10.31653/smf44.2022. 36-44

Khliyeva O., Sorokin R., Stukalenko O.
National University “Odessa Maritime Academy”

A DIRECT CONTRIBUTION OF MARINE REFRIGERATION TO ANTHROPOGENIC GREENHOUSE GASES EMISSION - A SHORT REVIEW

Introduction

The problem of reducing greenhouse gas (GHG) emissions in the maritime sector are currently important. The share of shipping emissions in global anthropogenic emissions was 2.89% in 2018 [1]. The main contribution to GHG emissions (indirect emission) on the marine fleet generates the main and auxiliary engines, and boilers during fuel combustion as well as incinerators [1, 2]. However, marine merchant and passenger ships have another significant source of direct GHG emissions, which is currently not directly regulated and considered as not mandatory inventory – hydrofluorocarbons (HFCs) refrigerants emissions from refrigeration and air conditioning systems. It should be highlighted, that reduction of the direct GHG emissions for marine refrigeration systems is the most difficult among all types of refrigeration systems.

According to the 4th IMO GHG Study [1], the total refrigerant emissions (international, domestic, and fishing) correspond to 18.2 million tonnes CO_2-eq., which is an increase from the 15.7 million tonnes CO_2-eq. emitted in 2012. HFCs emissions in the EU from ships in 2007 amounted to 232 metric tons or 361 kilotons of CO_2-eq. [3].

The emissions of three main GHGs – CO_2, CH_4, and N_2O – of total shipping (international, domestic, and fishing) were estimated as 1076 million tonnes CO_2-eq. in 2018 compared to 977 in 2012 (9.6% increase) [1]. The emission of main GHG (CO_2) was estimated as 1056 million tonnes CO_2-eq. in 2018 compared to 962 in 2012 [1]. Nowadays, such GHG as HFCs refrigerants are not accounted in the results of the international shipping emissions calculation. However, the six gases initially considered under the UNFCCC process include HFCs – all refrigerants (excluding ammonia and CO_2), that utilize in marine refrigeration.

A direct contribution of marine refrigeration to GHG emission

Due to the physical properties of refrigerants, it is very difficult to control their leakage during the repair and maintenance of vapor compression refrigeration equipment. Additional problems are concerned with the operating conditions for marine refrigeration systems. The main reason for the high level of refrigerant leakage from marine refrigeration systems, compared to land-based, is agreed to be the exposition of vibrations from sea-waves. This is made worse because there is often no crewmember onboard skilled in refrigeration. In this case, leakages are not repaired but simply refrigerant is topped up to the system [3].

The emission factor for air conditioning systems and refrigeration systems with direct expansion (pure cargo and "other" ships) is estimated at 40% per year [3]. For indirect systems (ships with passengers), a leakage of 20% per year is assumed [3].

The annual refrigerant leakage rate for marine refrigeration equipment could be as high as 20 to 40% [4]. The typical value of leakage is 30 % [4].

The service experts from the two leading European suppliers of ship air conditioning/refrigeration equipment (York, Germany, and Grenco, The Netherlands) estimate annual use-phase refills on merchant ships to range from 20 to 40% and from 35 to 40%, respectively [3].

According to the Dutch “Inventory Refrigerant Emissions Sea Shipping” for the year 2000 the “yearly leakage rate of merchant shipping amounts to 33% and 39% for fishing” [3].

After reviewing the Scandinavian ship owners about refrigerant refills in their vessels in 2006 the average refill per ship was estimated as 38.3% (for 36 vessels with air conditioning and provision refrigeration) [3].

In a survey on 2006 refrigerant refills in 10 Baltic ferries, the annual leakage rates average 21.2% for the indirect air-conditioning systems and 25.1% for the direct refrigeration systems [3].

In [5], the average annual leakage rate for Swedish passenger and cargo vessels was estimated as 18.9% and 29.5 % in 2015, correspondently, and 11.9 % and 22.3 % in 2016, correspondently.

In all considered in [3, 5] cases, the high variability in individual refill refrigerant rates (annual leakage rates) was mentioned for each analyzed passenger ship and each cargo vessel - from 1% to 62%.

For comparison, the leakage rates of air-conditioning systems of rail vehicles were estimated at 5% per year [3]. In [4] annual leak rates for road transport are proposed to accept 20 % per year (15…23 %). This value is significantly lower for other types of refrigeration equipment and application [4].

The report [6] states that every 10 % loss of refrigerant in a ship’s refrigeration system increases energy consumption by up to 20 %. Refrigerant leaks result in more energy needed to deliver the necessary level of cooling and could contribute to higher emissions from the ship (indirect emissions resulting from consumption of electricity). Although the numerical values are questionable, this statement should not be completely ignored. A large number of operation factors, including optimal refrigerant charge, affect on efficiency and energy consumption of refrigeration equipment.

Low-GWP refrigerants for marine refrigeration

International environmental legislation shows a steady increase in the restrictions on the use of high-GWP refrigerants.

According to MARPOL Annex VI (Regulations for the Prevention of Air Pollution from Ships, Regulation 12 – Ozone-depleting substances) from January 1, 2020, the use of chlorine-containing refrigerants is prohibited in refrigeration equipment on ships. That is, the problem of the replacement of ozone-depleting refrigerants in marine refrigeration equipment can be considered solved. But the current requirements of MARPOL Annex VI concerning the HFC high-GWP refrigerants focus mainly on accounting the refrigerants consumption and safe handling. Moreover, requirements for the replacement of the high-GWP refrigerant with low-GWP are not declared in MARPOL Annex VI.

Besides, according to the Kigali Amendment to the Montreal Protocol, the most common refrigerants in marine refrigeration (R134a, R404A, R407F, and similar) should be phased out because of the high GWP. But, according to IMO (International Maritime Organization), there are no mandatory requirements on GWP value for refrigerants on board ships.

In 2014 a new EU Regulation on F-gases, № 517/2014, was adopted and applied from 1 January 2015. Besides strengthening the existing leakage prevention measures it also limits the production and use of F-gases. The regulations concerning leakage prevention, record keeping, and certification, still do not apply to ships, while the recovery regulation does. There is also a general obligation (for all types of plants) to avoid unintentional HFC leakages. However, there is a service ban on existing marine refrigeration systems operated with high GWP refrigerant ships. Equipment on an EU-flagged ship using an HFC with a GWP > 2500 and an amount corresponding to 40 tonnes of CO_2 equivalents is prohibited to be recharged with new refrigerant after 1 January 2020 and with recycled refrigerant after 1 January 2030 [7].

Legislation on the use of high GWP agents in marine propulsion is expected to be strengthened, so it is necessary to be prepared in time for the transition to the use of “new” generation low GWP refrigerants. Stated on the above-mentioned and in view of the fact that the supplementary section of the regulation [8] on air pollution reduction recommends the use of refrigerants with GWP ≤ 2000, there are only a few possible alternative refrigerants for marine vapor compression systems: R407C (GWP = 1), R134a (GWP =1 430), R717 – ammonia (GWP = 0), R744 – carbon dioxide (GWP = 1). Prospective refrigerant R290 – propane (GWP = 5) is forbidden to be used in the vessel’s refrigeration equipment (except the cases when a mass of the refrigerant charge is less than 150 g), as they are class A3 hazard refrigerants (fire hazardous) [9]. Other prospective refrigerants are considered to be newly introduced agents such as R32 (GWP = 675), R1234yf (GWP = 4), R1234ze (GWP = 7). But they all do belong to the A2L class (mildly flammable). Concerning the possibility of using A2L class flammable refrigerants, there is no information given in sources [8] and [9]. But in [10] it is advised that the A2L class refrigerants should not be applied to retrofit existing refrigeration systems.

By [8, 9], only HFCs, or in other words ‘natural’ refrigerants such as R717 (ammonia NH_3) and R744 (carbon dioxide CO_2) can be used as a refrigerant in marine refrigeration plants.

R717 has not found itself to be used as a refrigerant in air conditioning systems and refrigeration equipment for provision chambers and is also used infrequently in specialized high-capacity vessel refrigeration equipment. The use of R744 as a refrigerant is an area of very active development. There are already some examples of the actual implementation of refrigeration systems in the maritime industry that use R744 (CO_2) as the refrigerant. For example, there is a very small amount of shipping containers that are currently equipped with refrigeration R744 units [11]. But such systems are not yet common practice. Moreover, CO_2 as a refrigerant requires a fundamentally different design of the refrigeration system compared to HFCs, so its utilization is possible only in case of a complete replacement of the refrigeration system or on new built vessels. Concerning the above-mentioned, it should be stated that the price for such CO_2 system tends to be 2 or 3 times higher than for a similar capacity HFC system [6]. Besides, the poor energy efficiency of R744 is a serious barrier as the vessel power generation is tightly constrained by Owners' regulations [11].

It can be assumed that in the nearest future mixed refrigerants such as R407C type might be widely used in the vessels' refrigeration systems which are currently in operation. But, in its turn, they also need an alternative to be found, because the existing requirements and limit levels of direct emissions from marine refrigeration plants are expected to become stricter.

Possible technical solutions to reduce direct emissions during the operation of marine refrigeration systems

The current situation with the available on the market refrigerants indicates that the existing standards might be changed towards the possibility of using flammable substances in marine refrigeration systems (this trend is already observed, for example, in the EU in 2022 the issue of allowing the utilization of class A2L refrigerants in railway transport is being considered). Moreover, there are already a number of scientific papers on the topic of the possibilities of using flammable refrigerants in marine refrigeration equipment [12, 13]. In mentioned studies it was reported, that the inconvenience coming from refrigerant flammability and explosion risks can be overcome through some measures such as enclosing operations, ensuring local exhaust ventilation in the location of leakage, the use of special equipment, etc. For example, Heinen & Hopman proposes an evident technical solution for onboard refrigeration systems with flammable refrigerants: “By placing the cooling system inside a casing, the possible explosive atmosphere is located inside the casing when leakage occurs. By using a fan, the casing can be ventilated so the mixture of gas and air can be discharged outside the casing” [14]. However, there is no information on whether such a solution has been implemented in practice for the vessel's refrigeration system. Such technical solution along with the use of R290 refrigerant is quite possible, first of all, for air conditioning systems. However, the requirements for utilizing flammable refrigerants onboard have not been developed yet (except ammonia, which can be used in systems of high capacity, but not for air conditioning systems). As was already mentioned in the paper, generally flammable refrigerants (like hazard class A3 refrigerants – flammable) are prohibited from being used in vessel refrigeration plants, except when the mass of the refrigerant charge is less than 150 g, according to the source [9]. However, the PRS (Polski Rejestr Statków) rules [15] note that “The refrigerants of group III (flammable, such as R290) may be used, upon agreement with PRS, only for refrigerating plants of liquefied gas carriers where the cargo is used as refrigerant”. At the same time, in [15] it was mentioned that refrigerating plants operating on group II or III refrigerant (mildly or highly flammable) shall be installed in separate gas-tight spaces.

It should be noted that the flammable refrigerants utilized in indirect refrigeration systems will contribute to the reduction of the refrigerant leakage rates by up to 90% compared to direct systems, due to the compact design and significantly shorter refrigerant lines [5]. In the meantime, unfortunately, indirect refrigeration systems have inherent lower energy efficiency in comparison with refrigeration systems with direct evaporation.

Another perspective way to reduce direct greenhouse gas emissions from marine refrigeration equipment is the introduction of a cascade vapor compression-steam ejector refrigeration plant. The most preferable can be considered the use of R744 (CO_2) refrigerant in the first stage (vapor compression part) [16, 17] since R744 performs poorly in tropic regions with high sea and/or air temperatures. However, if we talk about steam ejector systems, the issue of choosing a refrigerant with a low GWP remains relevant, at the same time, indirect greenhouse gas emissions from the process of electricity consumption are significantly reduced (when using waste heat, which can be found in the sufficient amount on vessels). However, mentioned particular branch of research requires further study.

When implementing a new refrigerant or a new refrigeration system, it is advisable to apply an economic, energy, and environmental comparative analysis in order to justify the feasibility of the adopted technical solution for improving energy efficiency and reducing the environmental impact of the new option comparing to the traditional one [18, 19].

Conclusion

This brief review allows us to state the following conclusions:

- the issue of choosing an alternative refrigerant with a low global warming potential for marine vapor compression refrigeration systems is quite complicated, additional challenges are associated with the requirements of standards that impose certain restrictions on the use of flammable substances as the refrigerants in marine refrigeration plants;
- it is important to keep aware of changes in the refrigeration industry standards as they are changing rapidly in order to meet the demands of today's shipping industry and global environmental legal regulations;
- the service of the existing onboard refrigeration systems may move to a refrigerant with intermediate GWP, such as R407C (retrofit procedure), but the use of flammable low GWP alternative agents is unlikely for currently operating refrigeration systems;

- the sea-freight ships with refrigerated holds tend to use R717 (with brine secondary), R404A, or R407C; there will be expected a few new ships due to the ongoing shift to container vessels, but they likely are going to use indirect systems with R717 or R744; applying the flammable refrigerants, such as R290 propane, is not expected;
- in the new vessel's refrigeration systems of small and medium capacity for various purposes, it is preferable to use CO_2 as a refrigerant or, in the long-term prospect, there is a possibility of introducing the indirect refrigeration systems with secondary coolant which operate with flammable refrigerants as R290, however, this solution requires further study and standardization.

REFERENCES

1. Fourth IMO Grenhouse Gase Study 2020. Publ. by the International Maritime Organization. 4 Albert Embankment, London, SE1 7SR. 2021. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20Executive-Summary.pdf

2. Gray N., McDonagh Sh., O'Shea R., Smyth B., Murphy J. D. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors // Advances in Applied Energy. 2021. Vol. 1. 100008. https://doi.org/10.1016/j.adapen.2021.100008

3. Schwarz W. Rhiemeier J.M. The analysis of the emissions of fluorinated greenhouse gases from refrigeration and air conditioning equipment used in the transport sector other than road transport and options for reducing these emissions Maritime, Rail, and Aircraft Sector, Brussels: European Commission. 2007. https://ec.europa.eu/clima/system/files/2016-11/2_maritime_rail_aircraft_en.pdf

4. Methods of calculating total equivalent warming impact (TEWI). Best practice guidelines, Australian Institute of Refrigeration, Air-conditioning and Heating. AIRACH. 2012. https://www.airah.org.au/Content_Files/BestPracticeGuides/Best_Practice_Tewi_June2012.pdf

5. Hafner I., Gabrielli C., Widell K. Refrigeration units in marine vessels: Alternatives to HCFCs and high GWP HFCs. Copenhagen: Nordic Council of Ministers. 2019. https://doi.org/10.6027/TN2019-527

6. Responsible refrigeration on ships – Enabling you to comply with regulations and reduce carbon emission. Wilhelmsen insights. 16. Nov 2021. https://www.wilhelmsen.com/

7. EU F-gas Regulation Guidance Information Sheet 31: Marine Refrigeration and AiRConditioning. Gluckmann Consulting. 2016 http://www.gluckmanconsulting.com/wp-content/uploads/2014/12/IS-31-Marine-Applications.pdf

8. DNV GL AS. Rules for classification. Ships. Edition July 2019. *Part 6 Additional class notations*. *Chapter 7 Environmental protection* and *pollution control*

9. Rules for the classification and construction of sea-going ships Part XII Refrigerating Plants ND No. 2-020101-138-E. 2021

10. An introduction to A2L refrigerants and their use in Refrigeration, Air Conditioning and Heat Pump applications. FETA. 2018. http://www.refcom.org.uk/media/1202/an-introduction-to-a2l-refrigerants-final.pdf

11. Hennessy W., Cleland D. Projections of HFC stocks and emissions to 2050 in relation to key factors influencing HFC consumption. Prepared for Ministry for the Environment, Wellington. 2020. https://environment.govt.nz/assets/publications/Projections-of-HFC-stocks-and-emissions-to-2050-in-relation-to-key-factors-influencing-HFC-consumption.pdf

12. Mota-Babiloni A., Haro-Ortuno J, Navarro-Esbrí J. Experimental drop-in replacement of R404A for warm countries using the low GWP mixtures R454C and R455A // Int. J. Refrig. 2018. Vol. 91. P. 136-145. https://doi.org/10.1016/j.ijrefrig.2018.05.018

13. Memet F. Exergy and energy analysis of a vapour compression refrigeration system for the investigation of a new refrigerant to be used on board the ships // IOP Conference Series: Materials Science and Engineering. ModTech 2021, 23-26 June 2021, Eforie Nord, Romania.Vol. 1182. https://doi.org/10.1088/1757-899X/1182/1/012046

14. Propane Chiller. Heinen&Hopman. https://heinenhopman.com/en/markets/merchant/propane-chiller/

15. Rules for the Classification and Construction of Sea-going Ships. Part VI. Machinery Installation and Refrigerating Plants, edited by Polski Rejestr Statków S.A., Gdansk. January 2022. https://www.prs.pl/uploads/mor_p6.pdf

16. Ierin V., Chen G., Volovyk O., Shestopalov K. Hybrid two–stage CO_2 transcritical mechanical compression–ejector cooling cycle: Thermo-

dynamic analysis and optimization // Int. J. Refrig. 2021. Vol. 132. P. 45-55. https://doi.org/10.1016/j.ijrefrig.2021.09.012

17. Chen G., Ierin V., Volovyk O., Shestopalov K. An improved cascade mechanical compression–ejector cooling cycle // Energy. 2019. Vol. 170. P. 459-470. https://doi.org/10.1016/j.energy.2018.12.107

18. Jan W., Mrozek M., Fornalik-Wajs E. Combined cold supply system for ship application based on low GWP refrigerants-Thermo-economic and ecological analyses // Energy Convers. Manage. 2022. Vol. 258. 115518. https://doi.org/10.1016/j.enconman.2022.115518

19. Chen G., Zhelezny V., Khliyeva O., Shestopalov K., Ierin V. Ecological and energy efficiency analysis of ejector and vapor compression air conditioners // Int. J. Refrig. 2017. Vol. 74. P. 127-135. https://doi.org/10.1016/j.ijrefrig.2016.09.028