THE COMPARISON OF THEORETICAL TO PRACTICAL CARGO LOADING RATE OF BUTANE - ANALYSIS OF LPG CARRIER RELIQUEFACTION PLANT

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Abstract

This paper presents a performance of reliquefaction plant analysis in order to assess possible cargo loading rate for Butane (C_4H_{10}). The highest cargo loading rate is essential in use of LPG carriers because of economical point of view. Loading and discharging cargo time at ports substantially influences on a financial effect of the ship owner. Because of different cargo grades, which number is continuously increasing, crucial is to know real efficiency of gas plan, before signing some contract with customer. On board these types of ships the highest efficiency of reliquefaction plant is crucial. After short description of fully refrigerated gas carrier, theoretical data of analysed ship, taken from ship documentation is shown. Taking into account this data, expected cargo compressors parameters and cargo loading rate are discussed, explained and assumed. In next step, real ambient Butane loading process carried out on board LPG carrier is described. All essential values and reliquefaction plant readings, taken in loading port are presented. The comparison of theoretical result based on available documentation to practical effects obtained in the port is performed. Analysis, mainly taking into account gas plan, answers if it operated with the highest possible efficiency and met cargo loading parameters expected according to ship manuals. Conclusions are discussed.

Keywords: *LPG carrier, cargo loading rate, CC4 – cargo, Butane, reliquefaction plant*

1. Introduction

Fully refrigerated ships carry their cargoes at approximately atmospheric pressure and are designed to transport large quantities of LPG and ammonia. For this class of ship the most widely used arrangement is independent tanks with single hull but double bottom and hopper tanks. Here, the tank itself is a Type 'A' prismatic free-standing unit capable of a maximum working pressure of 0.7 barg. The tanks are constructed of low-temperature steels to permit carriage temperatures of about -48°C. Fully refrigerated ships range in size from about 20,000 to 100,000m^3 [3].

Described below ship is 22500m^3 LPG carrier built in 2010. The ship is certified to carry the following cargoes: Anhydrous Ammonia, 1.3 – Butadiene, Butane (ISO and normal), Butylene, Propane (Pure), Propane (Commercial – having a maximum of 2.5 mole% Ethane), Propylene, Vinyl Chloride Monomer, Propane and Butane mixtures. Design seawater temperature: 32°C, design ambient air temperature: 45°C.

The reliquefaction plant, comprising three compressor units, is necessary for the following reasons [4, 7]:

- condensation of vapour produced by heat ingress to cargo whilst at sea and in port to keep cargo tanks pressure on required level,
- condensation of vapour displaced by liquid as the vessel is loaded where no vapour return to shore is available or is used,
- reduction of the temperature of a cargo during voyage, in accordance with charterer's requirements,
- cooldown of a warm cargo tank prior to loading a refrigerated cargo.

The cargo compressors may also be used separately for purging vapour ashore, transferring vapour between tanks, clearing lines of liquid, assisting in inerting, purging and gas freeing. They are arranged to allow one stage operation, two stage operation with no interstage cooling and two stage operation with interstage cooling.

2. Theoretical Butane loading process

On board fully refrigerated ship, pressure in cargo tanks should not exceeds 1.2 bar absolute pressure. For this reason Butane temperature in cargo tank has to be approx. +4ºC [2]. Shore supplier provides "ambient temperature" +26ºC of cargo at ship manifold. All three cargo compressors will operate. According to gas plant manufacturer diagram [7], for Butane cargo loading rate is expected to be approx. 90 tonnes per hour (by sea cooling water temperature +32ºC), the actual sea water temperature in the port during cargo loading is +27ºC, so it may increase expected refrigeration capacity and final loading rate [1].

Total refrigeration capacity of one compressor Burckhardt 2K-160 type can be calculated with following assumption (Fig. 1):

- compressor suction temperature t1=+9ºC (5K superheat), pressure p1=1.2 bar (abs),
- condensing temperature t3=+32ºC (5 K of increasing to sea water), pressure p3=3.0 bar (abs),
- isentropic efficiency of one stage cycle: 0.8,
- butane approx. mass flow for 2K – 160 compressor (one stage cycle) [7]: approx. m=3500 kg/h.

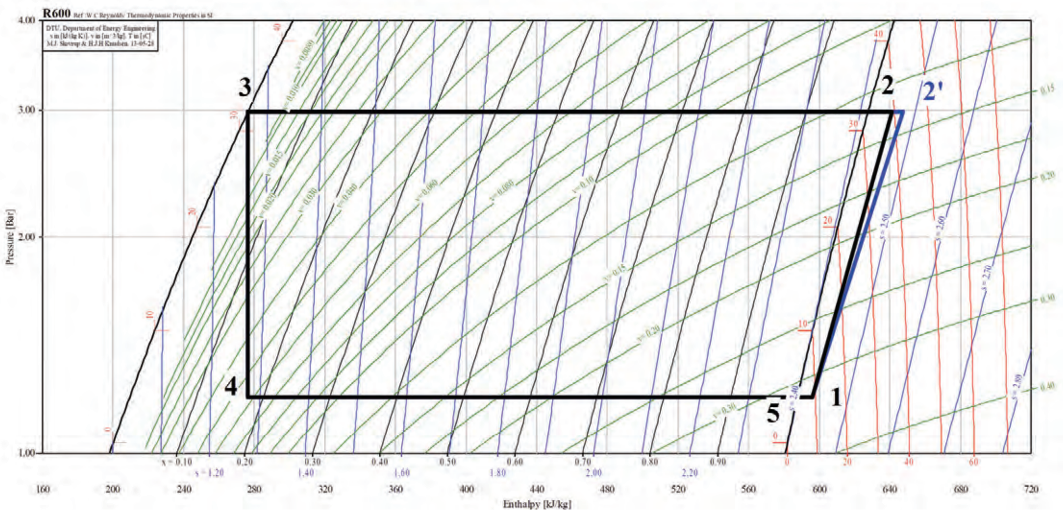

Fig. 1. Reliquefaction plant recommended cycles for Butane [2, 7]

Taking into account above, cycle 1-2-3-4-5-1 (shown in Fig. 1) can be drawn, where specific refrigeration capacity is described as the difference between enthalpies (process 5-1 superheat of vapour takes place in suction pipe):

$$q_e = h_5 - h_4 = 310 \ \ kJ/kg\,, \tag{1}$$

where:
q_e – specific refrigeration capacity,
h_1 – vapour enthalpy of compressor suction,
h_2 – condensate enthalpy entering cargo tank.

Total refrigeration capacity of one compressor is described by formula:

$$Q_e = m \cdot q_e = 300 \ \ kW\,, \tag{2}$$

where:
Q_e – total refrigeration capacity,
m – Butane one stage cycle mass flow.

Theoretical compressor discharge temperature of this cycle is t_2=39ºC. Cycle 1-2’-3-4-1 represents two stage compression without intercooler [5, 8], which also may be used to cool down the cargo. Specific refrigeration capacity is the same, but lower mass flow causes higher discharge temperature ($t_{2'}$=43ºC) and decreases isentropic efficiency up to 0.7. Mass flow approx. m’=3000 kg/h [7] gives total refrigeration capacity Q'_e:

$$Q'_e = m' \cdot q_e = 260 \ kW \ , \tag{3}$$

i.e. less than 87% of one stage capacity. It is recommended, that two stages cycle should be used when absolute pressure ratio discharge/suction is higher than π=4.5 [7]. Because the ratio is:

$$\pi = p_3 : p_1 = 2.25 \, , \tag{4}$$

theoretically one stage operation should be used in this reliquafection plant in order to get the highest refrigeration capacity and cargo loading rate.

3. Butane loading process performed on board the ship

The reliquefaction installation employed on board of analysed fully refrigerated ship is used to carry mentioned before cargoes, but not for Ethylene, because of lack of cascade system [6, 8]. In Fig. 2 are shown it’s the most essential equipment. Basic machinery of the same three units is two cylinder, double acting, oil free reciprocating compressor 2-3, which is protected against liquid hammering by suction separator 1. Cargo economiser (interstage cooler) 4 is used in order to reduce compressor discharge temperature of cargo vapour and for subcooling condensate. In this case is not used because of cargo grade [5]. Compressed vapour is directed to Alfa Laval plate condenser 5 with heat transfer coefficient approx. 2500 W/m^{2}K. It is cooled by sea water (SW). In the condensate accumulator pressure vessel 6, the condensate level of cargo is controlled by means of the level control valve 7. All incondensable gases can be removed from installation through manual or automatic pressure valve 8 and directed either to condensate line or by vent mast to atmosphere.

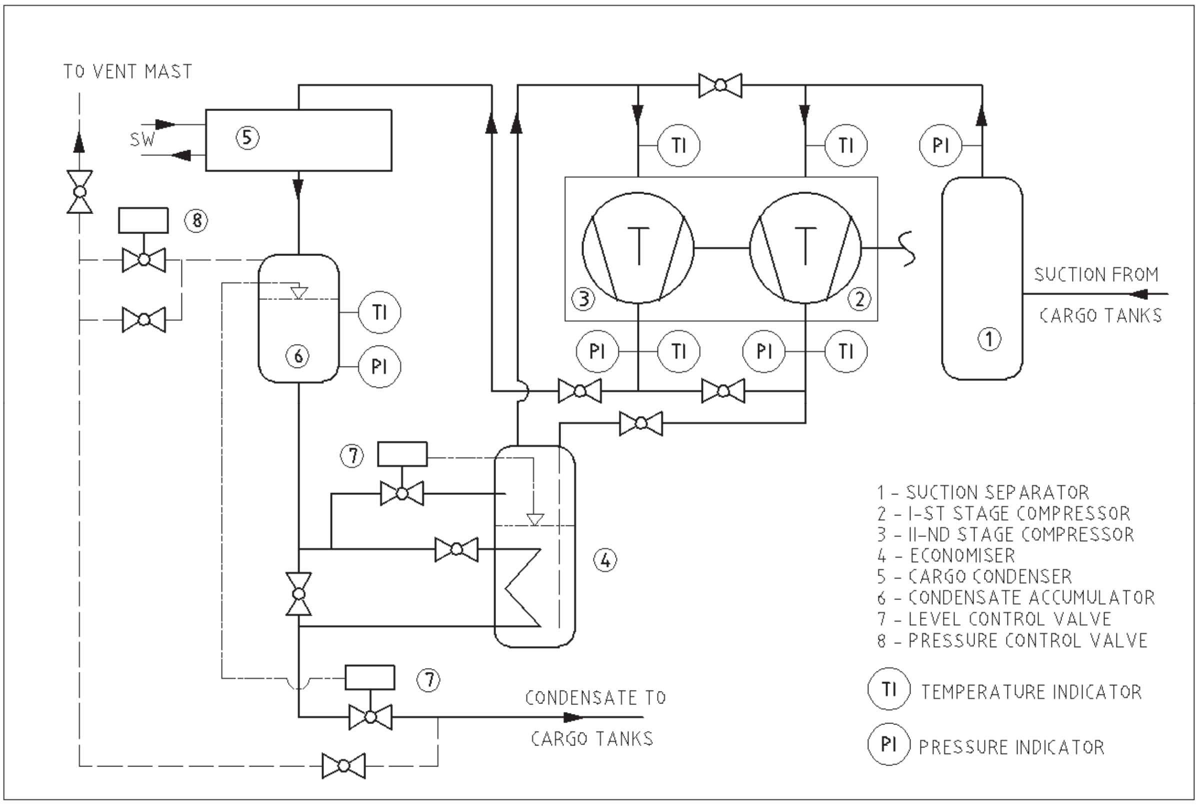

Fig. 2. A diagram of ship`s reliquefaction plant

In Table 1 are shown three compressors average Butane loading parameters. Sea water temperature in the port is 27ºC, all three compressors running in one stage operation mode. Pressure in cargo tanks before loading was approx. 80 mbar pressure gauge with vapour from previous cargo CC4 (composition of 6% Butane, 50% 1-Butenes, 43% 1.3 Butadiene and less than 1% Nitrogen). This data are related to loading to one tank (CT2) only and during this time cargo tanks CT1&3 were closed (vapour and liquid line). During first 12 hours vents 8 of all three condensate accumulators 6 (Fig. 1) were fully open to condensate line and gradually closed in next hours. At 24th hour of loading they were almost completely closed.

Tab. 1. Cargo tank no2 Butane loading parameters taken in the port

Loading hour	Comp. suction presssure	Comp. suction temp.	I stage discharge pressure	I stage discharge temp.	II stage discharge pressure	II stage discharge temp.	Condensate accumulator pressure	Condensate accumulator temp.	Cargo tank pressure	Average cargo tank temp.	Avrg. Butane temperature at manifold	Loading rate
	bar abs	ºC	bar abs	ºC	bar abs	ºC	bar abs	ºC	bar abs	ºC	ºC	t/h
3	1.2	12	6	80	6	88	6	34	1.36	4	26	68
24	1.2	15	5.5	74	5.5	80	5.5	34	1.35	7	26	75
48	1.2	15	4.8	70	4.8	75	4.8	34	1.33	7.5	26	80

Utilising data in Tab. 1, it is possible to create real cycle performed by the cargo gas plant during. Cycle 1-2-3-4-5-1 shown in Fig. 3 is constructed according to data taken at 48th hour of loading, when some stabilization of parameters appeared. Process 5-1 as in theoretically process (Fig. 1) includes vapour superheat and also real pressure drop on suction of the cargo compressor.

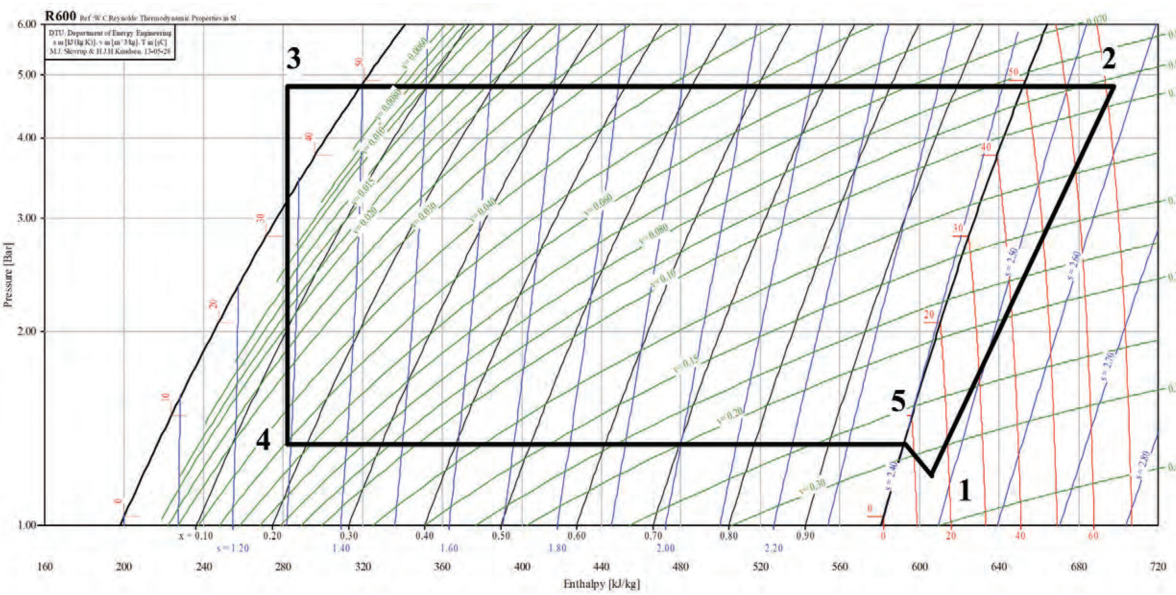

Fig. 3. Real cycle performed by reliquefaction plant during loading Butane [2]

Specific refrigeration capacity calculated from this cycle by using formula:

$$q_e = h_5 - h_4 = 310 \ \ kJ/kg \ , \tag{5}$$

it is the same like in the theoretical cycle, but this is caused by lower (+27ºC not +32ºC) sea water temperature. It could be seen as a subcooling of condensate from boiling line x=0 to point 3. If sea water temperature is +32ºC then specific refrigeration capacity would decrease about 20 kJ/kg i.e. approx. 6%. To assess total refrigeration capacity of the reliquefaction plant, real flow mass of cargo through cargo compressor must be known.

In process performed by the cargo compressor shown in Fig. 3 Butane is compressed to real discharge pressure 4.8 bar abs, not theoretical 3.0 bar abs and condensed by +48ºC. It is related with some mass flow losses. According to the cargo compressor manufacturer data [7], for considered above cycle's parameters real flow mass is decreased to approx. 2200 kg/h i.e. to 63% described by (2) for one compressor:

$$Q_e = 0.63 \cdot m \cdot q_e = 190 \ \ kW \ . \tag{6}$$

At 48th hour of loading reliquefaction plant performs process of cooling down the cargo with 63% efficiency in the comparison to the theoretical cycle described by the manufacturer. On the other hand achieved loading rate 80t/h is 12% lower than it is assumed by manufacturer.

4. Conclusions

1. In order to achieve the highest efficiency of reliquefaction plant it is important to operate with the optimal cycle. In this case taking into account all parameters of loading the one stage cycle is 15% more efficient than two stage (300 kW to 260kW).
2. Condensing pressure 4.8 bar abs instead of theoretical 3.0 bar is caused by presence of incondensable gases from previous CC4 grade in cargo tanks. Higher Butane condensing pressure decreases approx. 37% refrigeration capacity from 300kW to 190 kW. In this case, carefully removing incondensable gases before loading a new cargo grade is essential in order to get the highest efficiency of the reliquefaction plant.
3. Real achieved loading rate 80 t/h shows that without influence of incondensable gases which reduced refrigeration capacity of reliquefaction plant approx. 37%, the gas plant manufacturer diagram [7], for Butane cargo loading rate approx. 90 tons per hour is real.

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