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GAS PLANT OF ETHYLENE GAS CARRIER AND A TWO STAGES COMPRESSION OPTIMIZATION OF ETHYLENE AS A CARGO BASED ON THERMODYNAMIC ANALYSIS

Dariusz Nanowski

Gdynia Maritime Univeristy
ul. Morska 81-87, 81-226 Gdynia, Poland
tel.: +48 586901449
e-mail: dariuszn@am.gdynia.pl

Abstract

Ethylene as a cargo is more and more popular in maritime transport. Its temperature approx. -104°C during discharging requires sufficient efficiency of reliquefaction plant. Short description of that gas plant is shown including cascade system and processes are described. Based on Mollier diagram and ethylene mass flows, refrigeration capacity of the system is calculated when some changes in the cargo economizer are done. Some of these changes are carried out by crew members of gas carriers in order to reduce second stage discharge temperatures of reciprocating compressors. These losses of refrigeration efficiency are calculated to assess its influence on Ethylene temperature in the cargo tanks. On the other hand some assumptions are used to improve refrigeration capacity by Ethylene compression process.

Keywords: *refrigeration cycle, reliquefaction plant, thermodynamic analysis, Ethylene gas carrier*

1. Introduction

Ethylene is one of the primary petrochemical building blocks. It is used in the manufacture of polyethylene plastics, ethyl alcohol, polyvinyl chloride (PVC), antifreeze, polystyrene and polyester fibres. It is obtained by cracking either naphtha, ethane or LPG. About 85 million tonnes of ethylene is produced worldwide each year but, because most of this output is utilised close to the point of manufacture, only some 2.5 million tonnes is moved long distances by sea on semi-pressurised carriers [5].

Boiling point of Ethylene at atmospheric pressure is −103.8°C means that cooling processes are not belong to cryogenics e.g. below 111.1 K when at the same pressure Methane has boiling point [2]. However temperatures below −100°C achieved in Ethylene carriers cargo tanks require using cascade systems, because cooling down the cargo between −60°C till −100°C with multi-stages cycles is very difficult or even impossible [4]. Of course, Ethylene is not only one grade of cargo for these ships [6,7].

2. The gas plant of Ethylene carrier

General principles of cargo gas plant operation are being described by using as an example simplified layout of reliquefaction and cascade systems, whereas processes parameters are shown on Mollier diagrams [3]. The layout and parameters of processes of gas plant described in this paper are taken from real ship, and are different from those one which can be found in some references [9].

Reliquefaction system with reciprocating compressor is shown on Fig. 1. The characteristic points of system and processes are marked by figures 1 to 10. The same figures denote thermodynamic processes drawn on Mollier diagram (Fig. 2). Values of the parameters are taken from compressor data sheet of real ship with Ethylene as a cargo [8]. When Ethylene vapour is sucked from the cargo tank by first stage of cargo compressor (point 1 – temperature $t_1 = -35°C$), vapour has already left suction drum, where liquid phase could be separated from compressor suction line (to avoid liquid hammering). After discharging by interstage absolute pressure $p_2 = 5$ bar (point 2) and temperature $t_2 = 85°C$, before compressing in the compressor second stage, vapour is cooled down by mixing with saturated vapour after its vaporization (from point 9 to 10) in the cargo economizer:

$$h_3 = (m_1 * h_2 + m_2 * h_{10}) / m_1 + m_2, \tag{1}$$

where:

m_1, m_2 – Ethylene vapour mass flows, kg/s,

h_1, h_3, h_{10} – specific enthalpy of Ethylene vapour, kJ/kg.

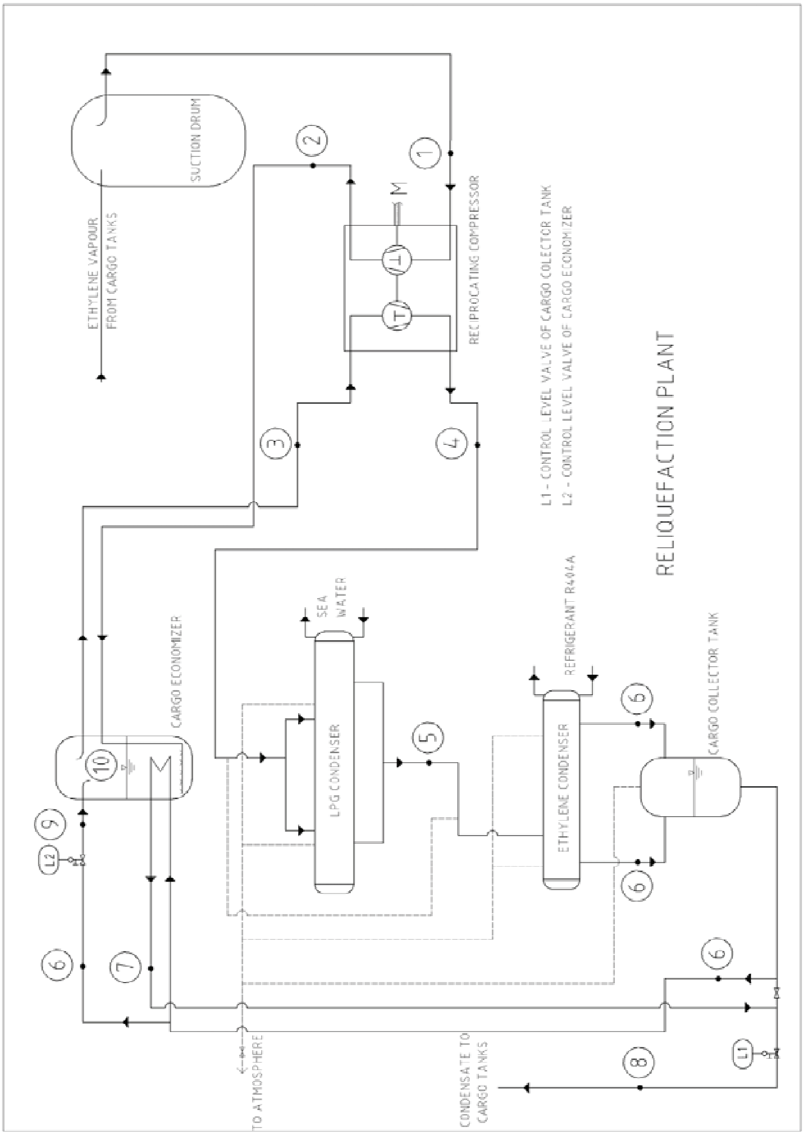

Fig. 1. Layout of reliquefaction plant

By this way vapour temperature in compressor second stage suction is decreased from t_2 to t_3 = 50°C. Second stage compression increases vapour temperature up to t_4 = 130°C, by pressure p_4 = 18.5 bar and Ethylene is directed to LPG condenser. There is no any Ethylene condensing process in this heat exchanger, but only cooling down of vapour from t_4 to temperature t_5 = 30°C by using sea water as a cooling medium. Condensing process 5-6 takes place in Ethylene condenser. In this heat exchanger are connected two systems: reliquefaction (Fig. 1) and refrigerant (Fig. 3), because Ethylene condensing process is carried out by vaporization of refrigerant R404A in Ethylene condenser, common heat exchanger of both systems: reliquefaction and refrigerant, as a one cascade system. By high gauge pressure p_4 = 18.5 bar is possible to condense Ethylene and cooling down to temperature t_6 = –30°C by means of R404 of which evaporating temperature is –40°C. In next step, flowing through the cargo economizer coil Ethylene condensate is subcooled in process 6-7 to temperature t_7 = –63°C with the use of Ethylene, which evaporates (process 9-10) by interstage pressure p_2 = 5 bar and temperature t_9 = –72°C in the cargo economizer.

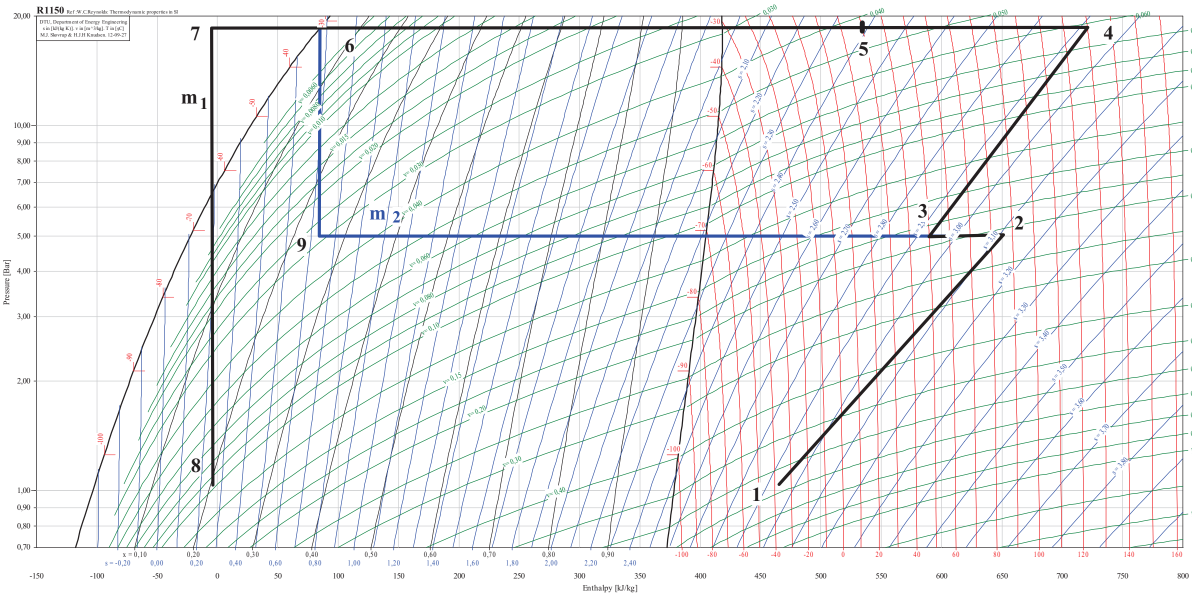

Fig. 2. Mollier diagram of reliquefaction plant

Total refrigeration capacity Q of Ethylene in the cargo tank is equal:

$$Q = m_1 * (h_1 - h_8) \text{ [kW]}. \tag{2}$$

Subcooled in the cargo economizer Ethylene condensate is expanded to the cargo tank pressure where evaporates by temperature t_8= –103°C.

Second part of gas plant called **refrigerant system** is shown on Fig. 3 and its Mollier diagram on Fig. 4. General aim of using refrigerant system is to achieve temperature –40°C in the Ethylene condenser and enable condensing of Ethylene vapour. As a close system – refrigerant R 404A does not mix with cargo.

After vaporization in Ethylene condenser by temperature t_7 = –40°C and increasing temperature for superheat to t_1 = 0°C (Fig. 4), R404A is sucked by first stage of screw compressor. By interstage pressure, before second stage compression this flow of refrigerant connects with another after subcooling process in the refrigerant economizer according to equation:

$$m_1 * h_2 + m_2 * h_9 = (m_1 + m_2) * h_3. \tag{3}$$

R404A vapour with parameters of point 3 is compressed in second stage (discharging parameters: temperature t_4 = 80°C and pressure p_4 = 17 bar) and through an oil separator directed to the refrigerant condenser, where cooled by sea water changes its phase into liquid (parameters of point 5).

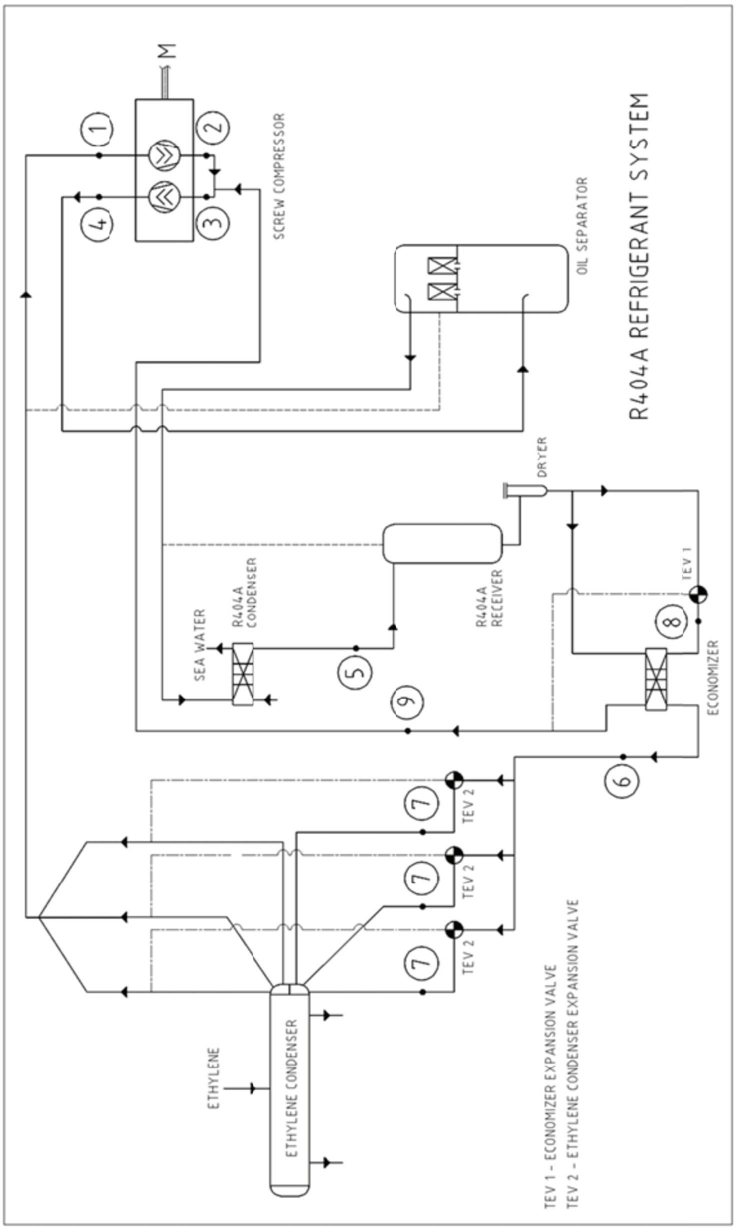

Fig. 3. Layout of refrigerant system

When compressor is loaded 85% or more, then the refrigerant economizer is used in the system and then it operates with increased refrigeration capacity. The refrigerant economizer enables to achieve subcooling of liquid R404A before thermostatic expansion valves (TEV) in isobaric process 5-6 (from temperature t_5 = 40°C to t_6 = 20°C). Isenthalpic expansion of refrigerant 6-7 is carried out by means of three TEVs, which operate as a controllers for supplying R404A to Ethylene condenser.

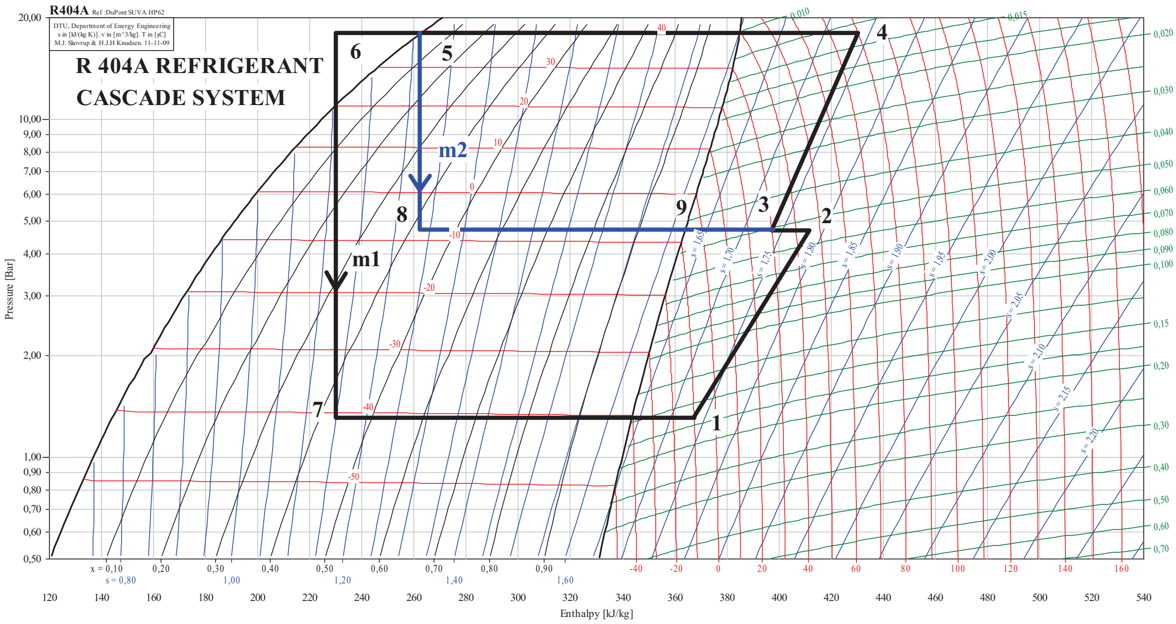

Fig. 4. Mollier diagram of refrigerant system

Above on Fig. 4 real parameters of refrigerant system are shown. In comparison with cycle shown on Fig. 2 it looks very similarly, but it has to be emphasized that increasing part of mass flow m_2 (Fig. 2) used to cool down Ethylene vapour from temperature t_2 to temperature t_3 (suction of second stage compression) decreases refrigeration capacity of reliquefaction plant, whereas increasing mass flow m_2 of refrigerant system increases refrigeration capacity of this system.

3. Optimization of Ethylene compression

Taking into account reciprocating compressor Sulzer- Burckhardt 2K160-2H with 580 rpm, it may be assumed that with 1.5 bar absolute pressure of Ethylene on first stage suction its suction volume is approx. 700m^3/h. Specific volume of Ethylene under this pressure and temperature –35°C is v_1 = 0.5 m^3/kg (Fig. 5).

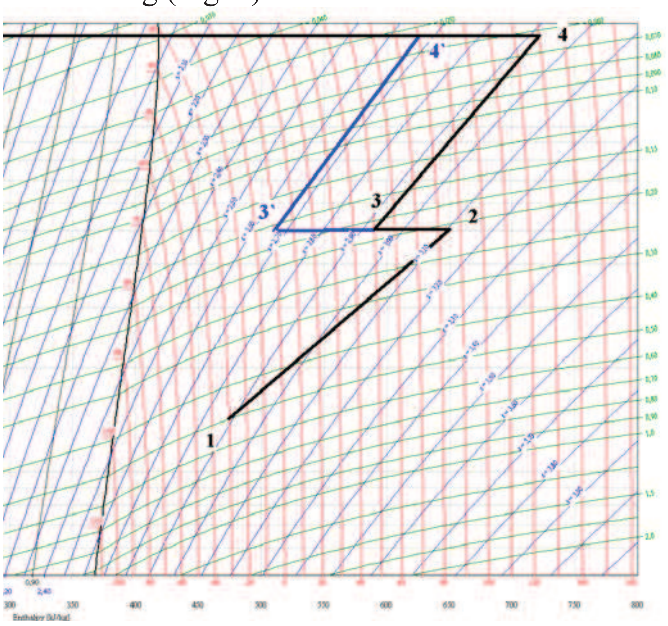

Fig. 5. Compression processes

It very easy to calculate [1] that mass flow m_1 (Fig. 2) of Ethylene is equal $m_1 = 0.4$ kg/s. It means that total refrigeration capacity of reliquefaction plant may be calculated according to equation (2), after finding enthalpies h_1 and h_8 on Mollier diagram (Fig. 3):

$h_1 = 465$ kJ/kg

$h_8 = -10$ kJ/kg

total refrigeration capacity is equal:

$$Q = m_1 * (h_1 - h_8) = 0.4 * (465 + 10) = 190 [kW]. \tag{4}$$

Part of mass flow m_2 is used to cool down Ethylene vapour after first stage e.g. from temperature t_2 to t_3. By this process required refrigeration capacity Q_1 (Fig. 2, Fig. 5):

$$Q_1 = m_1 * (h_2 - h_3) = 0.4 * (650 - 590) = 24 [kW] \tag{5}$$

is excluded from total refrigeration capacity, only to reduce discharge temperature of the compressor second stage. At the ships temperature t_3 is reduced by crew member even to $t_{3'} = 0°C$ (discharge $t_{4'} = 80°C$) , see point 3' on Fig. 5. Then enthalpy of point 3' is decreased to $h_{3'} = 510$ kJ/kg and necessary refrigeration capacity Q'_1 increases to value:

$$Q'_1 = m_1 * (h_2 - h_{3'}) = 0.4 * (650 - 510) = 56 [kW]. \tag{6}$$

To asses a part of mass flow m_2, which is used to achieve this refrigeration capacity, this Q'_1 has to be used in equation (Fig. 2):

$$Q'_1 = m_2 * (h_{3'} - h_9),$$

(7)

$$m_2 = Q'_1 / (h_{3'} - h_9) = 56 / (510 - 80) = 0.13 [kg/s]. \tag{8}$$

It means that second stage of Sulzer-Burckhardt type 2K160-2H is loaded with 30% higher mass flow of Ethylene only for reducing second stage suction temperature $t_{3'}$. Of course the best way to achieve most efficiency cycle of reliquefaction plant is not use interstage cooler at all, as shown on Fig. 6.

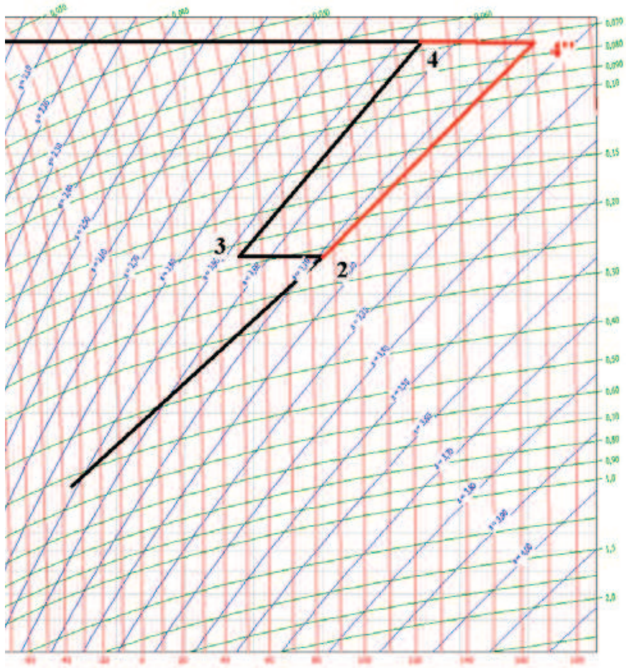

Fig. 6. Compression processes without intercooling

Process 2-4'' ensures the best efficiency of reliquefaction cycle from thermodynamic point of view (exergy!). Of course high discharge temperature $t_{4''}$=170°C causes some limitations regarding cargo or compressor.

Below is shown a list of typical cargoes carried by gas carriers with description of cycles which may be used in the reliquefaction plant:

- **Ammonia**: single stage, 2 stage NIC, 2 stage LSC;
- **isoButane**: single stage, 2 stage NIC;
- **Butadiene**: single stage, 2 stage NIC (included);
- **Butylene**: single stage NIC, 2 stage NIC (included);
- **n-Butane**: single stage (included), 2 stage NIC (included);
- **Propane**: single stage, 2 stage NIC, 2 stage LSC;
- **Commercial Propane** (2.5 mole% ethane): single stage, 2 stage NIC, 2 stage LSC;
- **Propylene**: single stage, 2 stage NIC, 2 stage LSC;
- **Vinyl Chloride Monomer** – single stage, 2 stage NIC;

where:

2 stage NIC – denotes 2 stage compression without using intercooler,

2 stage LSC – denotes 2 stage compression with liquid subcooling and using the cargo economizer as interstage cooler.

It should be noted, that LSC cycle is not used, if some another limitations do not appear. It has to be realized that cooling down +80°C hot Ethylene vapour in the interstage cooler by minus 70°C liquid is not efficient process from exergy point of view. Sea water temperature for cooling LPG condenser of reliquefaction plant, is also some condition, which allow for example by its low temperature to employ for VCM (Vinyl Chloride Monomer**)** single stage cycle with higher refrigeration capacity, instead of 2 stage cycle.

The last issue is volume efficiency of reciprocating cargo compressor. When pressure ratio between discharge and suction of the compressor exceeds 6, then 2 stage compression is recommended because of decreasing performance of compressor. It means that volume losses during compression are too high and less mass flow of cargo decreases total refrigeration capacity of the gas plant.

Conclusions

Unnecessary cooling down the cargo vapour in the interstage cooler always decreases refrigerant capacity of reliquefaction plant. During cargo gas plant operation second stage discharge temperature from thermodynamic point of view should be as high as possible. Ethylene example presented and calculated in this paper is based on real parameters taken from the ship during operation at sea. Calculations show that cooling down vapour in the interstage cooler and reduction second stage discharge temperature from 130°C to 80°C, increases loss of refrigeration capacity from 24kW (equation 5) to 56 kW (equation 6) e.g. from 13% to 30% of total reliquefaction plant refrigeration capacity.

Using the cargo economizer (Fig. 1) for decreasing compressor discharge temperature without reason, always causes either reduction of refrigeration capacity or increasing of fuel consumption for the compressor driving.

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