawater temperature (t_w) will make Q greater and MCRM applicable; decreasing of t_k and increasing of t_w will save energy and make OECM applicable. The t_w in R-22 condenser can be controlled by adjusting seawater (SW) current; the t_w in cargo condenser can be controlled by adjusting freon superfeed current.

For R-22 condenser, decreasing of P_m will reduce ΔT between R-22 and SW. For cargo condenser, increasing T_o (corresponding to P_o) will slightly change the value of ΔT between ethylene and R-22 since T_6 will automatically match with T_o. The ΔT between ethylene and R-22 normally is 2~4 K. If ΔT exceeds 6 K, it means some troubles have occurred in the condenser.

Regulating methods on OECM and MCRM

Besides the regulating methods of condenser, the following should be noted.

If MCRM is used, the plant should be adjusted as follows: (1) With P_1 falling, increase the opening of the cargo compressor suction valve step by step. If the suction valve is not opened properly in time, the compressor will be impossible to run at full capacity. (2) Keep the superfeed current full open. (3) Keep P_S, P_L, T_S & T_L as high as possible. (4) Use boost compressor for making P_1 steady, if any.

If OECM is used, the plant should be adjusted as follows: (1) Properly choose the number of plant to be used. (2) Properly determine the division point, if necessary. (3) Close the superfeed current gradually, while the cargo plant running under partial load. (4) Adjust SW current smaller than that of MCRM.

During the operation of all the modes, the following should be adjusted: (1) Keep the compressor satisfactorily cool. (2) Keep the condenser at good performance and clean the SW side of R-22 condenser in time. (3) Keep R-22 compressor at 100% of capacity all the time. (4) Purge void space with dry air at appropriate intervals to protect the insulation from water or humidity.

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