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An experimental ethylene carrier gassing-up operation

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Abstract

Gas carriers are one of the most advanced types of ships and are equipped with the latest technological achievements. Due to the development of this industry, the demand for ethylene transport by sea has increased significantly in recent years. Nonetheless, it is one of the most problematic loads in terms of loading operations. Due to the small density differences between ethylene and nitrogen, ethylene is one of the most problematic hydrocarbons with respect to the efficient gasification of cargo tanks. Additionally, ethylene is one of the most expensive cargoes carried on gas carriers. The above aspects make it necessary to carry out a detailed analysis of the flushing of nitrogen-loaded cargo tanks with ethylene vapors to determine the range of technical parameters to enable more efficient tank gassing-up. This paper provides a detailed analysis of an experimental cargo tank gassing-up operation on an ethylene carrier. The process was carried out in accordance with previously-determined assumptions to optimize the discussed operations, assess how the cargo tank pressure influences this process, reduce cargo loss during gassing-up, and eliminate cargo loss during its cooling. The conclusions from this experiment provide guidelines for subsequent tests.

Introduction

Ethylene (C_2H_4) is a colorless gas that is present in small amounts in natural gas (McGuire & White, 2000; Wieczorek, 2017). On an industrial scale, it is obtained during the thermal decomposition of gaseous and liquid hydrocarbons from the gas products of crude oil refining (Włodarski, 1993). Ethylene is one of the basic raw materials of the petrochemical industry and is used to produce plastics (mainly plastic packaging), as well as polyethylene, chlorostyrene derivatives, ethanol, and higher aliphatic alcohols (McGuire & White, 2000; Schaller, 2012). The largest producer of this gas is the United States of America – almost 20 percent of the global potential – followed by China and Saudi Arabia (each accounting for 9% of global production), and Japan (about 5%) (Włodarski, 1993; Schaller, 2012).

There has recently been an enormous increase in ethylene demand in China, the Middle East, and the Far East, which has caused an unprecedented increase in the demand for the maritime transport of this type of cargo. Ships used to transport ethylene are specially-constructed LPG ships with a cascade cycle reliquefaction plant that uses propylene as a medium – and less-frequently, the refrigerant R 404 A. In addition, the cargo tanks of these vessels must be adapted to transport liquid cargo at –104°C. Most often, liquefied ethylene is transported in tanks at atmospheric pressure or slight overpressure at –103.9°C to –98°C, respectively. Ethylene can explode in mixtures with air (within concentrations of 2.75–2.6%) and during heating under increased pressure. Therefore, it must be transported in an inert shield gas. Furthermore, the recipients in ports require a fully-refrigerated charge at atmospheric pressure (Schaller, 2012).

To transport cargoes by sea on gas carriers, several operations must be repeated, the most important of which are inerting and gassing-up. Inerting involves forming an inert atmosphere in cargo tanks to prevent the creation of an explosive mixture between oxygen and the gas. This process uses nitrogen produced by pressure swing absorption (PSA) on the ship. Gassing-up involves removing an inert gas – nitrogen, which is incondensable during cargo cool down – using ethylene vapor to prevent cargo contamination (McGuire & White, 2000; Nanowski, 2014; Wieczorek, 2017). In the case of ethylene gassing-up, the operation is also important because the pressure of a discharge of the second stage of a cargo compressor is limited to 18.5 bar·g; and it is impossible to compress mixtures of ethylene and nitrogen at such a low pressure (Nanowski, 2016; Wieczorek & Giernalczyk, 2018). So far, the inaccurate gassing-up operation has resulted in additional cargo loss during tank cooling or when cargo compressors are switched off because the pressure during the second discharge stage is too high (Ship owner's data, 2018). Table 1 shows the values of a bubble pressure with reference to the mass fractions of ethylene and nitrogen for a tank temperature of –40°C.

The acceptable levels of oxygen and previous cargo content and operations that must be performed before cargo loading are specified in Table 2. The exact characteristics of inerting and gassing-up operations are described in a previous paper (Wieczorek, 2017).

Efficiently gassing-up ethylene carriers is one of the most problematic issues concerning operations on this type of ship because both gases have very similar densities at particular temperatures (Serwiński, 1982; Nanowski, 2016). Secondly, ethylene cargo is one of the most expensive cargoes to carry by sea (Schaller, 2012). Furthermore, there are no detailed guidelines for the gassing-up process on ethylene carriers.

Table 1. Incondensables in mixture vapor composition (Nanowski, 2016)

Conditions	Mixture vapor composition (Mass)		Results
Temperature (°C)	Ethylene	Nitrogen	Bubble pressure (bar·g)
–40	0.97	0.03	21.44
–40	0.98	0.02	18.81
–40	0.99	0.01	16.17
–40	1.00	0.00	13.52

Assumptions of the experiment

The gassing-up process often involves the loss of significant amounts of ethylene cargo, resulting in financial losses for the shipowner. The estimated loss of ethylene is about 40 tons (about 80 m^3 of liquid ethylene), which equals 40,000 USD, at a price of about USD 1,000 per ton. The magnitude of these losses depends to a large extent on the qualifications of the ship's crew; thus, it is variable. Effective methods to optimize the gassing-up process so that the operation can be completed in the shortest possible time with the lowest loss of cargo, have not been developed.

Table 2. Operations that must be completed before cargo loading (Ship owner's data, 2018)

Next Previous	**Ethylene**	**Propylene**	**Butadiene**	**Butene-1**	**Raffinate 1**
Ethylene		Purging N_2 O_2 < 0.3% < 1000 ppm P.CG Dewpoint −25°C	Purging N_2 O_2 < 0.2% < 5% P.CG	Purging N_2 O_2 < 0.1% < 5% P.CG Dewpoint −40°C	Acceptable to load on top & Low pressure + Temperature
Propylene	Purging N_2 O_2 < 0.3% < 1000 ppm P.CG Dewpoint −40°C		Purging N_2 O_2 < 0.2% < 5% P.CG	Purging N_2 O_2 < 0.1% < 5% P.CG Dewpoint −40°C	Purging N_2 O_2 < 0.3% < 5% P.CG
Butadiene	Visual inspection required Purging N_2 O_2 < 0.3% Dewpoint −40°C	Visual inspection required Purging N_2 O_2 < 0.3% Dewpoint −25°C		Visual inspection required Purging N_2 O_2 < 0.1% Dewpoint −40°C	Purging N_2 or IG O_2 < 0.3% < 5% P.CG
Butene-1	Visual inspection required Purging N_2 O_2 < 0.3% Dewpoint −40°C	Visual inspection required Purging N_2 O_2 < 0.3% Dewpoint −25°C	Purging N_2 O_2 < 0.2% < 5% P.CG		Purging N_2 or IG O_2 < 0.3% < 15% P.CG
Raffinate 1	Visual inspection required Purging N_2 O_2 < 0.3% Dewpoint −40°C	Visual inspection required Purging N_2 O_2 < 0.3% Dewpoint −25°C	Purging N_2 O_2 < 0.2% < 5% P.CG	Visual inspection required Purging N_2 O_2 < 0.1% Dewpoint −40°C	

Optimization of the gassing process was undertaken (in a doctoral thesis) by creating a theoretical mathematical model of a tank filled with nitrogen and gassed-up with ethylene. The theoretical calculations showed that gassing-up should be carried out with the minimum calculated nitrogen and ethylene pressures in tanks. This makes it possible to separate the gas (stratification) and allows the gassing-up process to be performed in the shortest time with the smallest loss of ethylene cargo.

To verify the accuracy of the performed calculations and their effectiveness, an experimental gassing-up operation was carried out in real conditions – on a gas carrier, consistent with theoretical assumptions and calculations.

Based on the analysis of the gassing-up process on two twin ethylene carriers – m/v Saturn and m/v Orion, explained fully in the paper (Wieczorek & Giernalczyk, 2018) – and also on the results of one cargo tank gassing-up calculations, a third experimental attempt was made to gas-up a third twin ethylene carrier's cargo tanks – m/v Neptune. The entire process was superintended by the Captain of the m/v Neptune.

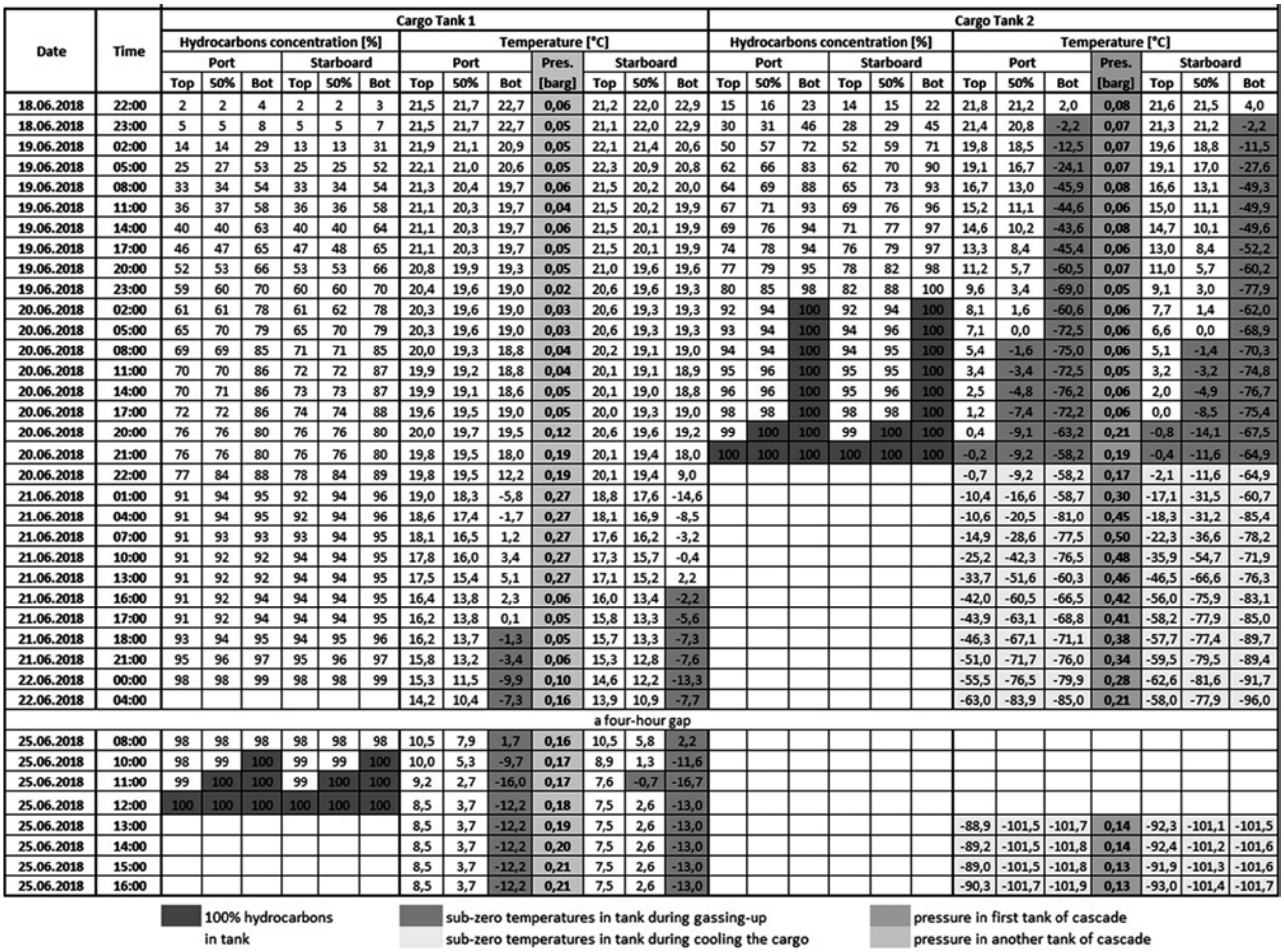
Since:

1. the cascade of a few cargo tanks on m/v Saturn displayed high pressure differences between the gassed-up tanks (e.g., from 0.34 bar·g to 0.16 bar·g or from 0.16 bar·g to 0.06 bar·g), which caused considerable ethylene loss during the gassing-up process;
2. the cascade of the two cargo tanks combined with a parallel gassing-up process on m/v Orion included carrying out the operation at lower pressures, resulting in slightly lower cargo loss and less loss during cargo cooling;
3. the results of loss calculations showed that during the gassing-up of cargo tanks, there is no total mixing of gases, meaning that stratification occurs, and also that performing the gassing-up process at low pressures results in less cargo loss;

the following gassing-up guidelines of four cargo tanks on m/v Neptune were specified:

1. tanks must be gassed-up in pairs, in cascade;
2. after the first tank of each cascade is gassed-up, it should be separated from the other tank in the cascade, and cargo cooling must be started;

Table 3. Measurements of pressures, temperatures, and HC volume of CT 1 and CT 2 gassing-up on m/v Neptune



Date	Time	Cargo Tank 1												
		Hydrocarbons concentration [%]						Temperature [°C]						
		Port			Starboard			Port			Pres. [barg]	Starboard		
		Top	50%	Bot	Top	50%	Bot	Top	50%	Bot		Top	50%	Bot
18.06.2018	22:00	2	2	4	2	2	3	21,5	21,7	22,7	▦ 0,06	21,2	22,0	22,9
18.06.2018	23:00	5	5	8	5	5	7	21,5	21,7	22,7	▦ 0,05	21,1	22,0	22,9
19.06.2018	02:00	14	14	29	13	13	31	21,9	21,1	20,9	▦ 0,05	22,1	21,4	20,6
19.06.2018	05:00	25	27	53	25	25	52	22,1	21,0	20,6	▦ 0,05	22,3	20,9	20,8
19.06.2018	08:00	33	34	54	33	34	54	21,3	20,4	19,7	▦ 0,06	21,5	20,2	20,0
19.06.2018	11:00	36	37	58	36	36	58	21,1	20,3	19,7	▦ 0,04	21,5	20,2	19,9
19.06.2018	14:00	40	40	63	40	40	64	21,1	20,3	19,7	▦ 0,06	21,5	20,1	19,9
19.06.2018	17:00	46	47	65	47	48	65	21,1	20,3	19,7	▦ 0,05	21,5	20,1	19,9
19.06.2018	20:00	52	53	66	53	53	66	20,8	19,9	19,3	▦ 0,05	21,0	19,6	19,6
19.06.2018	23:00	59	60	70	60	60	70	20,4	19,6	19,0	▦ 0,02	20,6	19,6	19,3
20.06.2018	02:00	61	61	78	61	62	78	20,3	19,6	19,0	▦ 0,03	20,6	19,3	19,3
20.06.2018	05:00	65	70	79	65	70	79	20,3	19,6	19,0	▦ 0,03	20,6	19,3	19,3
20.06.2018	08:00	69	69	85	71	71	85	20,0	19,3	18,8	▦ 0,04	20,2	19,1	19,0
20.06.2018	11:00	70	70	86	72	72	87	19,9	19,2	18,8	▦ 0,04	20,1	19,1	18,9
20.06.2018	14:00	70	71	86	73	73	87	19,9	19,1	18,6	▦ 0,05	20,1	19,0	18,8
20.06.2018	17:00	72	72	86	74	74	88	19,6	19,5	19,0	▦ 0,05	20,0	19,3	19,0
20.06.2018	20:00	76	76	80	76	76	80	20,0	19,7	19,5	▦ 0,12	20,6	19,6	19,2
20.06.2018	21:00	76	76	80	76	76	80	19,8	19,5	18,0	▦ 0,19	20,1	19,4	18,0
20.06.2018	22:00	77	84	88	78	84	89	19,8	19,5	12,2	▦ 0,19	20,1	19,4	9,0
21.06.2018	01:00	91	94	95	92	94	96	19,0	18,3	-5,8	▦ 0,27	18,8	17,6	-14,6
21.06.2018	04:00	91	94	95	92	94	96	18,6	17,4	-1,7	▦ 0,27	18,1	16,9	-8,5
21.06.2018	07:00	91	93	93	93	94	95	18,1	16,5	1,2	▦ 0,27	17,6	16,2	-3,2
21.06.2018	10:00	91	92	92	94	94	95	17,8	16,0	3,4	▦ 0,27	17,3	15,7	-0,4
21.06.2018	13:00	91	92	92	94	94	95	17,5	15,4	5,1	▦ 0,27	17,1	15,2	2,2
21.06.2018	16:00	91	92	94	94	94	95	16,4	13,8	2,3	▦ 0,06	16,0	13,4	▩ -2,2
21.06.2018	17:00	91	92	94	94	94	95	16,2	13,8	0,1	▦ 0,05	15,8	13,3	▩ -5,6
21.06.2018	18:00	93	94	95	94	95	96	16,2	13,7	▩ -1,3	▦ 0,05	15,7	13,3	▩ -7,3
21.06.2018	21:00	95	96	97	95	96	97	15,8	13,2	▩ -3,4	▦ 0,06	15,3	12,8	▩ -7,6
22.06.2018	00:00	98	98	99	98	98	99	15,3	11,5	▩ -9,9	▦ 0,10	14,6	12,2	▩ -13,3
22.06.2018	04:00							14,2	10,4	▩ -7,3	▦ 0,16	13,9	10,9	▩ -7,7
a four-hour gap														
25.06.2018	08:00	98	98	98	98	98	98	10,5	7,9	▩ 1,7	▦ 0,16	10,5	5,8	▩ 2,2
25.06.2018	10:00	98	99	■ 100	99	99	■ 100	10,0	5,3	▩ -9,7	▦ 0,17	8,9	1,3	▩ -11,6
25.06.2018	11:00	99	■ 100	■ 100	99	■ 100	■ 100	9,2	2,7	▩ -16,0	▦ 0,17	7,6	▩ -0,7	▩ -16,7
25.06.2018	12:00	■ 100	■ 100	■ 100	■ 100	■ 100	■ 100	8,5	3,7	▩ -12,2	▦ 0,18	7,5	2,6	▩ -13,0
25.06.2018	13:00							8,5	3,7	▩ -12,2	▦ 0,19	7,5	2,6	▩ -13,0
25.06.2018	14:00							8,5	3,7	▩ -12,2	▦ 0,20	7,5	2,6	▩ -13,0
25.06.2018	15:00							8,5	3,7	▩ -12,2	▦ 0,21	7,5	2,6	▩ -13,0
25.06.2018	16:00							8,5	3,7	▩ -12,2	▦ 0,21	7,5	2,6	▩ -13,0

Date	Time	Cargo Tank 2												
		Hydrocarbons concentration [%]						Temperature [°C]						
		Port			Starboard			Port			Pres. [barg]	Starboard		
		Top	50%	Bot	Top	50%	Bot	Top	50%	Bot		Top	50%	Bot
18.06.2018	22:00	15	16	23	14	15	22	21,8	21,2	2,0	▒ 0,08	21,6	21,5	4,0
18.06.2018	23:00	30	31	46	28	29	45	21,4	20,8	▩ -2,2	▒ 0,07	21,3	21,2	▩ -2,2
19.06.2018	02:00	50	57	72	52	59	71	19,8	18,5	▩ -12,5	▒ 0,07	19,6	18,8	▩ -11,5
19.06.2018	05:00	62	66	83	62	70	90	19,1	16,7	▩ -24,1	▒ 0,07	19,1	17,0	▩ -27,6
19.06.2018	08:00	64	69	88	65	73	93	16,7	13,0	▩ -45,9	▒ 0,08	16,6	13,1	▩ -49,3
19.06.2018	11:00	67	71	93	69	76	96	15,2	11,1	▩ -44,6	▒ 0,06	15,0	11,1	▩ -49,9
19.06.2018	14:00	69	76	94	71	77	97	14,6	10,2	▩ -43,6	▒ 0,08	14,7	10,1	▩ -49,6
19.06.2018	17:00	74	78	94	76	79	97	13,3	8,4	▩ -45,4	▒ 0,06	13,0	8,4	▩ -52,2
19.06.2018	20:00	77	79	95	78	82	98	11,2	5,7	▩ -60,5	▒ 0,07	11,0	5,7	▩ -60,2
19.06.2018	23:00	80	85	98	82	88	100	9,6	3,4	▩ -69,0	▒ 0,05	9,1	3,0	▩ -77,9
20.06.2018	02:00	92	94	■ 100	92	94	■ 100	8,1	1,6	▩ -60,6	▒ 0,06	7,7	1,4	▩ -62,0
20.06.2018	05:00	93	94	■ 100	94	96	■ 100	7,1	0,0	▩ -72,5	▒ 0,06	6,6	0,0	▩ -68,9
20.06.2018	08:00	94	94	■ 100	94	95	■ 100	5,4	▩ -1,6	▩ -75,0	▒ 0,06	5,1	▩ -1,4	▩ -70,3
20.06.2018	11:00	95	96	■ 100	95	95	■ 100	3,4	▩ -3,4	▩ -72,5	▒ 0,05	3,2	▩ -3,2	▩ -74,8
20.06.2018	14:00	96	96	■ 100	95	96	■ 100	2,5	▩ -4,8	▩ -76,2	▒ 0,06	2,0	▩ -4,9	▩ -76,7
20.06.2018	17:00	98	98	■ 100	98	98	■ 100	1,2	▩ -7,4	▩ -72,2	▒ 0,06	0,0	▩ -8,5	▩ -75,4
20.06.2018	20:00	99	■ 100	■ 100	99	■ 100	■ 100	0,4	▩ -9,1	▩ -63,2	▒ 0,21	▩ -0,8	▩ -14,1	▩ -67,5
20.06.2018	21:00	■ 100	■ 100	■ 100	■ 100	■ 100	■ 100	▩ -0,2	▩ -9,2	▩ -58,2	▒ 0,19	▩ -0,4	▩ -11,6	▩ -64,9
20.06.2018	22:00							░ -0,7	░ -9,2	░ -58,2	▦ 0,17	░ -2,1	░ -11,6	░ -64,9
21.06.2018	01:00							░ -10,4	░ -16,6	░ -58,7	▦ 0,30	░ -17,1	░ -31,5	░ -60,7
21.06.2018	04:00							░ -10,6	░ -20,5	░ -81,0	▦ 0,45	░ -18,3	░ -31,2	░ -85,4
21.06.2018	07:00							░ -14,9	░ -28,6	░ -77,5	▦ 0,50	░ -22,3	░ -36,6	░ -78,2
21.06.2018	10:00							░ -25,2	░ -42,3	░ -76,5	▦ 0,48	░ -35,9	░ -54,7	░ -71,9
21.06.2018	13:00							░ -33,7	░ -51,6	░ -60,3	▦ 0,46	░ -46,5	░ -66,6	░ -76,3
21.06.2018	16:00							░ -42,0	░ -60,5	░ -66,5	▦ 0,42	░ -56,0	░ -75,9	░ -83,1
21.06.2018	17:00							░ -43,9	░ -63,1	░ -68,8	▦ 0,41	░ -58,2	░ -77,9	░ -85,0
21.06.2018	18:00							░ -46,3	░ -67,1	░ -71,1	▦ 0,38	░ -57,7	░ -77,4	░ -89,7
21.06.2018	21:00							░ -51,0	░ -71,7	░ -76,0	▦ 0,34	░ -59,5	░ -79,5	░ -89,4
22.06.2018	00:00							░ -55,5	░ -76,5	░ -79,9	▦ 0,28	░ -62,6	░ -81,6	░ -91,7
22.06.2018	04:00							░ -63,0	░ -83,9	░ -85,0	▦ 0,21	░ -58,0	░ -77,9	░ -96,0
a four-hour gap														
25.06.2018	08:00													
25.06.2018	10:00													
25.06.2018	11:00													
25.06.2018	12:00													
25.06.2018	13:00							░ -88,9	░ -101,5	░ -101,7	▦ 0,14	░ -92,3	░ -101,1	░ -101,5
25.06.2018	14:00							░ -89,2	░ -101,5	░ -101,8	▦ 0,14	░ -92,4	░ -101,2	░ -101,6
25.06.2018	15:00							░ -89,0	░ -101,5	░ -101,8	▦ 0,13	░ -91,9	░ -101,3	░ -101,6
25.06.2018	16:00							░ -90,3	░ -101,7	░ -101,9	▦ 0,13	░ -93,0	░ -101,4	░ -101,7

■ 100% hydrocarbons in tank
▩ sub-zero temperatures in tank during gassing-up
░ sub-zero temperatures in tank during cooling the cargo
▦ pressure in first tank of cascade
▒ pressure in another tank of cascade

Table 4. Measurements of pressures, temperatures, and HC volume of CT 3 and CT 4 gassing-up on m/v Neptune

Date	Time	Cargo Tank 3												
		Hydrocarbons concentration [%]						Temperature [°C]						
		Port			Starboard			Port			Pres. [barg]	Starboard		
		Top	50%	Bot	Top	50%	Bot	Top	50%	Bot		Top	50%	Bot
18.06.2018	22:00	1	2	5	1	2	4	22,8	21,7	21,5	0,05	22,9	21,1	20,9
18.06.2018	23:00	3	3	9	3	5	9	22,8	21,7	21,5	0,04	22,9	21,1	20,9
19.06.2018	02:00	10	10	30	10	10	30	21,9	21,0	20,9	0,06	21,7	20,5	20,1
19.06.2018	05:00	26	27	48	26	26	47	21,2	20,6	20,1	0,05	21,1	19,8	19,6
19.06.2018	08:00	29	30	53	30	30	53	21,6	20,5	19,9	0,07	21,6	19,7	19,5
19.06.2018	11:00	32	33	57	33	33	57	21,4	20,4	19,9	0,06	21,4	19,7	19,5
19.06.2018	14:00	35	35	62	35	35	60	20,9	19,9	19,9	0,05	20,9	19,5	19,2
19.06.2018	17:00	42	43	67	42	44	65	20,9	19,9	19,7	0,05	20,9	19,5	19,2
19.06.2018	20:00	46	46	68	46	46	66	20,5	19,6	19,4	0,05	20,5	19,1	18,9
19.06.2018	23:00	53	54	69	53	53	66	20,2	19,3	19,0	0,04	20,3	18,8	18,8
20.06.2018	02:00	56	56	76	54	56	76	20,1	19,3	19,0	0,04	20,2	18,8	18,8
20.06.2018	05:00	59	60	77	59	59	76	20,1	19,3	19,0	0,04	20,2	18,8	18,8
20.06.2018	08:00	61	61	80	61	61	80	19,7	19,0	18,8	0,05	19,8	18,6	18,6
20.06.2018	11:00	62	62	81	62	62	81	19,6	18,9	18,8	0,04	19,6	18,6	18,5
20.06.2018	14:00	64	64	85	64	64	85	19,6	18,8	18,4	0,04	19,6	18,5	18,2
20.06.2018	17:00	66	67	85	65	66	85	19,2	19,0	18,8	0,50	19,3	18,7	18,6
20.06.2018	20:00	71	71	73	71	71	72	19,1	18,9	18,8	0,04	19,2	18,5	18,5
20.06.2018	21:00	71	71	73	71	71	72	20,0	19,8	-1,4	0,19	19,8	19	-7,1
20.06.2018	22:00	71	72	75	72	73	74	20,0	19,8	-1,4	0,19	19,8	19	-7,1
21.06.2018	01:00	76	76	77	76	76	78	18,4	17,3	-7,2	0,10	17,6	16,6	-9,1
21.06.2018	04:00	76	76	77	76	76	78	17,7	16,6	-0,2	0,11	16,9	15,9	-3,5
21.06.2018	07:00	76	77	78	76	76	78	17,1	15,9	0,2	0,10	16,2	14,8	-5,5
21.06.2018	10:00	77	80	91	78	80	91	16,2	14,6	-10,8	0,10	15,2	12,5	-10,4
21.06.2018	13:00	86	93	94	93	94	95	14,7	11,3	-27,8	0,09	13,4	9,1	-25,5
21.06.2018	16:00	93	95	97	94	95	97	13,2	8,1	-40,4	0,04	11,4	5,7	-46,9
21.06.2018	17:00	93	95	97	94	95	97	12,9	7,5	-38,1	0,04	10,9	5,3	-45,4
21.06.2018	18:00	94	97	98	95	97	99	12,5	7,1	-36,5	0,05	10,7	5	-46,3
21.06.2018	21:00	97	98	98	97	98	98	11,3	5,9	-36,9	0,11	9,5	3,8	-47,1
22.06.2018	00:00	97	98	99	97	98	99	10,0	3,9	-34,7	0,10	8,1	2,1	-45,8
22.06.2018	04:00							10,1	2,5	-24,9	0,12	8,6	1,2	-33,6
a four-hour gap														
25.06.2018	08:00							8,8	3,5	3,3	0,14	8,4	3,6	2,9
25.06.2018	10:00							8,8	3,5	3,3	0,14	8,4	3,6	2,9
25.06.2018	11:00							8,8	3,5	3,3	0,14	8,4	3,6	2,9
25.06.2018	12:00	97	98	98	97	98	98	8,8	3,5	3,3	0,14	8,4	3,6	2,9
25.06.2018	13:00	97	98	99	98	99	99	8,8	3,5	3,3	0,14	8,4	3,6	2,9
25.06.2018	14:00	98	98	99	98	99	100	8,8	3,5	3,3	0,14	8,4	3,6	2,9
25.06.2018	15:00	99	100	100	99	100	100	5,6	2,5	-1,7	0,15	5,1	0,7	-5,1
25.06.2018	16:00	100	100	100	100	100	100	4,9	2,3	-1,7	0,21	4,1	1	-3,5

Date	Time	Cargo Tank 4												
		Hydrocarbons concentration [%]						Temperature [°C]						
		Port			Starboard			Port			Pres. [barg]	Starboard		
		Top	50%	Bot	Top	50%	Bot	Top	50%	Bot		Top	50%	Bot
18.06.2018	22:00	20	21	22	12	13	22	22,0	21,8	-3,0	0,07	21,9	21,3	-1
18.06.2018	23:00	23	24	42	25	26	48	21,8	21,7	-12,0	0,06	21,2	21,3	-10
19.06.2018	02:00	44	48	64	51	57	75	20,1	19,6	-18,4	0,07	19,2	18,6	-26,4
19.06.2018	05:00	59	60	86	57	65	87	19,0	17,1	-39,1	0,07	18,1	15,8	-52,5
19.06.2018	08:00	62	65	92	64	72	94	17,2	13,7	-60,4	0,09	15,9	12,6	-68,3
19.06.2018	11:00	65	70	98	66	74	97	15,6	11,1	-64,6	0,08	14,5	10,3	-61,9
19.06.2018	14:00	67	74	98	70	74	98	14,8	10,1	-65,5	0,07	13,6	9,1	-63,7
19.06.2018	17:00	72	76	99	75	78	98	13,4	8,1	-67,6	0,08	12,1	7,2	-67,9
19.06.2018	20:00	74	78	100	77	78	100	11,9	6,0	-72,1	0,07	10,7	5,1	-69,2
19.06.2018	23:00	76	78	100	79	80	100	10,2	3,8	-73,4	0,05	8,8	3,0	-70,6
20.06.2018	02:00	78	80	100	79	82	100	8,7	2,0	-75,4	0,06	7,3	1,2	71,7
20.06.2018	05:00	82	92	100	92	94	100	7,9	0,5	-76,4	0,06	6,5	-0,1	-71,4
20.06.2018	08:00	85	92	100	92	94	100	6,4	-0,9	-73,7	0,06	4,9	-1,7	-71,7
20.06.2018	11:00	90	94	100	94	95	100	4,8	-2,5	-75,1	0,05	3,3	-3,3	-74,4
20.06.2018	14:00	94	95	100	95	96	100	3,7	-3,8	-78,2	0,05	2,2	-4,7	-78,2
20.06.2018	17:00	98	98	100	98	98	100	1,6	-6,1	-69,9	0,60	0,7	-6,4	-72,5
20.06.2018	20:00	99	100	100	99	100	100	-1,7	-14,5	-71,9	0,20	-3,6	-17,9	-67,9
20.06.2018	21:00	100	100	100	100	100	100	-1,6	-11,9	-73,5	0,16	-3,5	-14,5	-67,6
20.06.2018	22:00							-1,9	-11,9	-73,5	0,16	-3,4	-12,9	-66,2
21.06.2018	01:00							-7,3	-17,9	-75,4	0,28	-8,3	-16,9	-68,0
21.06.2018	04:00							-21,6	-37,6	-73,6	0,44	-20,6	-34,1	-76,7
21.06.2018	07:00							-31,0	-43,1	-73,3	0,49	-25,5	-41,2	-76,7
21.06.2018	10:00							-39,3	-55,5	-72,7	0,46	-33,6	-45,8	-74,3
21.06.2018	13:00							-46,5	-62,5	-73,9	0,44	-39,6	-52,1	-72,9
21.06.2018	16:00							-53,6	-70,0	-76,9	0,40	-45,3	-58,6	-72,8
21.06.2018	17:00							-55,2	-70,4	-79,3	0,39	-48,0	-61,0	-74,1
21.06.2018	18:00							-57,0	-72,7	-79,7	0,36	-51,2	-65,5	-76,1
21.06.2018	21:00							-60,7	-76,0	-83,9	0,32	-55,9	-69,9	-80,3
22.06.2018	00:00							-64,3	-79,1	-87,1	0,27	-59,6	-73,1	-83,1
22.06.2018	04:00							-71,2	-85,8	-91,5	0,19	-68,0	-81,9	-88,2
a four-hour gap														
25.06.2018	08:00													
25.06.2018	10:00													
25.06.2018	11:00													
25.06.2018	12:00													
25.06.2018	13:00							-77,6	-101,8	-101,8	0,10	-77,1	-101,5	-101,7
25.06.2018	14:00							-77,5	-101,9	-101,9	0,10	-77,0	-101,6	-101,7
25.06.2018	15:00							-77,5	-101,9	-101,9	0,10	-77,4	-101,6	-101,8
25.06.2018	16:00							-79,0	-102,0	-102,1	0,09	-78,4	-101,8	-101,9

■ 100% hydrocarbons in tank
▨ sub-zero temperatures in tank during gassing-up
□ sub-zero temperatures in tank during cooling the cargo
▨ pressure in first tank of cascade
□ pressure in another tank of cascade

3. cold ethylene vapor must be leaded, and parallel gassing-up must be commenced in the two other tanks that were not gassed-up during the cascade method;
4. the minimum possible pressure must be maintained in tanks;
5. the tanks in a cascade must have similar pressures.

The gassing-up of m/v Neptune was carried out based on the above guidelines. The process consisted of two stages (Figure 1). Stage I lasted for 47 hours and consisted of introducing cold ethylene vapor at –85°C into Cargo Tank 2 and Cargo tank 4, while maintaining pressures of 0.05–0.07 bar·g in the tanks. At the same time, two cascade systems were made – from Cargo Tank 2 to Cargo Tank 1 – in which the pressure was maintained at 0.03–0.06 bar·g, and from Cargo Tank 4 to Cargo Tank 3 at a pressure of 0.04–0.06 bar·g. The level of hydrocarbons gradually increased for 47 hours, eventually reaching 100%. After gassing-up Tank 2 and Tank 4, the cargo cooling began, and stage II began for Tank 1 and Tank 3, which involved introducing cold ethylene vapor into both tanks. At the beginning of stage II, the level of hydrocarbons was about 76% in Tank 3 and 71% in Tank 1. For another 26 hours ethylene vapor at –85°C was introduced into Tank 1 and Tank 3, and the pressure rose about 0.01 bar·g. After 26 hours, the process was stopped, and the level of hydrocarbons reached about 98% in the tank. Eight hours later, the gassing-up operation of Tank 1 was restarted, and the level of hydrocarbons reached 100% 4 hours later. At this moment, introducing cold ethylene vapor into Tank 3 was restarted. The process was also finished after 4 hours, while maintaining a tank pressure of 0.14–0.15 bar·g. The technical

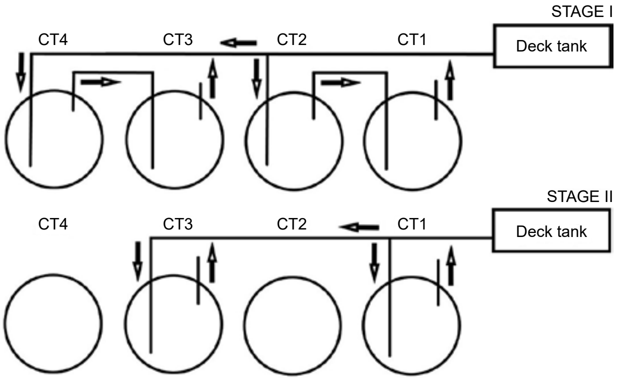


Figure 1. Diagram of gassing-up operation on m/v Neptune

parameters used during the gassing-up procedure for tanks on the m/v Neptune are presented in Tables 3 and 4.

Observations

First tanks of cascade system – Cargo Tank 2 and Cargo Tank 4

Throughout the entire gassing-up process, a slight temperature drop was measured in the tanks, which suggests gas stratification. In Cargo Tank 4, in which the pressure was only slightly higher than in Cargo Tank 2 (about 0.01 bar·g), the absence of 100% hydrocarbons was measured earlier. After completing the gassing-up operation, at all three levels of the tank (top, middle, bottom), sub-zero temperatures were measured.

Next tanks of cascade system – Cargo Tank 1 and Cargo Tank 3

26 hours after beginning the gassing-up process with cold ethylene vapors from the deck tank, the measured hydrocarbon level was about 97–99%. The process was interrupted at 8 hours, which resulted in the loss of stratification between ethylene and nitrogen, and in Tank 1, all three levels (top, middle, bottom) showed identical values of hydrocarbons (98%).

During the gassing-up of Tank 1, the pressure increased to 0.27 bar·g, whereas the pressure only increased to 0.11 bar·g in Tank 3. After completing the gassing-up, sub-zero temperatures were measured only at the bottom.

Conclusions and guidelines concerning cargo tanks gassing-up experiment on Ethylene carrier

The hydrocarbon concentrations on both the m/v Saturn and m/v Orion were measured using the same device, a portable Riken Keiki GX 8000 gas detector, with an accuracy of 5%. The two ethylene carriers during the gassing-up process were analyzed fully in a previous paper (Wieczorek & Giernalczyk, 2018). Therefore, it must be controlled if the accurate measurements are to be obtained. A chromatograph can fulfill this purpose and can measure hydrocarbons an accuracy of up to 0.01%.

A rapid pressure increase to 0.27 bar·g in Tank 1 towards a pressure of 0.11 bar·g in Tank 3 did not affect the gassing-up time, and both tanks reached 97–99% hydrocarbons 26 hours after the cold ethylene vapors were first directed into the tanks.

The cause of the interruption during the gassing-up of Tank 1 and Tank 3 is unknown. Contrary to Tank 2 and Tank 4, after completing the gassing-up of Tank 1 and Tank 3, sub-zero temperatures were measured only on the bottom of tanks before pausing gassing-up or after resuming the process in both tanks. At all three measurement levels, positive temperatures were measured, which indicates complete mixing between ethylene and nitrogen. During the next experiment, this pause in gassing-up must be prevented.

Approximately 43 tons of ethylene were lost during the gassing-up of all 4 tanks on the m/v Neptune. Lower pressures in the m/v Neptune's cargo tanks were maintained, as well as lower mass flow versus those on m/v Saturn and m/v Orion during its gassing-up process after inerting. This prevented the need to switching off all three cargo compressors (which operates up to a pressure of 18.5 bar·g) during ethylene cargo cooling. This means that after completing the discussed process, no cargo loss occurred. The pressures on the compressor discharge of all three cascade systems are presented in Table 5.

Table 5. Pressures during the second stage of compressor discharge of all three cascade systems on m/v Neptune

Date of measurements	Pressure of the compressor discharge [bar·g]		
	No. 1	No. 2	No. 3
22.06.2018			16.5
23.06.2018		17.8	17.2
24.06.2018		15.8	15.9
25.06.2018	15.8		15.9
26.06.2018	17.3	17.3	14.5

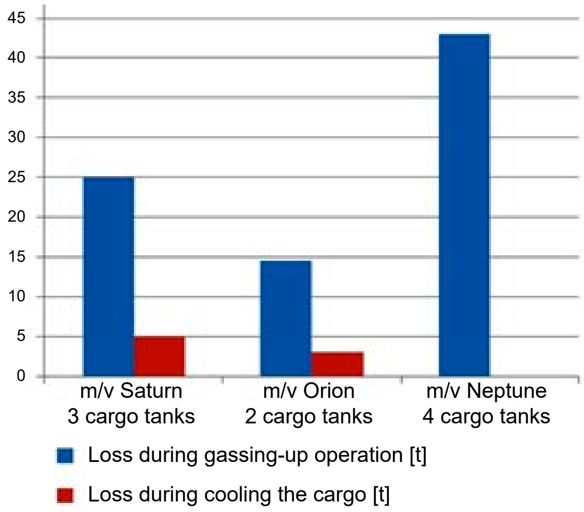


Figure 2. Comparison of ethylene cargo loss during gassing-up

A comparison of ethylene loss on m/v Saturn, m/v Orion, and m/v Neptune is shown in Figure 2. After completing the gassing-up operation of the first cascade's cargo tanks, i.e. Tank 2 and Tank 4, sub-zero temperatures were measured in whole tanks (at all three levels of the tank – top, middle, bottom).

Conclusions

Here, we have elaborated guidelines for the gassing-up operation on m/v Neptune to carry out the whole process in a more efficient manner. During the experiment, ethylene loss was decreased, and there was no loss during ethylene cargo cooling – no cargo compressor stopped working because of excessively high pressure on the second stage of discharge. This provides an appropriate direction for the analysis of a gassing-up process that will allow further testing to determine the optimal way to complete the operation.

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