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THE OPERATION LIMITATION OF THE TWO-STAGE RELIQUEFACTION CYCLE EMPLOYED ON BOARD THE ETHYLENE CARRIER

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Abstract

Ethylene, propane, commercial propane or HD-5 is cargoes very often carried by sea. In order to reduce the time of loading and later cooling down to required parameters of temperature and pressure in the cargo tanks two-stage reliquefaction cycle is used. For above-mentioned cargoes, two-stage cycle with liquid subcooling and interstage cooler is one of the most often utilized. In this paper operation of this cycle is discussed, based on parameters of the reciprocating cargo compressor and its cycle used on board the one of the biggest – 21 500 m^3 – ethylene carrier in the world. It is explained how some vapour mixtures decrease cooling rate during reliquefaction of the cargo and some parameters of pressure and temperature of these mixtures are calculated with help of ProSimPlus – thermodynamic simulator. In this way, changes of the mixtures composition across reliquefaction plant are discussed. Increased pressure of the cargoes condensing as a way of solving of explained problem is analysed. Three stage – cycle of reliquefaction plant used for pure propane or ethylene is shown and some of its disadvantages are explained. Based on this discussion, three-stage cycle with liquid injection is proposed to fulfil operation requirements of the cargoes and improve their loading and cooling processes on board the ethylene carrier. Analysis of refrigeration capacity for both cycles is carried out.

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

1. Two-stage liquid subcooling cycle

The reliquefaction plant operates with this cycle on board the ethylene carrier when ethylene, ethane, propane and gas mixtures are carried such as commercial propane [5, 8, 12]. Two-stage reciprocating cargo compressor is able to provide a condensing pressure up to 18.5 bar g. According to the ship data, the maximum ethane content in the liquid phase of commercial propane at atmospheric pressure should be 7.5% mole in the cargo tanks [11]. The first stage discharge vapour is cooled down in the interstage vessel with cargo liquid boiling at interstage pressure (Fig. 1). This liquid phase of the cargo is also used for subcooling main condensate stream expanded to the cargo tanks. The ethylene condenser by-pass valve is closed when the ethylene condenser is in operation and opened when the reliquefaction plant is used without the cascade. LC valve controls level of the cargo in the interstage cooler and PC valve is employed to avoid overpressure in the system.

Utilizing the reliquefaction plant shown in Fig. 1 the ethylene carrier during voyage had problem with low cooling rate when propane – ethane mixtures was as a cargo. In fact, cooling rate was almost zero i.e. temperature of liquid cargo could not be decreased at all. The cascade cycle did not operate.

2. Two-stage liquid subcooling cycle – parameters of operation [6, 7]

Temperature of mixture in the interstage cooler was minus 4°C, pressure 4.7 bar g. Pressure of

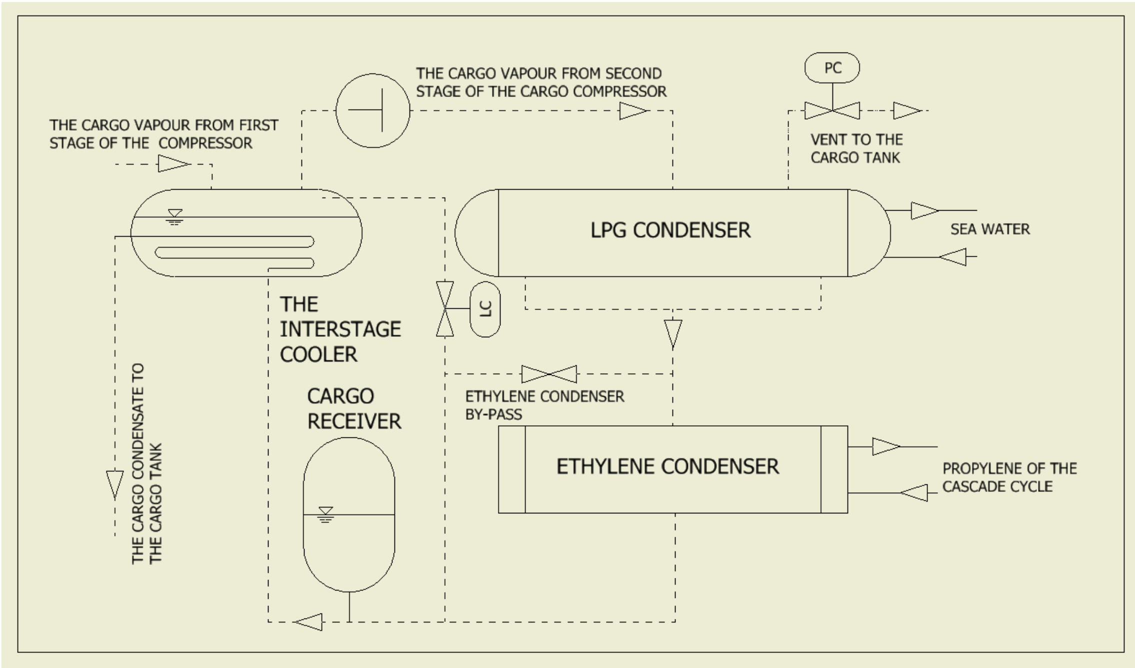

Fig. 1. Two-stage reliquefaction plant with liquid subcooling cycle

cargo receiver was 18.0 bar g, controlled by PC valve (Fig. 1) all time slightly opened with hot gases directed to the cargo tanks. Temperature of the cargo in this vessel was +10°C.

Employing ProSimPlus – thermodynamic steady state simulation software and taking into account mixtures parameters in the interstage cooler the composition of the mixtures can be assessed. In Fig. 2 is shown as an example isobaric evaporation for mixture propane – ethane for pure propane and increasing molar content of ethane up to pure ethane. Zeotropic mixture has different temperatures of bubble and dew points [10]. For achieved on board the ship temperature minus 4°C and pressure 4.7 bar g in the interstage cooler, it could be read off in Fig. 3 that molar content of ethane is approx. 10.5% mole for liquid phase and 29% mole for the vapour above liquid in this vessel. Simulation was performed with Peng-Robinson equation of state [3, 9].

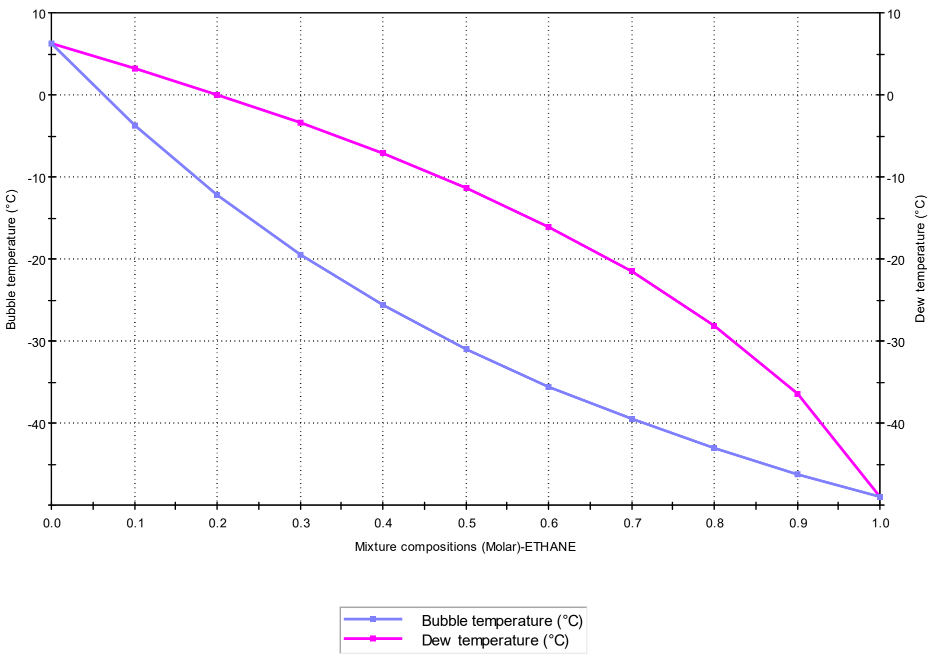

Fig. 2. Isobaric process of evaporation of propane – ethane compositions at 4.7 bar g [9]

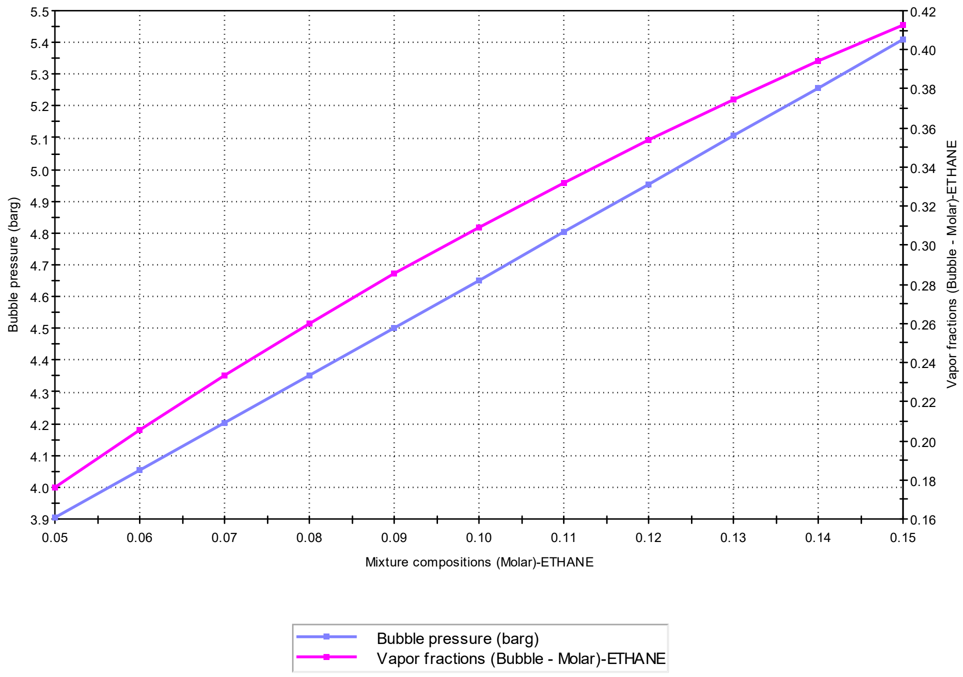

Fig. 3. Equilibrium parameters for propane-ethane mixtures at –4°C [9]

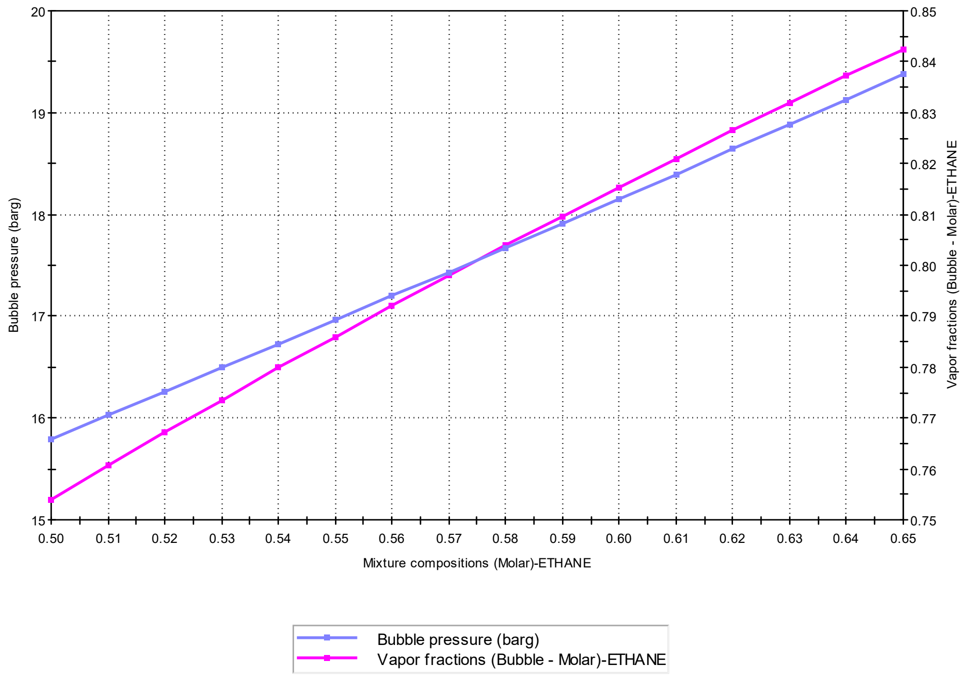

Fig. 4. Equilibrium parameters for propane-ethane mixtures at +10°C [9]

Second stage suction from the interstage cooler causes increased content of ethane in the mixture, which is condensed in LPG condenser. According to above mentioned data taken from the ship (pressure in cargo receiver 18.0 bar g and condensate temperature +10°C) diagram in Fig. 4 explains why in cargo receiver there is at least 59% mole ethane in the liquid phase and 81% mole in the vapour. At least, because vent valve PC is permanent slightly opened and hot gases flows from LPG condenser to the cargo tanks.

Above a way of increasing content of ethane in the cargo was explained. The same situation takes place with nitrogen or methane, especially with ethylene as a cargo. The result of this is increased condensing pressure and lost refrigeration capacity of the reliquefaction plant. Finally, similar like in above described ship, the vent valve from LPG condenser to the cargo tanks must be kept opened because second stage discharge pressure of reciprocating cargo compressor is limited up to 18 bar g. In this case, cooling rate is dramatically reduced.

3. Three-stage reliquefaction plant

In order to avoid such problems three-stage reliquefaction plant is consider with liquid injection to three-stage suction line shown in Fig. 5. In this way, condensing pressure could be increased up to 30-40 bar g and a liquefaction of mixtures with higher content of volatile components possible.

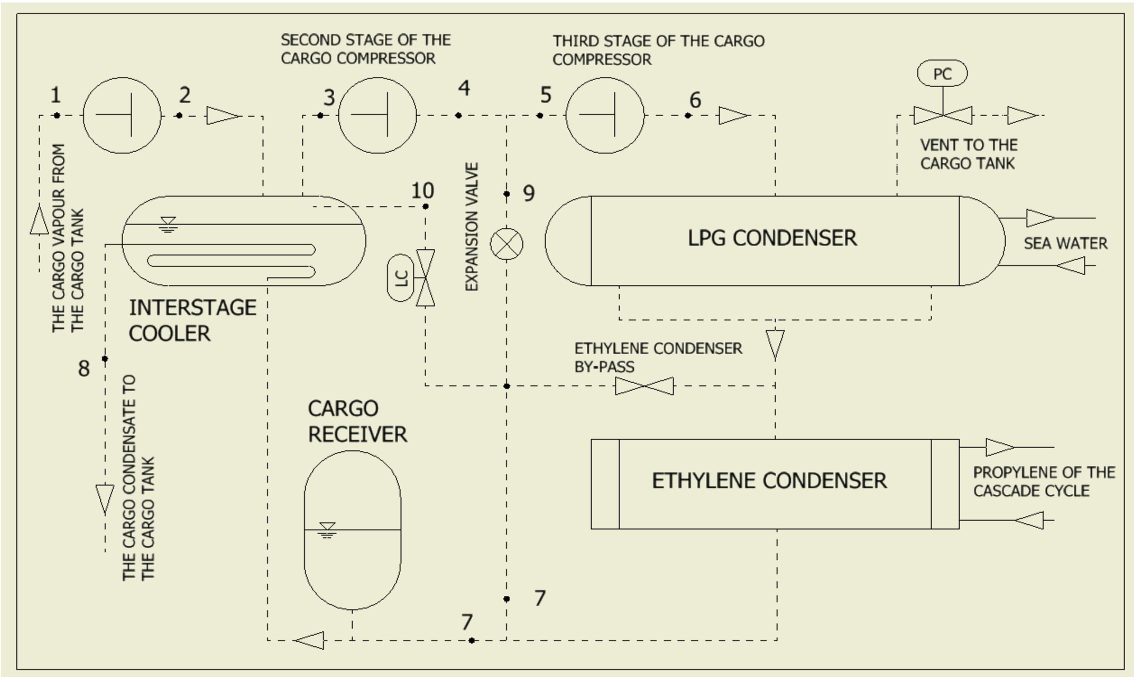

Fig. 5. Three-stage reliquefaction plant with liquid injection

In this way, condensing pressure could be increased up to 30-40 bar g and a liquefaction of mixtures with higher content of volatile components possible. An advance of three-stage cycle with two interstage coolers is described as follows: "The savings, while not as dramatic as the two stage versus one-stage, can still be significant enough to justify the additional equipment" [4].

In the plant shown in Fig. 5 employed liquid injection decreases temperature of the cargo vapour before third stage compression (point 5 in Fig. 6) and protects the cargo receiver against unnecessary high content of volatile component like nitrogen, ethane or methane.

Specific refrigeration capacity of the cycle with liquid injection q_o is lower in comparison with cycle with two interstage coolers q_o' only because of 5-7 K higher temperature at point 8 (Fig. 6) than boiling temperature of the mixture propane-ethane at interstage pressure p_{m1} [1]:

$$q_o = h_1 - h_8 \quad [\text{kJ/kg}], \tag{1}$$

where:
q_o – specific refrigeration capacity of the cycle with liquid injection,
h_1 – vapour enthalpy of compressor suction,
h_8 – condensate enthalpy entering the cargo tanks.

Interstage pressures p_{m1} and p_{m2} are calculated according to formula [2]:

$$p_{m2} = \sqrt[3]{p_k^{\,2} \cdot p_o}\,, \tag{2}$$

$$p_{m1} = \sqrt[3]{p_o^{\,2} \cdot p_k}\ , \tag{3}$$

where:
p_o – absolute pressure in the cargo tanks,
p_k – condensing pressure of the cargo.

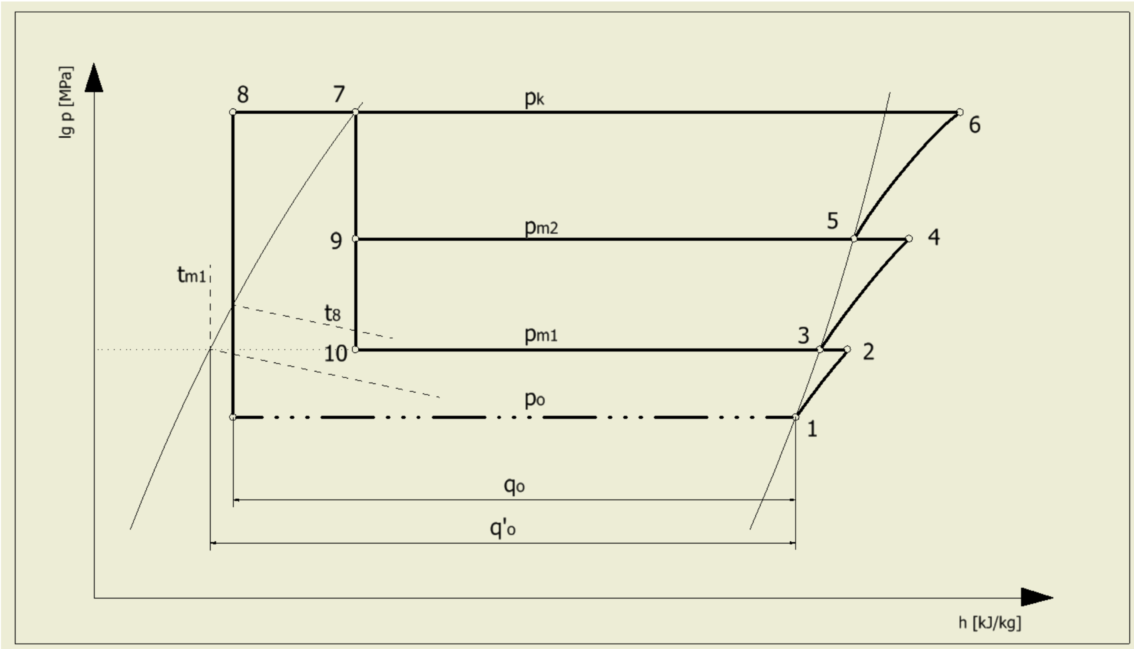

Fig. 6. Three-stage cycle with liquid injection

Working on the assumption that pressures in the cargo tanks $p_o = 2$ bar abs and condensing pressure $p_k = 30$ bar abs, then first interstage pressure $p_{m1} = 4.85$ bar abs and second interstage pressure is $p_{m2} = 11.8$ bar abs. Of course different grade of the cargo changes pressures of the reliquefaction plant.

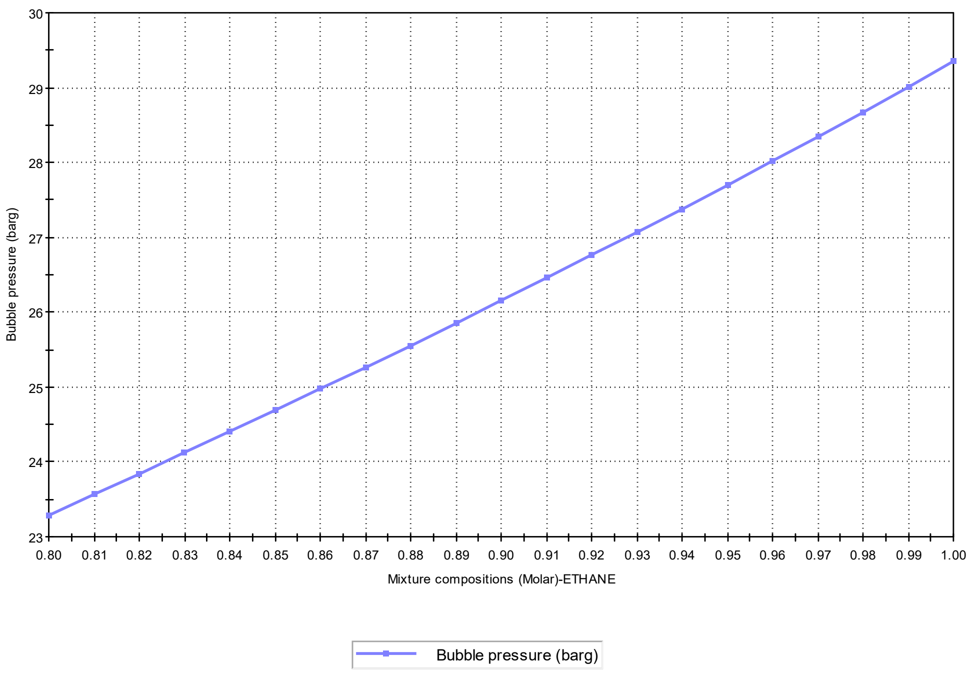

Fig. 7. Condensing equilibrium for propane-ethane mixture at +10°C [9]

Above in Fig. 7 is shown molar content of ethane in the liquid mixture propane-ethane which could be condensed at higher pressures in the three-stage reliquefaction plant at temperature +10°C. Below in Fig. 8 is explained how change condensing pressure at temperature +32°C – typical conditions when the condenser is cooled with sea water in the tropical regions.

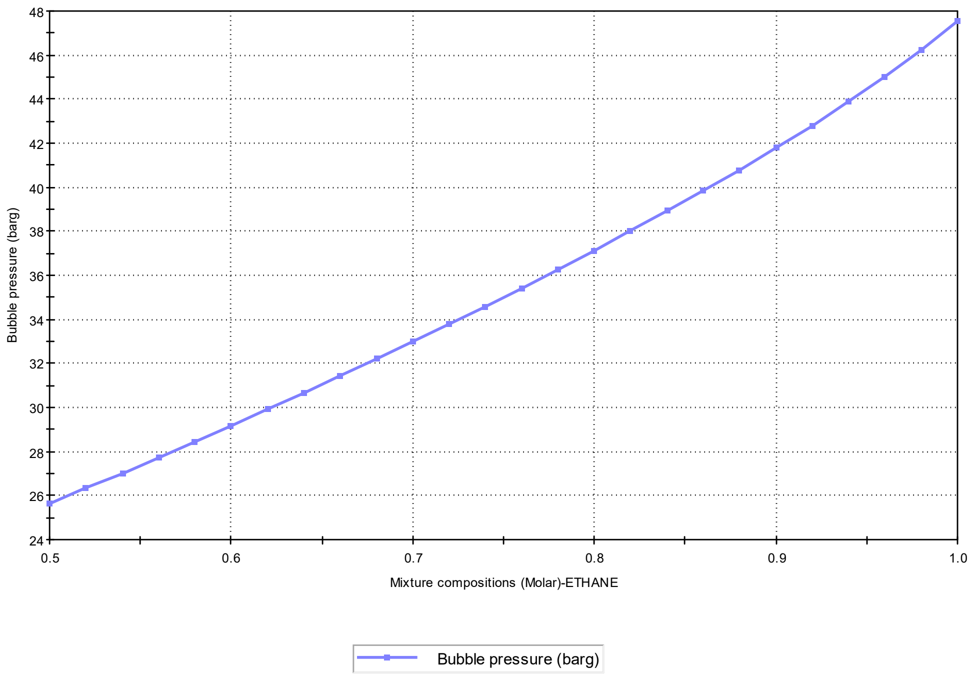

Fig. 8. Condensing equilibrium for propane-ethane mixture at +32°C [9]

4. Conclusions

1. Cargo mixture composition of two components changes through parts of the reliquefaction plant. Equilibrium conditions liquid-vapour in the vessels increase vapour content of more volatile component what requires higher condensing pressure or lower temperature.
2. Presence of ethane, nitrogen or methane in the cargo tanks can substantially reduce the cooling rate of typical two-stage reliquefaction plant on board the ethylene or LPG carrier.
3. Three-stage cycle with liquid injection is a proposal for the cargo, which contain volatile additives and could solve the problems of two-stage cycles of the reliquefaction plants with very poor cooling rate, caused by high condensing pressures.

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