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THE INFLUENCE OF INCONDENSIBLE GASES ON THE REFRIGERATION CAPACITY OF THE RELIQUEFACTION PLANT DURING ETHYLENE CARRIAGE BY SEA

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Abstract

This paper presents a performance of the reliquefaction cascade plant during ethylene carriage by sea. Parameters of this plant are discussed because of dramatic low cooling rate of the cargo. Ability to decrease ethylene temperature from approx. minus 96°C to minus 103°C on board the ship is essential. Modern ethylene carriers are able to keep cooling rate about 2K per day, on the other hand old ones do it with rate approx. 0,2 K per day and require weeks to achieve proper temperature of ethylene for discharging. Of course, economic issue of such journey is not very satisfying but many factors influence on this. In this paper almost new one – nine months – old ship is considered, with capacity 21 000m^3. Main reason of problem is analysed, including heat ingress through the cargo tanks insulation. Gassing-up of the ship is explained and influence of presence incondensable gases in the cargo tanks described. Operation of the reliquefaction plant is shown, especially with the vent valve of LPG condenser. Analysis of pressures in the cargo tanks is carried out – on board the ship and with help of ProSimPlus – thermodynamic simulator. Conclusions contain discussion of the reliquefaction plant problems and remarks what should be improved on board the ethylene carrier to avoid such problems.

Keywords: *Ethylene carrier, cargo cooling rate, reliquefaction plant*

1. Gassing-up

After discharging some cargo and preparing the ship for ethylene loading, the inspection of the cargo tanks has to be done. Next step is to replace the atmospheric air with the inert gas – nitrogen, in order to avoid getting explosive mixture oxygen-ethylene [4, 9, 10]. There are a few ways for gassing-up the ethylene carrier, it depends on port of ethylene loading as well, but this process is carried out with taking into account:

- the ratio of the cargo tanks cooling down is not allowed higher than 10K per hour,
- the reliquefaction plant may be used when atmosphere on the cargo tank top achieves 98% vol. of ethylene,
- the amount of ethylene used for gassing-up should be as low as possible.

Above conditions make the gassing-up process not very easy to perform. The cooling rate 10K per hour protects the cargo tanks against the damage; nitrogen is required to be removed as an incondensable gas which presence increases condensing pressure of reliquefaction plant. Finally, the minimum of ethylene as a cargo should be removed with nitrogen to the atmosphere.

2. The cooling down of ethylene

On board one of the biggest of capacity 21 000 m^3, one-year old ethylene carrier, there are four cargo tanks and three reciprocating cargo compressors used to achieve the highest cooling down rate of the cargo. For ethylene, the designer of the reliquefaction plant calculates the cooling down rate shown in Fig. 1.

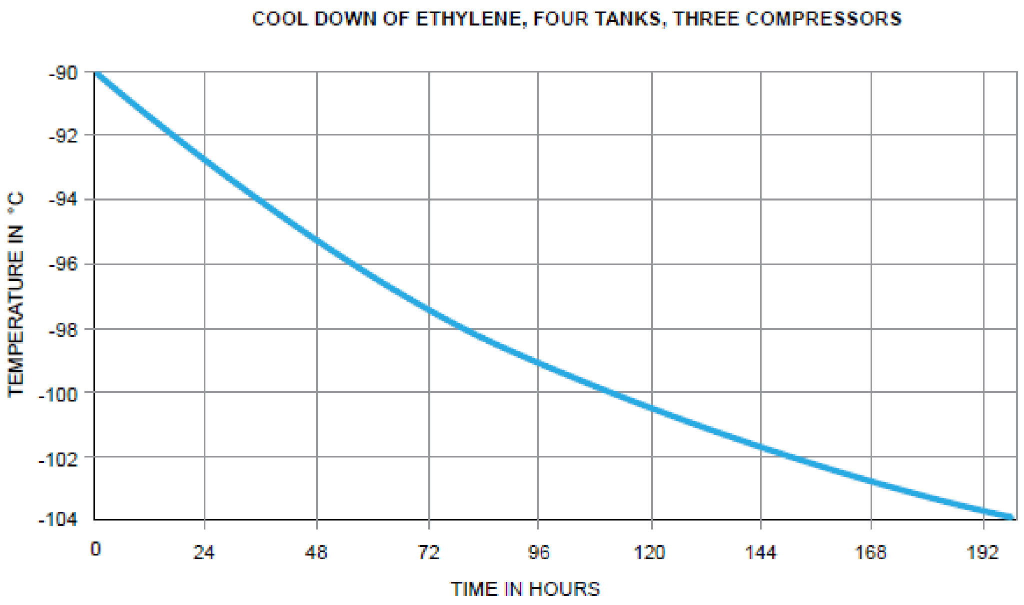

Fig. 1. The cooling down rate of the ethylene carrier [9]

The reliquefaction plant used for this purpose is typical, the two-stage cycle of cargo with liquid subcooling in the interstage cooler. The shell-tube ethylene condenser liquefies ethylene-utilizing propylene as a refrigerant of the cascade cycle [2, 6]. The highest pressure of the cargo compressor second stage discharge is 18 bar g, it means that the highest temperature of pure ethylene in the ethylene condenser may be minus 31ºC.

According to the curve shown in Fig. 1 the ship needs approx. 24 hours to decrease ethylene temperature from minus 101.5ºC to minus 102.5ºC but in fact, the real cooling rate was lower than 0.5K per 24 hours and the ethylene carrier since ten days after gassing-up and loading the cargo, does this rate very poor. The new ethylene carrier performs cooling down of ethylene with approx. 50% designed refrigeration capacity. For the reliquefaction plant, the highest cooling rate is essential [3].

3. The reliquefaction plant

Ethylene vapour is sucked up by the cargo compressors from the cargo tanks with temperature minus 60ºC and discharged at second stage with pressure 18.5 bar g to the LPG condenser (Fig. 2). LPG condenser is a place where ethylene vapour is cooled down from +120ºC to +30ºC. The cargo is liquefied in ethylene condenser where propylene cascade decreases the cargo temperature up to minus 34ºC. The condensate is collected in the cargo receiver. Some level of liquid is kept in this vessel, from which the condensate flows to the cargo tanks, through the economizer with liquid ethylene of temperature minus 72ºC. All parameters of this liquid subcooling two-stage cycle are according to the designer data, excluding second stage discharge pressure of the cargo compressors. The insulation provides outside temperature from +15 to +17ºC of the cargo tanks – a heat ingress is not a problem.

The reciprocating cargo compressors operate with the highest allowed second stage discharge pressure 18.5 bar g. With ethylene temperature in the cargo receiver minus 34ºC, discharge pressure is expected to be below 17 bar g. In fact, the compressors reached 18.5 bar g discharge pressure and an automatic vent valve PVK shown in Fig. 2 opened, then hot vapour from LPG condenser instead of being liquefied in the ethylene condenser, flows back to the cargo tanks. The total refrigeration capacity of the reliquefaction plant is described by the formula [1]:

$$Q_o = m \cdot (h_1 - h_2)\ [kW], \tag{2}$$

where:
Q_o – total refrigeration capacity,
m – mass flow of ethylene condensate,
h_1 – vapour ethylene specific enthalpy in the cargo tank,
h_2 – condensate specific enthalpy of ethylene flowing into the cargo tank.

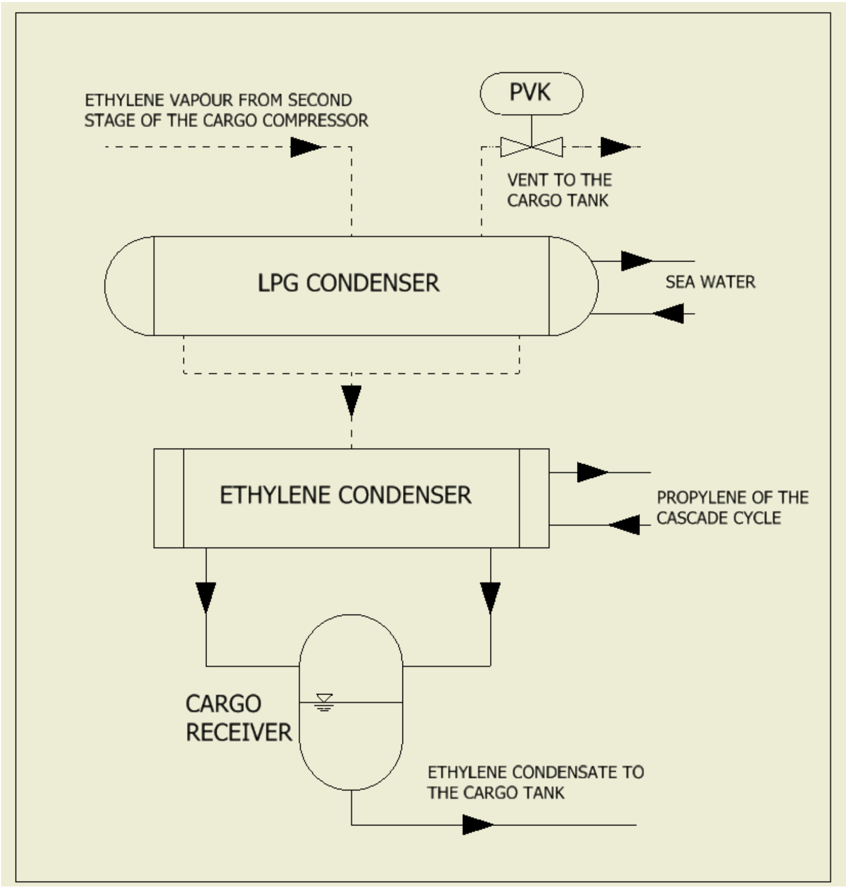

Fig. 2. The condensers lay out

Because enthalpies h_1 and h_2 of ethylene are according to designed, 50% decreasing of cooling rate is caused by lower mass flow of ethylene condensate. The loss of not condensed ethylene getting back as a hot vapour to the cargo tanks is analysed in Fig. 3.

In Fig. 3 is shown original graph made on board the ship. The x-axis – time: hours, minutes and seconds of the record made on 09th of June 2015, the y-axis – pressures. Between 18 and 18.5 bar g frequency of opening and closing PVK vent valve is shown. After time 17:37:00 frequency of PVK openings increased because of start third cargo compressor. If pressure 18.5 bar g is too low for condensing vapour in the ethylene condenser, it means that this is not pure ethylene in the reliquefaction plant.

4. The analysis of the vapour-liquid equilibrium

The reason for these problems with ethylene condensing pressure is nitrogen presence. It was the ship first voyage after the change of cargo and gassing – up. Utilizing ProSimPlus – steady state simulation software with Peng-Robinson equation of state, pressures and related temperatures in some vessels are analysed below.

In Tab. 1 is shown main reason of presence nitrogen in the reliquefaction plant. Very close values of ethylene and nitrogen vapour density cause some difficulties during gassing-up the cargo tanks.

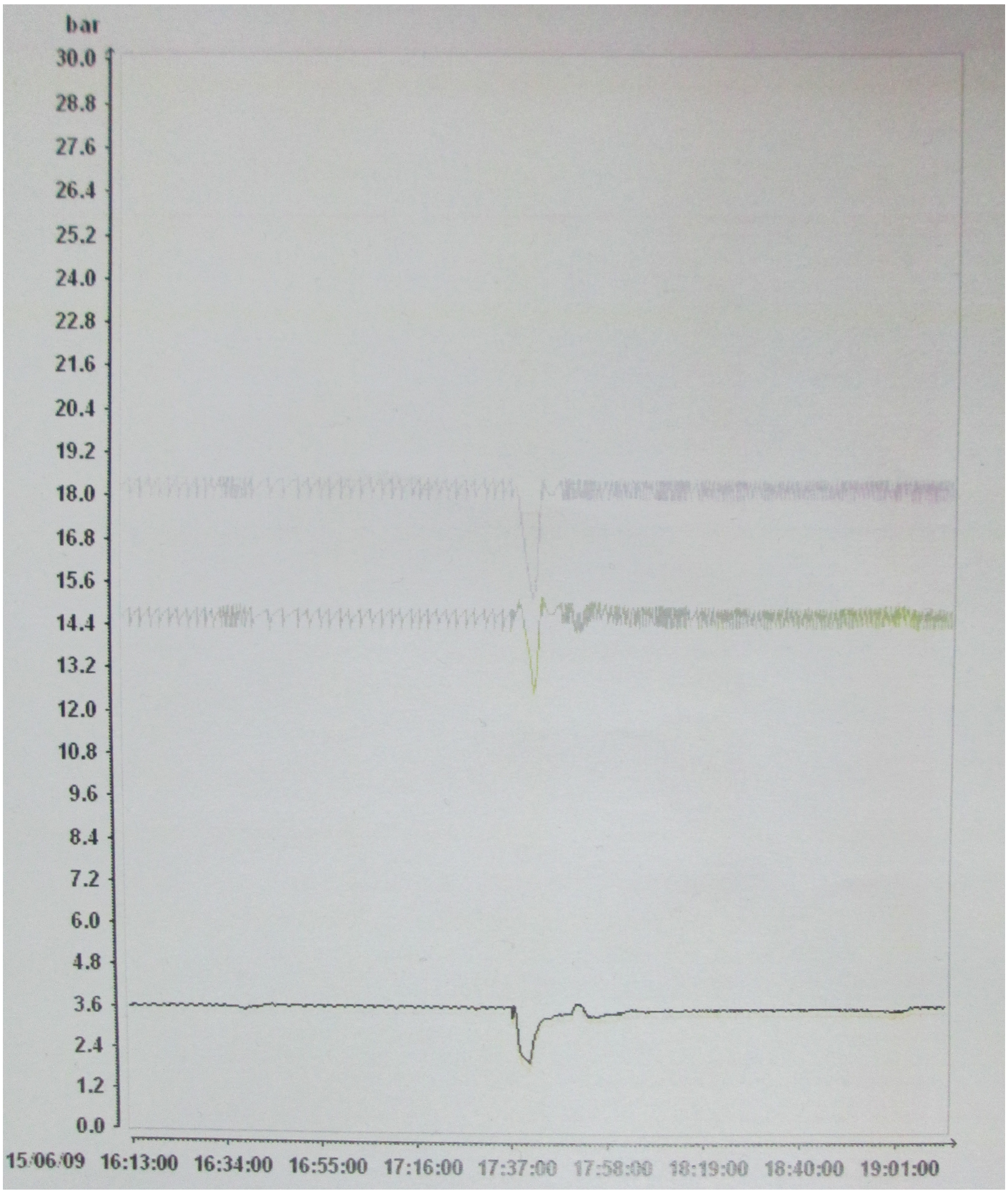

Fig. 3. The frequency of PVK valve openings [9]

In order to assess how much nitrogen is in the system, vapour-liquid equilibrium of pure ethylene is compared with readings of the cargo tanks, taken from the ship, in Tab. 2.

Taking into account these data and accuracy of the ship instruments, pressures show that according to Raoult`s law [8], nitrogen does not increase pressure in the cargo tanks of the ethylene carrier. Next vessel to be analysed is the inter-stage cooler of the cargo compressor. Two processes take place in this vessel – decreasing temperature of vapour after first stage compression and subcooling of ethylene condensate up to minus 65ºC. In this vessel, some level of ethylene liquid is kept so substantial influence of nitrogen should be seen at equilibrium pressure.

Measured temperature of liquid phase of ethylene in this interstage cooler is minus 74ºC and average gauge pressure: 3.5 bar g, i.e. 4.51325 bar abs. For pure ethylene and its equilibrium at temperature minus 74ºC, pressure should be 4.40103 bar abs. Difference 0.11 bar between pressures expected and measured is not reliable information about the presence of nitrogen in the reliquefaction plant.

Ethylene temperature in the cargo receiver (Fig. 2) is minus 34ºC, but condensing pressure 18.5 bar g is too low for condensing mixture of vapours on board the ethylene carrier. Tab. 3

presents relations between compositions and required condensing pressures for ethylene-nitrogen mixtures.

Because the cargo compressors second-stage discharge pressure is limited up to 19 bar g [5], practically there are no possibilities to assess how much nitrogen flows with ethylene through the reliquefaction plant.

Tab. 1. Ethylene and nitrogen density [7]

Temperature (°C)	Ethylene (kg/m3)	Nitrogen (kg/m3)	Temperature (°C)	Ethylene (kg/m3)	Nitrogen (kg/m3)
0	1.2456	1.2344	-100	2.0043	1.9546
1	1.2409	1.2299	-99	1.9920	1.9432
2	1.2363	1.2254	-98	1.9798	1.9319
3	1.2317	1.2210	-97	1.9678	1.9208
4	1.2272	1.2165	-96	1.9559	1.9098
5	1.2227	1.2121	-95	1.9442	1.8990
6	1.2182	1.2078	-94	1.9326	1.8882
7	1.2137	1.2035	-93	1.9212	1.8776
8	1.2093	1.1992	-92	1.9099	1.8671
9	1.2049	1.1949	-91	1.8987	1.8567
10	1.2006	1.1907	-90	1.8877	1.8465
11	1.1963	1.1865	-89	1.8768	1.8363
12	1.1920	1.1823	-88	1.8660	1.8263
13	1.1878	1.1781	-87	1.8554	1.8164
14	1.1835	1.1740	-86	1.8449	1.8066
15	1.1793	1.1699	-85	1.8345	1.7969
16	1.1752	1.1659	-84	1.8242	1.7872
17	1.1710	1.1618	-83	1.8141	1.7777
18	1.1669	1.1578	-82	1.8040	1.7683
19	1.1629	1.1539	-81	1.7941	1.7590
20	1.1588	1.1499	-80	1.7843	1.7498

Tab. 2. Equilibrium pressure comparison of pure ethylene and from the cargo tanks [7, 9]

The cargo tank	Average liquid temperature	Equilibrium absolute pressure for pure ethylene	Gauge pressure measured on board	Absolute pressure measured on board	Average liquid temperature	Equilibrium absolute pressure for pure ethylene	Gauge pressure measured on board	Absolute pressure measured on board
	°C	bar abs	bar g	bar abs	°C	bar abs	bar g	bar abs
CT 1	-99.2	1.33106	0.31	1.32325	-101.5	1.17137	0.12	1.13325
CT2	-99	1.3457	0.31	1.32325	-101.65	1.1615	0.12	1.13325
CT3	-99	1.3457	0.31	1.32325	-101.65	1.1615	0.12	1.13325
CT4	-99.2	1.33106	0.32	1.33325	-101.83	1.14974	0.13	1.14325

5. Conclusions

1. Above analysis presents that even little remains of nitrogen in the cargo tanks pipes could dramatically reduce the cooling rate of the reliquefaction plant.
2. Experienced masters of the ethylene carries confirm that very often during whole first voyage with ethylene after gassing-up, nitrogen is constantly removed from the system.
3. Purge condenser employed in the reliquefaction plant is not a solution because of ethylene losses to the atmosphere.

Tab. 3. Equilibrium pressures for ethylene – nitrogen mixtures [7]

	Mixture compositions (Mass)		Results		Liquid fractions (Bubble - Mass)		Vapor fractions (Bubble - Mass)	
The cargo receiver temperature (°C)	ETHYLENE	NITROGEN	Bubble pressure (barg)	Dew pressure (barg)	ETHYLENE	NITROGEN	ETHYLENE	NITROGEN
-34	0.99	0.01	19.0000	16.5625	0.99	0.01	0.8975	0.1025
-34	0.991	0.009	18.7339	16.5392	0.991	0.009	0.9066	0.0934
-34	0.992	0.008	18.4676	16.5160	0.992	0.008	0.9158	0.0842
-34	0.993	0.007	18.2012	16.4929	0.993	0.007	0.9254	0.0746
-34	0.994	0.006	17.9346	16.4698	0.994	0.006	0.9351	0.0649
-34	0.995	0.005	17.6680	16.4468	0.995	0.005	0.9452	0.0548
-34	0.996	0.004	17.4011	16.4238	0.996	0.004	0.9555	0.0445
-34	0.997	0.003	17.1342	16.4009	0.997	0.003	0.9662	0.0338
-34	0.998	0.002	16.8671	16.3780	0.998	0.002	0.9771	0.0229
-34	0.999	0.001	16.5998	16.3552	0.999	0.001	0.9884	0.0116
-34	1	0	16.3325	16.3325	1	0	1	0

4. Gassing-up process with nitrogen is not draw up entirely for the ethylene carriers. Masters inform that even the measuring instruments show 99-100% pure ethylene during gassing-up (the reliquefaction plant should operate properly with 98% of pure ethylene), condensing pressure is higher than allowed for normal operation.
5. One of a way to avoid these problems is the reliquefaction plant designed for operation with higher condensing pressures or the cascade systems with lower temperature of the ethylene condenser

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