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An experimental gassing-up operation on an ethylene carrier using two cascades with two tanks each

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Abstract
Ethylene is one of the basic raw materials of the petrochemical industry that is used to produce plastics. One of the largest producers of this compound is the USA, and a substantial increase in the demand for ethylene has also been recently observed in the Middle East, the Far East, and China. This requires the transport of this cargo by sea. Ethylene carriers are a type of LPG ships and are equipped with a cascade cycle that uses propylene or refrigerant R404A as a coolant medium. These vessels have been designed to withstand the minimum temperature of ethylene of –104°C for fully-cooled cargo. A mixture of ethylene and air (from concentrations of 2.75–2.6%) becomes explosive during heating under elevated pressures. Hence, it is necessary to form an inert atmosphere in the tanks using mostly nitrogen before the ethylene cargo is loaded. The process of aerating, inerting, gassing-up, and cooling cargo tanks and cargo is constantly repeated during the operation of LPG carriers. Due to the large amounts of ethylene lost during gassing-up, which results in significant financial losses and disruptions in cargo compressors during the cooling of the tanks and cargo, this operation is the most problematic of all. In this article, a solution is proposed for performing the gassing-up procedure which prevents excessive ethylene loss.

Introduction

Gas carriers are one of the most advanced types of ships and are equipped with the latest ocean engineering and material engineering technologies (Wieczorek & Giernalczyk, 2018). Liquefied petroleum gas (LPG) carriers are used to transport liquefied gases. Depending on the temperature and pressure at which individual cargo should be transported, gas carriers can be divided into three groups: fully-refrigerated ships that carry cargo at ambient temperature, semi-pressurised vessels, and atmospheric pressure ships carrying cargo at atmospheric pressure, which transport cargo at temperatures down to –104°C (slightly below the boiling point of ethylene at atmospheric pressure) (McGuire and White, 2000).

Ethylene vessels are most often equipped with C-type pressure tanks made of steel that are resistant to low temperatures, which may cause material cracks. They have been designed to withstand operating pressures up to 5.4 barg (Gauge pressure) (McGuire and White, 2000; NGC, 2002). The most common cargo tanks used on semi-pressurised vessels carrying ethylene are bilobe tanks (SIGTTO, 2016).

Ethylene carriers are equipped with a cascade reliquefaction plant which consists of two cycles: open and closed. The open cycle uses the cargo as a refrigerant and cools the cargo in tanks, while the closed cycle uses propylene (R1270) or R404A as a refrigerant. The cascade part enables the full condensation of ethylene, ethane, and commercial propane. The ethylene cooling cycle is adapted to ensure the condensation of ethylene, ethane, and commercial propane. Achieving the correct condensation temperature is possible due to the ethylene condenser in the cascade reliquefaction system, which includes a screw compressor, propylene tank (R1270), and a seawater cooled propylene condenser (Włodarski, 1993; McGuire and White, 2000; NGC, 2002).

Gassing-up operation

None of the gases typically used as inert gases on ships, such as nitrogen or carbon dioxide, can be liquefied by the ship's reliquefaction system because the liquefaction temperatures of nitrogen and carbon dioxide are below the critical liquefaction temperature of ethylene (Nanowski, 2016). This makes it necessary to thoroughly remove inert gases from the cargo tank before loading cargo (Włodarski, 1993; PRS, 2001). This is possible due to the gassing-up of cargo tanks using the cargo vapor (coolant) to be loaded at ambient temperature (NGC, 2002). The removal of nitrogen from the cycle enables efficient operation of the reliquefaction system because nitrogen and ethylene form a mixture with a lower condensation temperature, which causes an emergency stop of the cargo compressors due to excessive condensing pressure (Nanowski, 2016; Wieczorek, 2018; Wieczorek & Giernalczyk, 2018).

To reduce the consumption of vapours intended to gas-up the tanks, strict procedures must be followed. If the density of the cargo vapours is higher than the atmosphere in the tank (filled with an inert gas), it may be introduced through the cargo pipeline at the bottom of the tank. When comparing the densities of both gases, they must be determined at the same temperature. Conversely, if the cargo vapors are less-dense than the atmosphere in the tank, the upper cargo pipeline must be used. In practice, inerting is carried out at ambient temperature, i.e. between 0°C and 40°C for about 30 hours (as marine practice shows). This process generates a safe atmosphere in the tank for loading cargo (McGuire and White, 2000; SIGTTO, 2016; Wieczorek, 2017). The process of gassing-up cargo tanks with ethylene is as follows: ethylene condensate at about –94°C is directed from the deck tank (onboard) to the ethylene evaporator, which consists of two heat exchangers. In the higher heat exchanger, ethylene evaporates in the pipes which flow the propylene refrigerant. In the lower heat exchanger, it evaporates with the assistance of seawater. The ethylene vapour temperature at the evaporator outlet is around –50°C. Ethylene vapours are fed into the tank in-cascade or in-parallel via the lower cargo pipeline (Wieczorek, 2017; 2018; Wieczorek & Giernalczyk, 2018).

Experimental assumptions

The gassing-up of experimental tanks on an ethylene carrier was carried out for the second time on m/v Neptune. All four tanks were subjected to the process. The Master was asked to create two separate cascade systems, with two tanks each to optimize the gassing-up operation and to increase the accuracy of the work of cargo compressors during tank cooling and ethylene cargo. Before connecting the second tank of the cascade, nitrogen was removed from the atmosphere and hydrocarbons were measured at the top. This step is important because the vapour was directed to another tank of a cascade from the top. Upon completing the gassing-up of the first tanks of the cascades, it is also recommended to directly connect the cold vapour to the second cascade tank. The tank pressures should not exceed about 0.2 barg (Gauge pressure). The Master was also asked to maintain a mass flow of ethylene between 1–1.5 t/h.

Gassing-up operation on m/v Navigator Neptune

All tanks were subjected to a gassing-up process according to the aforementioned requirements. The results of the gassing-up experiment on m/v Neptune, including the hydrocarbon concentration, temperatures, and pressures in tanks are presented in Tables 1 and 2.

Cascade of tanks No. 3 to No. 1

The pressure in cargo tanks connected in a cascade gradually increases, not higher than 0.01–0.02 barg per hour, reaching a maximum value of 0.25 barg (Figure 1). The pressure difference in tanks between the start of the process and its completion is about 0.15 barg.

The first tank (No. 3) was gassed-up in 19 hours, and the second one 21 hours. Cold ethylene vapour was introduced into the second cascade tank for the last 3 hours. During the first 10 hours of gassing-up

Table 1. Concentration of hydrocarbons in gassed-up tanks

Date	Time	Tank 1 – HC %Vol.						Tank 2 – HC %Vol.						Tank 3 – HC %Vol.						Tank 4 – HC %Vol.					
		Port			Stbd			Port			Stbd			Port			Stbd			Port			Stbd		
		Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot
08.11.	09:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	12:30	7	8	12	8	9	15	0	0	0	0	0	0	39	63	100	43	51	100	0	0	0	0	0	0
	15:30	26	27	29	28	29	30	0	0	0	0	0	0	62	70	100	59	64	100	0	0	0	0	0	0
	18:30	43	46	48	46	48	52	0	0	0	0	0	0	81	95	100	76	85	100	0	0	0	0	0	0
	21:30	67	69	69	70	71	72	0	0	0	0	0	0	94	100	100	90	95	100	0	0	0	0	0	0
09.11.	00:30	80	85	100	83	89	100	0	0	0	0	0	0	96	100	100	95	98	100	0	0	0	0	0	0
	03:30	92	94	100	90	95	100	0	0	0	0	0	0	99	100	100	98	100	100	0	0	0	0	0	0
	06:30	98	100	100	97	100	100	0	0	0	0	0	0	100	100	100	100	100	100	0	0	0	0	0	0
	09:30	100	100	100	100	100	100	1	1	4	2	3	7	100	100	100	100	100	100	27	30	95	21	21	90
	12:30	100	100	100	100	100	100	12	12	18	13	13	18	100	100	100	100	100	100	51	56	100	47	49	100
	15:30	100	100	100	100	100	100	30	31	38	31	31	38	100	100	100	100	100	100	67	71	100	66	70	100
	18:30	100	100	100	100	100	100	39	39	47	38	39	47	100	100	100	100	100	100	76	79	100	79	81	100
	21:30	100	100	100	100	100	100	52	52	62	52	52	62	100	100	100	100	100	100	86	92	100	87	92	100
10.11.	00:30	100	100	100	100	100	100	70	70	74	70	70	74	100	100	100	100	100	100	92	95	100	92	95	100
	03:00	100	100	100	100	100	100	79	79	81	79	79	81	100	100	100	100	100	100	96	97	100	96	97	100
	06:30	100	100	100	100	100	100	82	82	84	82	82	84	100	100	100	100	100	100	96	98	100	96	98	100
	09:30	100	100	100	100	100	100	83	83	85	83	83	85	100	100	100	100	100	100	97	98	100	97	98	100
	12:30	100	100	100	100	100	100	83	84	85	83	84	85	100	100	100	100	100	100	99	100	100	98	100	100
	15:30	100	100	100	100	100	100	86	86	88	86	87	88	100	100	100	100	100	100	100	100	100	100	100	100
	18:30	100	100	100	100	100	100	93	93	98	93	94	98	100	100	100	100	100	100	100	100	100	100	100	100
11.11.	04:00	100	100	100	100	100	100	98	99	100	99	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	08:00	100	100	100	100	100	100	99	99	100	99	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 2. Temperatures and pressures in gassed-up tanks

Date	Time	Tank 1 – HC %Vol.							Tank 2 – HC %Vol.							Tank 3 – HC %Vol.							Tank 4 – HC %Vol.						
		Port			Press [bar g]	Stbd			Port			Press [bar g]	Stbd			Port			Press [bar g]	Stbd			Port			Press [bar g]	Stbd		
		Top	Mid	Bot		Top	Mid	Bot	Top	Mid	Bot		Top	Mid	Bot	Top	Mid	Bot		Top	Mid	Bot	Top	Mid	Bot		Top	Mid	Bot
08.11.	09:30	20	19	19	0.02	20	20	19	19	18	18	0.05	19	18	18	19	18	18	0.03	19	18	18	20	19	18	0.05	20	19	18
	12:30	20	19	19	0.06	19	19	19	19	18	18	0.05	19	18	18	20	17	–24	0.09	19	17	–27	20	19	18	0.05	20	19	18
	15:30	19	20	19	0.07	20	19	19	19	18	18	0.05	19	18	18	17	14	–57	0.11	17	14	–58	20	19	18	0.05	20	19	18
	18:30	20	19	19	0.11	20	20	20	19	18	18	0.05	19	18	18	15	11	–87	0.13	15	11	–87	20	19	18	0.05	20	19	18
	21:30	19	19	19	0.13	19	19	19	19	18	18	0.05	19	18	18	13	6	–100	0.16	12	7	–100	20	19	18	0.05	20	19	18
09.11.	00:30	19	18	–10	0.18	19	18	–13	19	18	18	0.05	19	18	18	12	4	–100	0.19	11	4	–100	20	19	18	0.04	20	19	18
	03:30	18	16	–43	0.2	18	16	–46	20	18	18	0.05	19	18	18	12	2	–100	0.24	12	2	–100	20	19	18	0.04	20	19	18
	06:30	17	14	–75	0.22	16	13	–80	20	18	18	0.05	20	19	18	11	–1	–99	0.27	10	0	–100	20	19	18	0.03	20	19	19
	09:30	17	12	–74	0.25	17	12	–97	20	19	19	0.1	20	19	19	13	–2	–98	0.38	12	–2	–98	20	19	–5	0.14	20	19	3
	12:30	17	10	–72	0.27	16	9	–99	20	19	19	0.14	20	19	19	–1	–15	–99	0.28	–2	–16	–99	19	16	–33	0.17	18	17	–28
	15:30	3	–10	–48	0.3	3	–10	–98	20	18	19	0.17	20	19	19	–1	–16	–99	0.29	0	–16	–99	18	14	–63	0.18	17	15	–60
	18:30	–8	–19	–54	0.28	–4	–16	–99	21	19	19	0.18	21	19	19	0	–17	–99	0.29	0	–17	–99	18	13	–76	0.22	18	13	–76
	21:30	–4	–18	–69	0.21	–2	–14	–99	20	19	19	0.23	20	20	19	–11	–27	–100	0.22	–11	–26	–100	16	11	–70	0.28	16	11	–72
10.11.	00:30	–3	–17	–70	0.08	–2	–15	–101	20	19	20	0.26	20	20	19	–20	–35	–102	0.1	–19	–34	–102	16	10	–56	0.31	16	10	–63
	03:00	–5	–19	–63	0.04	–5	–18	–99	19	18	18	0.08	20	19	18	–12	–32	–103	0.05	–13	–31	–103	15	8	–53	0.26	15	8	–60
	06:30	1	–18	–61	0.16	–1	–17	–97	20	18	19	0.08	20	19	19	–2	–30	–101	0.15	–3	–30	–101	17	7	–56	0.34	16	8	–58
	09:30	5	–17	–59	0.25	3	–16	–93	20	19	19	0.06	20	19	19	–1	–29	–100	0.27	–3	–28	–100	14	5	–67	0.28	13	5	–72
	12:30	–9	–22	–65	0.29	–7	–22	–92	21	19	20	0.2	21	20	20	–8	–29	–99	0.3	–9	–28	–99	14	4	–79	0.3	13	4	–82
	15:30	–14	–23	–86	0.28	–10	–25	–94	21	19	19	0.14	21	20	19	–11	–29	–99	0.3	–11	–28	–99	14	3	–76	0.28	13	3	–79
	18:30	–9	23	–83	0.25	–7	–24	90	20	18	–2	0.2	21	18	–2	–11	–31	–99	0.28	–11	–29	–99	0	–13	–56	0.27	3	–10	–59
11.11.	04:00	–19	–31	–82	0.17	–18	–30	–88	18	14	–39	0.34	19	14	–62	–32	–50	–93	0.19	–28	–45	–101	–12	–33	–54	0.18	–8	–28	–58
	08:00	–25	–37	–94	0.07	–22	–31	–92	16	11	–52	0.31	17	12	–57	–28	–47	–98	0.09	–27	–44	–102	–13	–31	–50	0.08	–9	–28	–54

the first cascade cargo tank, a 90% hydrocarbon content was achieved, and it took about 9 hours to remove the remaining 10% of nitrogen. In the second cascade cargo tank (No. 1), it took about 6 hours to remove the remaining 10% nitrogen. At the end of the gassing-up process for tanks No. 3 and No. 1, a temperature of –99°C was measured at the bottom.

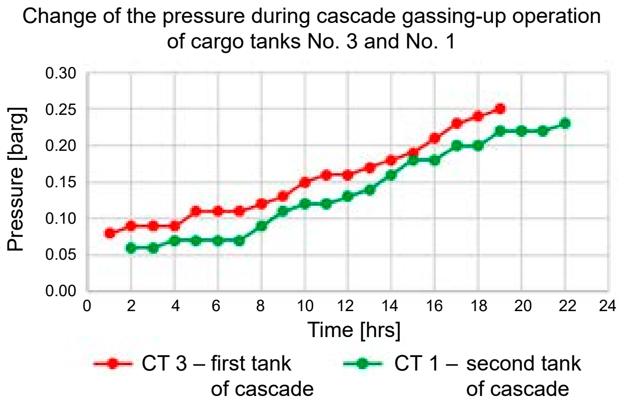

Figure 1. Pressure change in gassed-up tanks No. 1 and No. 3

Cascade of tanks No. 4 to No. 2

Tank pressures varied between 0.08 and 0.038 barg (Figure 2). The gassing-up process of the first cascade cargo tank (No. 4) with ethylene vapour lasted 32 hours, while the gassing-up of the second cascade cargo tank (No. 2) took almost 40 hours. At the start of gassing-up of the first cascade cargo tank, high hydrocarbon contents were measured: 19% on the top, 21% in the middle, and 90% in the bottom of the tank. During the middle of the process of gassing-up tank No. 4, the value fluctuated close to 90%. After completing the gassing-up process of tanks No. 4 and No. 2, the temperature reached –98°C at the bottom.

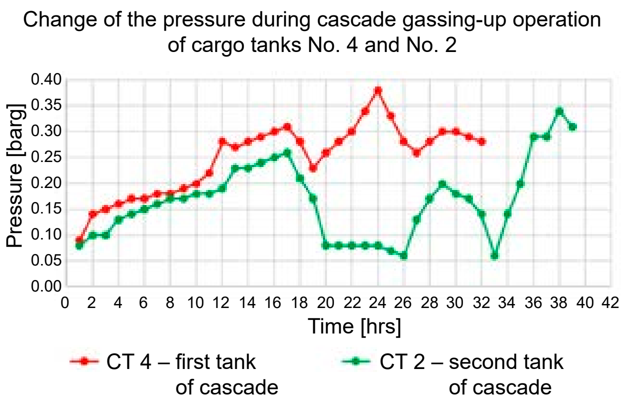

Figure 2. Pressure change in gassed-up tanks No. 2 and No. 4

Discussion

Ethylene loss during the gassing-up of all four cargo tanks on the m/v Neptune amounted to a total of 43 tons. No additional, excessive cargo loss occurred after gassing-up or during tank cool-down, indicating that the cargo compressors worked as intended.

Due to the pressure differences in tanks and the time of both cascades, it was not possible to estimate the exact flow rate of individual cascades. The average mass flow rate during the gassing-up of all four tanks was about 0.2 kg/s. Based on the pressure values in tanks, the mass flow in the cargo tanks cascade from No. 3 to No. 1 displayed a linear increase, which significantly shortened the time necessary to carry out the process. Pressure fluctuations in cargo tanks make it difficult to properly carry out the gassing-up operation. A small pressure difference between the start of the gassing-up process and its completion also significantly affected the time required to complete the gassing-up operation. Temperatures of –100°C measured at the bottom of the tanks indicated no vaporization occurred during the gassing-up operation. The most laborious part of the operation involved the removal of the remaining 5% of nitrogen from the cargo tanks.

Conclusions

The experimental gassing-up of cargo tanks with cargo vapor on ethylene carriers has shown that in order to minimize cargo loss, shorten the time of operation, decrease turbulence between ethylene and nitrogen, and increase its stratification, the process should be carried out in a cascade of no more than two cargo tanks. A cascade must be created at the moment at which hydrocarbons appear at the top of the tank, and the nitrogen in the first tank of a cascade should be removed to the atmosphere until then. After gassing-up the first cascade tank, i.e. after reaching 100% hydrocarbons in the tank, cold ethylene vapors should be directly injected into the second tank, and the cooling-down of the cargo tanks of the first cascade tank should begin.

Tank pressures should not exceed 0.2 barg and should be kept constant. The pressure in the first cascade tank should be as low as possible. If it is not possible to maintain a constant tank pressure, the pressure should increase linearly. A small differential pressure between the first and second cascade tanks should be maintained (max 0.03 barg).

In addition, the method of gassing-up cargo tanks with liquid ethylene that has previously been used must be replaced because it is incompatible with the procedures and instructions created. Liquid ethylene temperatures on the order of –104°C threaten the safe operation of the ship, by possibly contributing to the cracking of the bottom of tanks due to excessive thermal stress.

Performing the gassing-up operation on an ethylene carrier following the above guidelines shortens the gassing-up time and eliminates additional cargo loss during the cooling of cargo tanks due to incorrect operation of the cargo compressors. The presence of nitrogen exceeds the allowable operating pressure of the compressors, i.e. 18.5 barg, which requires opening the condenser valves and removing the ethylene and nitrogen mixture into the atmosphere which results in large financial losses.

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