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Short communication

Boil-off gas balanced method of cool down for liquefied natural gas tanks at sea

Maksym Kulitsa[1], David A.Wood[2]*

[1]*Independent FSRU Operations Consultant Odessa, Ukraine*

[2]*DWA Energy Limited, Lincoln, United Kingdom*

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Abstract:
Cooling down the cargo tanks of liquefied natural gas carriers (LNGC) prior to the ships arrival at discharge and loading ports follow various widely adopted operating procedures. The tank cool-down procedures typically followed cannot though be considered as best practice, because they consume considerable boil-off gas while reducing tank temperatures. An alternative tested method, described here, consumes considerably less liquefied natural gas (LNG) during the tank cool-down process, which is beneficial, particularly during the ballast voyages. In certain circumstances, LNGC consume liquid marine fuels so that they are able to preserve enough LNG heel to complete tank cool down at sea to required low temperatures before reloading can be commenced. The novel method devised for cooling down LNGC, particularly those fitted with membrane cargo tanks, at sea prior to arrival at a loading terminal involves much lower LNG heel consumption than conventional methods. The boil-off gas (BOG)-balanced tank-cool-down method applies continuous spraying, at very low rates, of the tanks with LNG extracted from the heel. This procedure enables the ship's engines to consume all excess BOG without the need to pass some of it as waste for combustion in the gas combustion unit or steam dump. It also ensures that the LNG cargo tanks are maintained at stable and constant pressure and reduces the coolant LNG quantity consumed. The BOG-balanced tank-cool-down is straightforward to implement and monitor, simplifying tank pressure control. Test results demonstrate that tank cool-down rates of 4 to 5 °C/per hour can be maintained such that tank temperatures can be reduced from +30 to -130 °C within 37 hours. The method could work on LNGC with Moss-type tanks but is likely to be less effective as they are typically fitted with fewer tank spraying nozzles.

1. Introduction

Today's tendency in LNG transport over sea is to minimize fuel spent and to maximize cargo delivered to discharge ports with minimum environmental impact. In recent years new technology has made significant advances in reducing engine fuel consumption, compared to the decades when the LNG shipping fleet consisted only of steam-powered ships. The past decade or so has seen the introduction of dual-fuel diesel electric (DFDE), and M-type electronically controlled gas injection (ME-GI) and other fuel-efficient marine engines on LNG carriers (LNGC), as well as improved LNG cargo tank designs. However, the requirements to efficiently control and handle boil off gas (BOG) is a common feature to all LNGC (Mokhatab et al., 2014).

Total voyage consumption of LNG is not only dependent on engine efficiency, it is influenced by other inherent operations during the voyage. Reducing the LNG heel required for tank cool down prior to arrival at a loading port leads to an overall reduction in LNG spent during a voyage. During cooling down at sea, excess of BOG is consumed in the gas combustion unit (GCU) on DFDE or steam dump (SD) on steam vessels. Such consumption provides no commercial benefit from that BOG and leads to atmospheric emissions. Thus, minimizing this consumption directly increases the overall commercial and environmental performance of an LNGC.

The mandatory Ship Energy Efficiency Management Plan (SEEMP) (MEPC, 2016), EU MRV (EU Monitoring, Reporting and Verification of CO_2; data collection became mandatory

*Corresponding author.
E-mail address: maksymkulitsa@gmail.com (M. Kulitsa); dw@dwasolutions.com (D.A. Wood).

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1 Jan 2018) and IMO DCS (IMO Data Collection System on fuel consumption; data collection became mandatory 1 Jan 2019) (ICS-Shipping, 2015; DNV-GL, 2019) all focus on fuel and emissions reduction. Under the requirements of the SEEMP there is a substantial opportunity to benefit from more efficient operational practices tailored to modern LNGC designs, in parallel with developing more efficient engine designs. Although, the reliquefication of BOG is technically feasible on LNGC (Shin and Lee, 2009; Li et al., 2012; Choi, 2018), few vessels are fitted with such facilities and therefore require proactive BOG management.

Tank pressure behaviour in marine LNG tanks is complex (Kulitsa and Wood, 2020), being influenced by many variables including the temperature and composition of the LNG cargo, and requires careful management (Pellegrini et al., 2014; Migliore et al., 2015; Wood and Kulitsa, 2018a). Changes in the composition, due to weathering effects of the LNG cargo over the timescale of single LNGC voyages, further complicate by evolving conditions in LNG cargo tanks (Wood and Kulitsa, 2018b) and the conditions of the insulation space (Cao et al., 2018). This makes prediction and modelling of BOG rates in LNGC for cargo management purposes challenging (Glomski and Michalski, 2011; Dobrata et al., 2013; Grotle and Esoy, 2018).

Procedures to cool down LNGC cargo tanks prior to arrival at discharge ports are in common use. However, the traditionally accepted method to conduct tank cool down cannot be considered as best practice, because an alternative method consumes less LNG for tank cool down. Additionally, sometimes there are situations where liquid marine fuels need to be consumed in order to preserve enough LNG heel for tank cool down at sea. This occurs if insufficient heel cargo is available due to excess fuel consumption on the ballast voyage due to delays or bad weather. The cost of marine diesel for engine fuel is much higher (e.g., ~US$700/tonne at the beginning of quarter 1, 2020) than BOG, and results in more atmospheric emissions.

A novel method is described for cooling down the LNGC membrane cargo tanks at sea prior to arrival at a loading terminal that requires minimum LNG heel consumption. The method described can also work in Moss-type, spherical rigid LNG tanks but tends to be less effective.

2. Cool-down issues for LNG cargo tanks prior to reloading

LNGC cargo tanks are routinely cooled down at sea shortly prior to arrival at a loading terminal. The typical scheme used for membrane LNG tanks is intermittent spraying twice a day (morning and evening) for three days prior to arrival at the loading terminal. The LNG quantity used for cooling down LNGC tanks at sea ranges from 800 to 1600 m^3 LNG. That typically involves three warm tanks and one semi-cold LNG heel tank being cooled down at sea. The energy consumption and related LNG heel used to achieve that cool down, directly influences an LNGC's commercial performance. The more energy required for tank cool down, the more heel cargo that has to be retained for the ballast voyage and the less commercial LNG cargo the vessel is able to deliver in the previous laden voyage. This traditionally used method for tank cool down at sea is convenient but is wasteful and not the optimal way to achieve it. Additionally, in rare cases, the marine diesel consumed in the engine for the sake of preserving enough LNG heel for tank cool down, is a further commercial disadvantage.

A common tank-cooling method applies a high-spraying regime for limited period of time. This increases the tank pressure to about 65%-70% of maximum allowable relieve valve setting (MARVS), which is 250 millibars (mbarg) for the tank. At that point spraying is discontinued to allow time to dispose of all the generated BOG into the LNGC/s engines and/or to the GCU or SD. Many operators do not introduce any LNG, even a small amount, into the tanks after the cooling-down is completed. This cooling-down schedule leads to high LNG heel consumption. The BOG extracted is involved not only in cooling down the tanks (Table 1). It is also used to cool down the LNG heel itself and re-cooling the tanks, which are warming up between spray sessions. The BOG quantity required for cooling the LNG heel prior to the next tank spraying session is not large but contributes to extra consumption. The extra LNG consumed (wasted) in repeatedly reheating tanks between spray sessions and can amount to 300-400 m^3 LNG. That constitutes between 30% and 50% of all the LNG consumed at sea during the traditional cool-down regime.

The minimum LNG quantity required by the design case cool-down tables for cooling down alongside the terminal jetty is achieved by continuous spraying for 10 to 15 hours, depending on the type of membrane tanks. LNG consumption at sea usually is double that quantity using the intermittent cooldown method (Fig. 1).

An additional issue with the traditional tank cool-down method is that sometimes ships' operators unintentionally permit higher tank cool-down rates than are actually stated in the cool-down tables certified for their vessels. This is not good practice for the tank structure due to the excessive thermal stress it potentially suffers (particularly the pump tower within the tank).

Also, there is no widely accepted standard way to calculate the quantity of LNG heel required for tank cool down at sea for ballast voyages. Approaches to this vary from operator to operator and a ship's specific features. Such calculations should be performed with reference to the cool-down tables issued by the tank manufacturer. These facilitate the correct estimation of LNG consumption based on higher heating value (HHV) of the actual LNG cargo transported relative to the cool-down table's HHV.

In cases where the LNG heel is calculated simplistically, it may result in an LNGC arriving at a loading terminal with a substantial quantity of LNG heel remaining on board (e.g., up to 0.6%-1.0% of total cargo capacity). Consequently, less LNG can be loaded for onward transport. In some rare cases, insufficient heel may result in an LNGC being unable to sufficiently cool down its tanks and this may lead to rejection of that ship by the loading terminal, or necessary to burn expensive fuel oil in order to preserve enough heel for tank

Table 1. Record of rates of LNG tank reheating between spraying sessions during the commonly applied 3-day cool down schedule. Heating of LNGC tanks is broadly linear occurring at a rate +35 to +55 °C per 24 hrs.

LNG reheating rates in LNGC tanks between spraying sessions							
LNG tank NBOR = 0.15%/day				LNG tank NBOR = 0.10%/day			
LNG temperature range (°C)		Approximaite heating rate (°C/hour)	Approximaite heating rate (°C/24 hours)	LNG temperature range (°C)		Approximaite heating rate (°C/hour)	Approximaite heating rate (°C/24 hours)
Low	-20	1.5	36.4				
High	-5						
Low	-40	1.5	35.9	Low	-40	1.9	45.0
High	-20			High	-25		
Low	-70	2.0	47.5	Low	-70	2.3	54.5
High	-50			High	-45		
Low	-95	2.1	51.1	Low	-90	2.3	55.4
High	-75			High	-75		
Low	-110	2.1	49.9	Low	-112	2.0	48.0
High	-85			High	-90		
Low	-130	2.1	50.4	Low	-130	1.7	40.5
High	-110			High	-116		

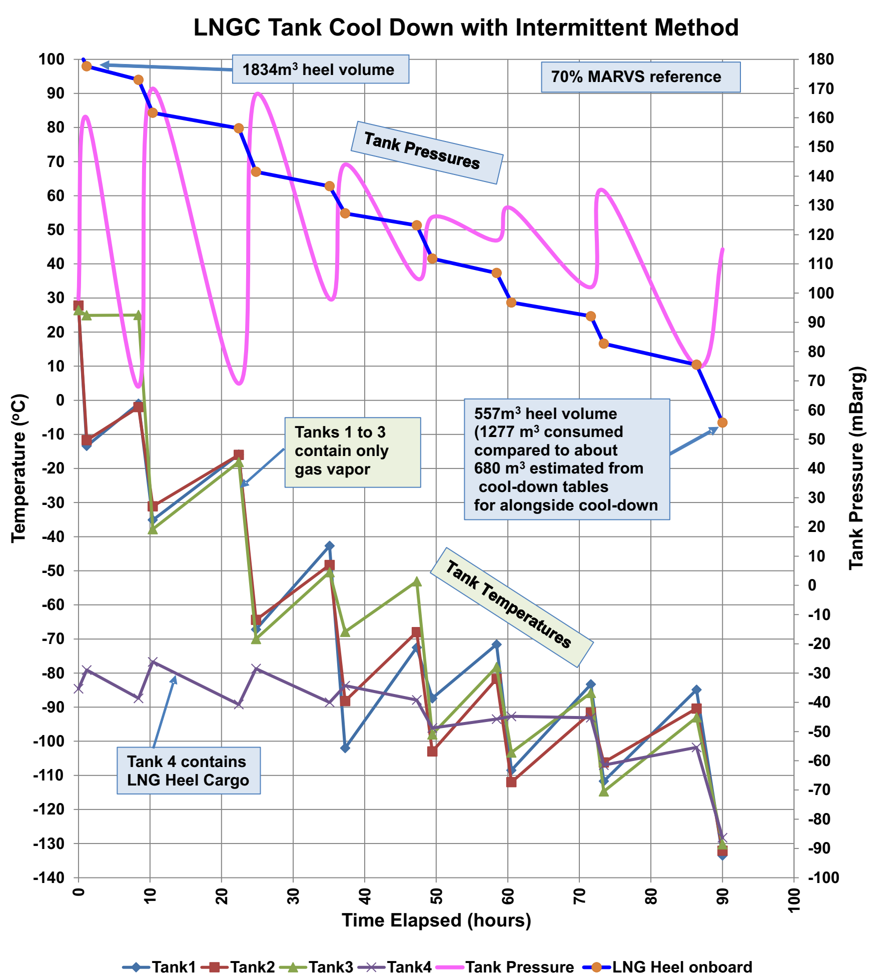


Fig. 1. Record of commonly applied LNGC tank 92 hours cooling down conducted at sea. Calculations using cool-down table estimates require 680 m^3 of LNG to be evaporated.

Table 2. Details of tank spraying capabilities on a typical DFDE LNGC vessel of 160,000 m^3 capacity based on the number of nozzles in the spray coil and the nozzle performance curve on Fig. 2.

LNGC tank spraying capacities versus nozzle pressure									
Pressure at nozzle	Barg	0.3	0.4	0.5	1.0	1.5	2.0	3.0	6.0
Flow at nozzle	ltr/min	6.1	7.4	8.1	11.4	14.0	16.1	19.7	28.0
	m^3/h	0.37	0.45	0.49	0.68	0.84	0.97	1.18	1.68
LNG sprayed in single tank (#2, #3 or #4) (single spray coil with 24 nozzles)	m^3/h	8.81	10.71	11.66	16.42	20.16	23.18	28.37	40.32
LNG sprayed in single tank (#1) (single spray coil with 15 nozzles)	m^3/h	5.51	6.70	7.29	10.26	12.60	14.49	17.73	25.20
Continuous LNG spraying in all tanks (except heel tank #3) (spray in tanks: #1 #2 & #4)	m^3/h	23.13	28.12	30.62	43.09	52.92	60.86	74.47	105.84
	ton/h	10.18	12.37	13.47	18.96	23.28	26.78	32.77	46.57
Continuous LNG spraying in two tanks at a time (2 by 2) (spray capacity assuming two large tanks)	m^3/h	17.63	21.43	23.33	32.83	40.32	46.37	56.74	80.64
	ton/h	7.76	9.43	10.26	14.45	17.74	20.40	24.96	35.48

cool down. These cases both impair an LNGC's commercial performance at the expense of their charterers.

It is not possible to achieve the "alongside-jetty" cool-down LNG consumption quantity at sea. However, a novel BOG-balanced method is proposed to conduct tank cool-down at sea with LNG consumption close it.

3. New efficient method to cool down LNGC cargo tanks at sea

A novel method for at-sea tank cool down exploits the ability to burn a certain amount of BOG generated during cooldown in the LNGC's engine, GCU or SD, without venting while conducting continuous tank spraying at slow rates. Ballast LNGC voyages typically follow two operating patterns as they approach the loading terminal: 1) vessel moves at high speed during the cool-down regime; and, 2) vessel has to cool down at anchor or at slow speeds. The LNGC's propulsion system, and the capacity of its GCU or SD define the BOG quantity that an LNGC is capable of handling per hour and per day. The BOG-balanced method of tank cool down involves continuous spraying of LNG in the tanks at such slow rates that the engine and/or GCU/SD will burn all BOG excess immediately. This causes the tank pressure to remain approximately constant.

The BOG-balanced method is easy to calculate based on the tank manufacturers cool-down tables. The cooling energy stated in MMBTU units in the cool-down tables is divided by HHV (in MMBTU) of the actual LNG heel. This ratio determines the quantity of the specific LNG that needs to be evaporated in order to lower the tank temperatures from their prevailing temperature to a specified "ready to load" temperature. For Gaztransport and Technigaz (GTT) tanks that is minus 130 °C determined as the average of the temperatures recorded in accordance with cooling-down tables.

Knowing the total LNG required to cool the three warm cargo tanks and the semi-cold heel tank and knowing the expected total possible gas consumption by engine and GCU/SD for specific voyage conditions, the time needed for tank cool down can be estimated. Specifically, to derive the tank cool-down time required, the quantity of LNG consumed to achieve "cold temperature" (minus extra accumulated vapor in tank due vapor shrinkage) is divided by the available BOG handling capacity rate at sea. This varies depending on voyage conditions. A uniform LNG tank cool-down rate can then be applied continuously for that time period for all tanks. That rate will be substantially lower and safer (avoiding potential tank damage) than a more rapid cool-down rate.

For example, to cool an LNGC's tanks down from +30 to -130 °C (using cool-down tables) 680 m^3 of LNG (i.e., 306 tons of LNG to evaporate) is required for cool down. Some vapor will accumulate in the tanks at a colder state. Therefore, the difference in total mass of vapor in the tanks, before and after cool down, will be about 123 tons (about 278 m^3) for an LNGC of 160,000 m^3 capacity. Thus, only 183 tons of BOG needs to be evacuated from the tanks. The time required for balanced tank cool down at a total BOG consumption of 5 t/h would require about 37 hours to complete. Continuous spraying at an average total rate of 18.5 m^3/h LNG would be required. Continuous spraying would therefore begin 37 hours before the loading terminal pilot arrives on board. From spray-nozzle performance curves (Table 2), it is also necessary to establish a spray pressure at the nozzles such that in total they spray continuously at 18.5 m^3/h LNG. This maintains a balance between the LNG sprayed in the tanks and excess BOG extracted from the tanks. Table 2 indicates spraying pressures required when cooling a 0.25 barg for three spray coils and 0.33 barg for two by two spray-coil configurations (two tanks sprayed alternately). The number of LNG spray nozzles and their spraying capacity should be taken into account when defining the spray pressure in each tank (Fig. 2).

The cooling progress is easy to monitor and control during BOG-balanced method as the cool-down rate can be controlled at 4-5 °C/per hour in order for tank temperature to descend from +30 to -130 °C within 37 hours (compare Fig. 3 and Fig.

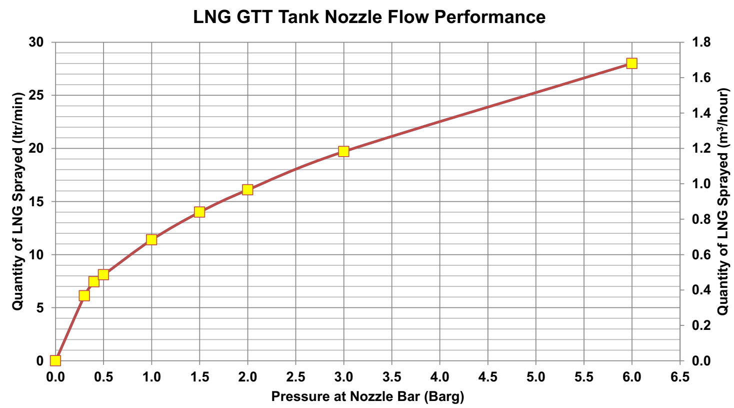
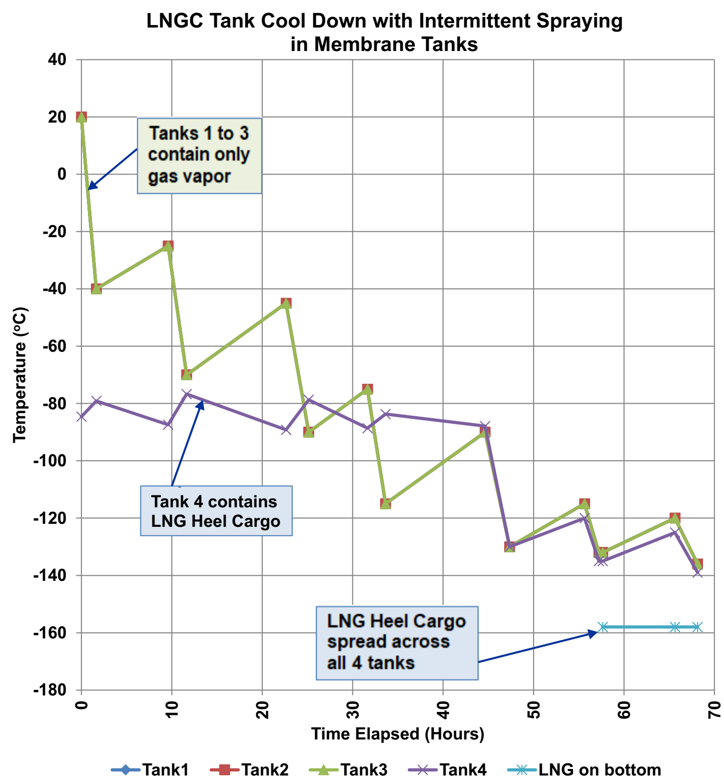
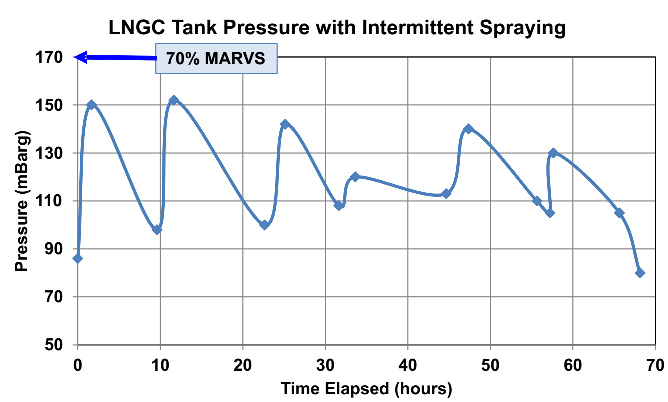


Fig. 2. Typical performance curve of LNG spray nozzles used in GTT tanks. Data from nozzle manufacturer.



(a)



(b)

Fig. 3. Typical record trends of tank (a) temperature and (b) pressure for the traditional three days of intermittent at sea cool down for membrane tanks.

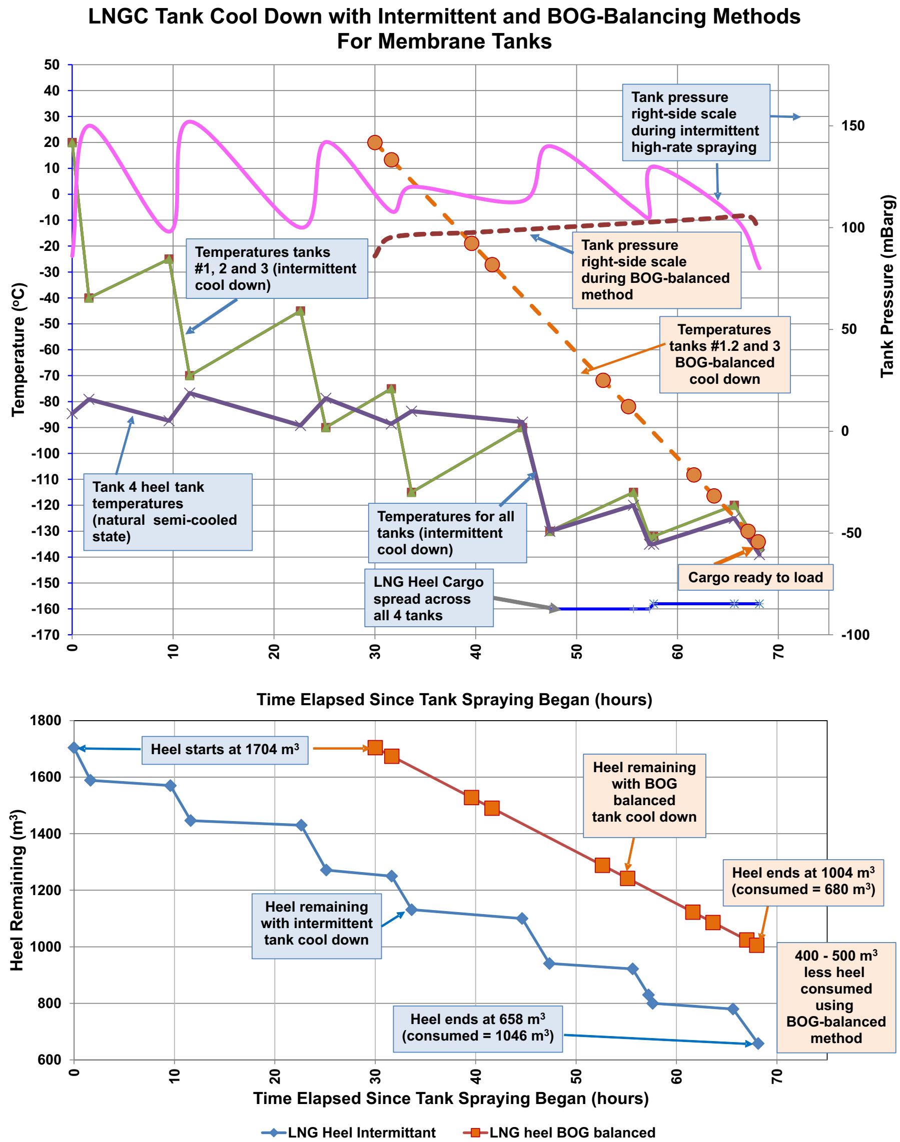


Fig. 4. Schedule comparison of traditional (intermittent) three days at sea tank cool-down method compared with the BOG-balanced method of continuous tank cool down at sea.

4).

Some additional adjustments need to be made to the cool-down LNG required. The exact LNG quantity needed for tank cool down should take into account a small margin of spare capacity in case of vessel delays and the requirement for an extended cooling period (i.e., more than 37 hours in the example described). It should also be adjusted to account for some excess natural heat ingress into the tanks and loading pipework during the cooling period. Some additional time also needs to be allocated for the LNG heel to be transferred into each of the cooled tanks after cooling-down, if necessary. Typically, accurate tank gauging radar will require at least 6 to 10 cm of LNG level on even keel conditions in each tank. A more accurate minimum LNG quantity needed for tank cool down at sea can be estimated taking into account the adjustments mentioned.

The BOG-balanced method plans to achieve ready-for-loading tank temperature conditions for the moment of arrival at the loading terminal (i.e., about one hour prior to, or at the start of, berthing) or, ideally, close to the moment that the loading gauge opens. If this can be achieved, it is not actually necessary to transfer any heel LNG into the cooled tanks. This means that even less LNG and time are consumed for tank cool down purposes.

Figs. 3(a) and 3(b) illustrate the temperature and pressure trends established during typical 3-day intermittent LNGC tank cool-down at sea, where it consumed about 1,046 m^3 of LNG.

Fig. 4 illustrates the BOG-balanced tank cool down method, where only about 680 m^3 of LNG is consumed, i.e., about 65% of that consumed using the intermittent method. Fig. 4 also shows a comparison of the typical intermittent LNGC tank cool down method (three days cooling in advance of arrival) and BOG-balanced tank cool down method. The

BOG-balanced method results in about 4-5 °C/h continuous temperature descent during the cool-down period at sea, and generally no need for LNG heel transfer. Here, the BOG-balanced method of cool down is faster (37 versus 68 hrs) and consumes approximately half the LNG heel, while providing fine tuning of tank pressure.

By using about 500 m^3 less LNG for tank cooling-down for each ballast voyage, the approximate commercial benefit of the BOG-balanced method would amount to US$588,600 per annum for an LNGC making ten voyages, assuming a delivered sales gas price of US$5/mmBtu and an energy conversion for LNG of 23.54 mmBtu/m^3.

4. Benefits of a BOG-balanced cool down of LNGC tanks at sea

- The method allows tank cool down to be conducted in an optimal, controlled, and safe manner that requires minimum LNG heel at sea to be consumed for tank cool down. This improves the commercial performance of LNGC for the benefit of charterers.
- The method can be easily planned using spreadsheet calculations using actual LNG quality and voyage schedule information for each specific LNGC voyage. This provides a standardized approach to LNG heel calculations and minimizes the potential for operator's error in heel estimation.
- The method allows for flexibility to make adjustments relating to loading schedule delays, which from time to time inevitably occur. In case of loading delay, the LNG heel also can be spread in cold tanks to minimise heating up. In such circumstances only a few hours of tank recooling is required, and in the worst case, tank cool down is finalized at the jetty. Jetty re-cool-down time is likely to fit within the laytime allowance of the LNGC charter party.
- Cool down can be stopped at any moment without the risk of venting over-heated vapor. This makes it easy to adapt schedule and keep tank pressure below 70% MARVS.
- LNGC tank cool down can alwayed intermittently if too much BOG is generated and cannot be burnt effectively (i.e., slowers be conduct vessel speed or at anchor). An alternative approach in such conditions is to spray each tank more intensely in frequent bursts, one tank in turn, for short periods. The only constraints that need to be adhered to are: 1) minimizing the total time that each tank is allowed to warm; 2) not allowing tank pressure to rise above 65%-70% MARVS due to vapor expansion; and, 3) observing the designated cool-down rates for the specific tank.
- The method does not result in excess nitrogen consumption in the tank's insulation barriers surrounding the tank as the tank cool-down rate is slow. In contrast, at high tank spraying rates, the nitrogen consumption can be a limiting factor.
- Application of this method do not require any extra knowledge or training for the ship crew as the simple calculations required can be standardized on a spreadsheet.
- Reduced atomization of sprayed LNG due to lower spray pressure is not a problem for tanks at temperatures higher than -140 °C and would not lead to LNG accumulating in the tanks before cooldown is completed. New-build ships could be designed to have a special spray rail in their tanks fitted with a small number of nozzles to increase atomization during tank cool down at sea. Alternatively, the existing two spray rails in most existing vessels, fitted with an almost equal number of spray nozzles, could be modified. In this case one spray rail would be fitted with a small number of spray nozzles, to be used for tank cool down at sea, and other spray rail would be fitted with the remaining nozzles.
- On vessels with liquefaction or partial liquefaction system, the cool-down task is easier with the BOG balancing method and the quantity of LNG heel required can be reduced.

5. Conclusions

Despite LNGC technology improving significantly in recent years, most operators have yet to unleash the full potential of modern vessel designs. Improvements in efficiency in terms of total LNG consumption and atmospheric emissions during voyages can be achieved for all membrane LNGCs. A new improved method of cooling down LNGC cargo tanks at sea prior to reloading is an example of such an improvement. It ensures the minimum LNG heel is consumed at sea in achieving that objective. It thereby improves the vessel's overall commercial performance. The method is sufficiently flexible to adjust for changing operating conditions and loading schedule amendments for any LNGC with membrane tanks. The method may also work on Moss-type ships, subject to trial testing to establish its effectiveness with the small number of spray nozzles available in such tanks.

From an improved design perspective, to optimize the BOG-balanced cool-down method, it would be beneficial to modify one spray coil per tank to consist of a reduced number of spray nozzles in new-build vessel's. This would make the tanks in those vessels easier to spray at sea at low rates with improved LNG atomizing, making the BOG-balanced cool-down method even more flexible and controllable.

Acknowledgement

This work benefited from observations recorded during multiple LNGC voyages.

Conflict of interest

The authors declare no competing interest.

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