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Overview of the development and status of carbon dioxide (R-744) refrigeration systems onboard fishing vessels

Aperçu du développement et de l'état des systèmes frigorifiques au dioxyde de carbone (R-744) à bord des navires de pêche

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ABSTRACT

Globally, most fishing vessels still use the ozone-depleting and climate-harmful R-22 in their freezing and refrigerated seawater (RSW) systems. However, in some regions, the natural refrigerant ammonia is the preferred refrigerant. Another natural refrigerant, carbon dioxide (R-744), is becoming a viable option and is increasingly used onboard. This option will not exclude ammonia, but rather will be a good alternative to it to meet the demand for different cooling/freezing needs in post-R-22 systems. There are currently major developments in R-744 refrigeration technology that are widening the potential applications of R-744. These include compressors with larger capacities, more energy-efficient components, system designs with lower freezing temperatures and integration of heat recovery and thermal storage. This paper provides a review of the development of refrigeration systems with R-744 onboard fishing vessels. It includes a description of the commonly used cooling and freezing methods and of the development in R-744 refrigeration technology, especially within the system and component design, capacity and performance. It also includes the current status of R-744 refrigeration technologies in fishing vessels. Although there are limited publications on R-744 systems for fishing vessel applications, the review shows positive prospects of utilizing R-744 and further research and innovation within this topic is recommended.

1. Introduction

According to estimations by the International Institute of Refrigeration (IIR), for 2014, 7.8% of global greenhouse gas (GHG) emissions were released by the refrigeration sector due to its direct and indirect contributions. These are the leakages of detrimental synthetic refrigerants -chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs)- from the system, and carbon dioxide from the electricity consumption for system operation and control (Dupont et al., 2019). These adverse impacts are also seen in the fisheries sector. R-22 (HCFC-22) is the most used refrigerant in the refrigeration systems of the global fishing fleet with a share of 70% (UNEP, 2016).

Despite its emissions, refrigeration has a crucial role in the post-harvesting process of fisheries because once the fishes are caught, they need to be kept at low temperatures in refrigerated seawater (RSW) to delay the spoilage and preserve the quality. These storage temperatures strongly depend on the fish type and are recommended to be between -0.5°C and 2°C. If the catch is stored at ideal temperatures, the storage life can be extended to up to 18 days. For long-term consumption, the catches need to be frozen to a temperature level of between -20°C and

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Nomenclature

Abbreviations

AC	air conditioning
BBS	basic booster system
CFC	chlorofluorocarbon
CSW	chilled seawater
CV	control valve
DHW	domestic Hot Water
EER	energy efficiency ratio
EJ	ejector
EUMOFA	European market observatory for fisheries and aquaculture products
EV	expansion Valve
FAO	food and agriculture organization of the United Nations
FGBV	flash gas by-pass valve
GHG	greenhouse gas
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluorolefin
HP	heat pump
HPV	high-pressure control valve

Symbols

h	specific enthalpy
P	pressure
T	temperature
IEA	international energy agency
IHX	internal heat exchanger
IQF	individual Quick Freezers
IIR	international institute of refrigeration
IPR	intermediate Pressure Receiver
IT	intermediate Temperature
LPR	low pressure receiver
LT	low temperature
ME	multi-ejectors
MT	medium temperature
ORV	oil return valve
PC	parallel compressors
PCM	phase change material
QDW	quick drainage valve
RSW	refrigerated seawater
SH	space heating
TES	thermal energy storage
WHO	World Health Organisation
UNEP	the United Nations environment programme

Subscripts

c	condensation
e	evaporation
gc	gas cooler

-30°C which can extend storage life to 12 months (ASHRAE, 2018). To preserve the nutritional values and quality of the fish, refrigeration systems are specially installed in vessels that spend many days at sea.

These facts necessitate either retrofitting the existing refrigeration systems or installing new ones. Some unsaturated refrigerants such as hydrofluorolefins (HFOs) R-1234yf, R1234ze and R-513A have been seen as candidates for retrofitting existing R-22 systems due to their low global warming potential (GWP). Nevertheless, the GHG emissions from their production, the environmental impact of their decomposition products and their impacts on human health and safety need to be understood (Hafner et al., 2019). They are also flammable and release hazardous combustion products when they burn. Lastly, in the case of chemical degradation, they produce trifluoroacetic acid which is toxic and may cause serious health hazards (Adamson, 2021). In terms of installing new units, natural refrigerants - particularly carbon dioxide (R-744) and ammonia (R-717) - supported with energy-efficient measures would be ideal alternatives. Other natural refrigerants, such as the hydrocarbons methane (R-50), ethane (R-170), propane (R-290), butane (R-600), ethylene (R-1150), and propylene (R-1270) have good refrigerant properties and are non-toxic. However, they are flammable and that restricts their application in fishing vessels (Adamson, 2021; ASHRAE, 2014).

R-717 has globally been the second most popular choice in the refrigeration systems for fishing vessels, following R-22 (UNEP, 2016), and is the main refrigerant used onboard Norwegian fishing vessels (Nordtvedt and Widell, 2020). This is because, firstly, it has zero global warming potential (GWP) and simple leak detection and oil management. Secondly, it needs less stringent drying procedures compared to other refrigerants (Lorentzen, 1988). Furthermore, its low molecular weight and high evaporation enthalpy enable utilisation of smaller piping size for suction vapor and liquid phase which also reduces valves and fittings costs (Lorentzen, 1988; Shanmugam and Mital, 2019). However, it is flammable, which therefore must be considered during the design phase and the necessary measures must be taken during operation. Moreover, the materials like copper, zinc and their alloys cannot be used with R-717 due to corrosion (Lorentzen, 1988). Lastly, a separate refrigerating machinery room is required for R-717 systems in the ships (DNV, 2011) which necessitates the usage of large space.

R-744 as a refrigerant was utilised until the 1950s, especially in marine applications. With the rising concerns over climate change, it has regained attention after the achievement of the effective control of the transcritical vapour compression cycle's capacity by Gustav Lorentzen (Lorentzen, 1990). It is estimated by Shecco that the number of transcritical R-744 refrigeration systems in 2020 is above 35,000 globally (Koegelenberg et al., 2020). Due firstly to it being non-toxic and non-flammable, and secondly having low GWP (1 at 100 years), and excellent thermophysical and transport properties. The number of R-744 refrigeration systems, particularly R-744-only systems, is increasing in the applications for supermarkets, hotels, malls, etc.

The use of R-744 in the global fishing fleet is mostly represented by R-717/R-744 cascade systems, while the implementation of R-744-only units is almost exclusively limited to Norwegian vessels. However, these installations, together with developments of R-744 units in other sectors, show that there is a global potential for R-744 in fishing vessel applications. In addition to enabling increased cooling capacities and lower freezing temperatures, as low as -53 °C (-50 °C is very often chosen as the lowest due to material considerations), such systems contribute to the green transition of the sector by reducing emissions of climate-harmful substances. R-744 refrigeration systems will play a major role in mitigating the fishery sector's emissions when these units are installed in existing or new fishing vessels (EIA, 2021).

The objective of this work is to provide an overview of the status and recent developments of the R-744 refrigeration systems in fishing vessels. For this, first, a description of the commonly used cooling and freezing methods is given in Section 2. Secondly, in Section 3, the latest developments in R-744 refrigeration technology are summarised. Thirdly, the current status of R-744 refrigeration technologies in fishing vessels is discussed in Section 4. Lastly, the prospects for R-744 refrigeration technologies in fishing vessels are mentioned in Section 5.

2. Cooling and freezing methods onboard a fishing vessels

The main cooling demands onboard a fishing vessel are related to cooling/freezing and maintaining the temperature of the fish. Fish and seafood are sensitive to high temperatures during processing, which means that chilled or frozen handling is often necessary (Duarte et al., 2020; Nordtvedt and Widell, 2020). In countries with higher sea water temperatures, the degradation is slower than in cold waters, because of different bacterial flora (ASHRAE, 2018). Smaller vessels commonly store fish on ice, while larger fishing vessels use refrigerated seawater (RSW) or freeze the fish to maintain product quality and shelf life. The different methods are described in the following sections.

2.1. Fish chilling with ice

Ice is commonly used for the conservation of fresh fish, keeping the temperature at slightly above 0 °C. Keeping the fish in ice boxes is very common and the ice is mainly brought from land (Larminat et al., 2018; Wang and Wang, 2005). The amount of ice necessary depends on the ambient temperature and the length of the trip, but it is typically between one to two kg of ice per kg of fish (Muir, 2015; Xu et al., 2017). A CSW system produces chilled seawater by adding ice to seawater. The ice keeps the water cold, and the water increases heat transfer between fish and ice as compared with only ice, while using less energy onboard than with a mechanical refrigeration system (Thorsteinsson et al., 2003).

A theoretical analysis was performed by (Saini et al., 2020) to see if there is a potential to have a small refrigeration system onboard only to keep the ice cold, covering the heat ingress from the outside. A single stage R-717/-R-718 vapour absorption system was found to be suitable. Heat was derived from the engine jacket exhaust, and the unit was cooled with seawater. This system can result in more predictability of the available ice volume and result in a higher product quality. Payback time was calculated to be one year and four months. Although this was only a theoretical survey, there is a potential for further development of these types of small onboard refrigeration systems.

2.2. Fish chilling in RSW

RSW is a suitable and common method for fast chilling of large fish quantities, typically found onboard purse seiners and trawlers equipped for pelagic fishing. The system consists of several tanks, tubes, circulation pumps and valves in which seawater is mechanically refrigerated and circulated (Thorsteinsson et al., 2003; Widell et al., 2016). Large fishing vessels have tank storage of more than 1000 m^3 (Brodal et al., 2018). An example of a RSW system is shown in (Fig. 1), with two separate R-717 systems and a sea water circuit supplying cold water to nine tanks. Herring and mackerel are species that are typically transported in RSW tanks, while species like Blue Whiting are stored in refrigerated fresh water. This is because Blue Whiting is used for fish oil and fish meal production and using freshwater lowers salt uptake in the fish compared with seawater (Grimsmo et al., 2016; Nordtvedt and Widell, 2020; Olsen and Norum, 2010).

RSW systems onboard fishing vessels have improved over the years, but they are still often far from optimal. Uneven cooling, especially in large tanks (>300 m^3), has been reported as a problem. If the fish are too warm, decomposition rates increase, which can be measured at landing. If volatile nitrogen values are too high, the price of the fish will be reduced. Another problem which previously occurred but which has been overcome was "lumping" of the fish. Blue Whiting can form a doughy mass, which is difficult to circulate water through. Adding acetic acid to the refrigerated fresh water has been shown to both act as a preservative and prevent lumping (Nordtvedt and Widell, 2019).

2.3. Fish chilling with ice slurry

An alternative to using RSW as a cooling medium is ice slurry, which is a promising technology utilized in some fishing vessels already (Rayhan et al., 2018). Slurry ice is a homogenous mixture of carrier liquid (e.g., sea water) and ice particles, also described as flow ice, fluid ice, slush ice or liquid ice. The cooling properties and the temperature of the slurry depend both on the thermal properties of the slurry and the ice particle characteristics. The advantages with slurry ice are faster chilling (compared with RSW or ice) and less damage to the fish (compared with

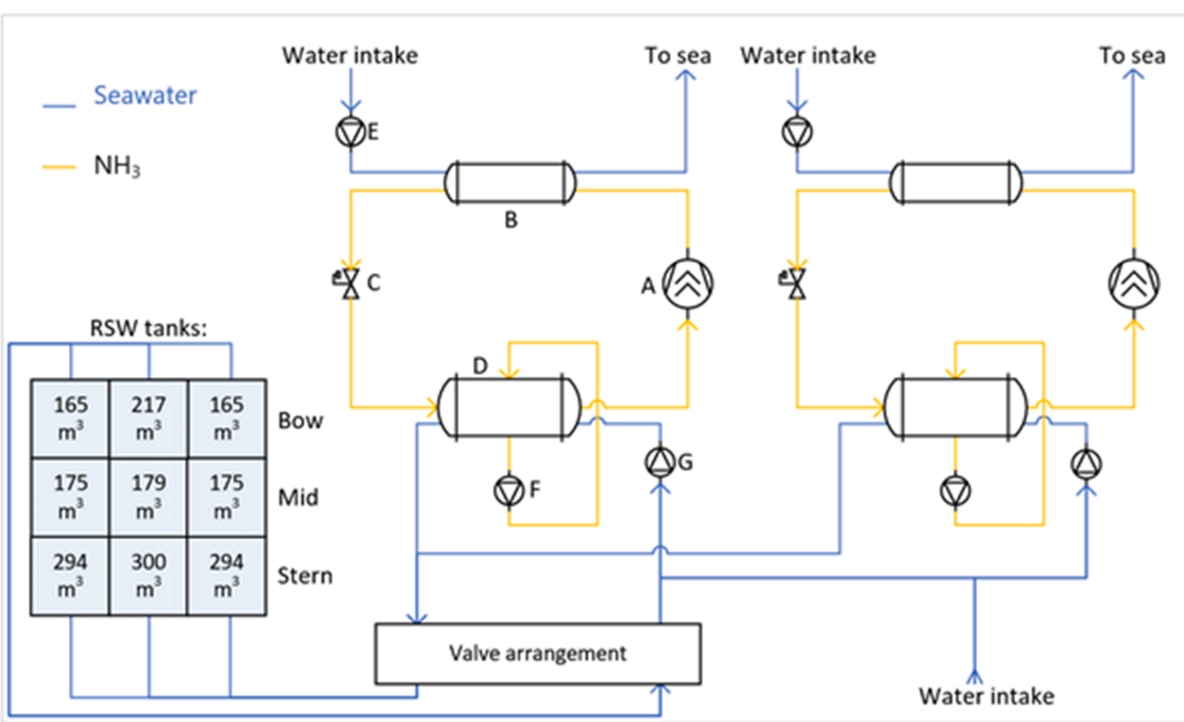


Fig. 1. Example of layout for RSW system onboard fishing vessel (Svendsen et al., 2021).

conventional ice) (Kauffeld et al., 2010; Piñeiro et al., 2004).

Lyu et al (Lyu et al., 2022) reviewed ice slurry processes in the food industry and described the layout and operation for a system onboard a fishing vessel. They also report that there are over 700 ice slurry systems installed worldwide. Ntzimani et al. (2021) compared ice slurry with flake ice for preservation of fish, and they found improved product-quality stability and shelf-life extension with slurry ice storage. Eliasson (2021) compared RSW chilling with ice slurry/CSW and brine chilling. They found that with similar industrial systems, the RSW chilling method resulted in faster chilling than slurry ice/CSW, but slightly longer than brine chilling. Some larger fish species are frozen in brine, which would be at a temperature below the freezing point of seawater. This is achieved by adding salt to the sea water, to keep it from freezing (Ayub et al., 2020).

2.4. Fish freezing in plate freezers

On board trawlers the fish are frozen in vertical plate freezers, and fillets in horizontal plate-freezers as interleaved fillets or standardized blocks (Bøknes et al., 2001). In a plate freezer, whole fish, packed fillets or smaller pieces of fish are frozen by contact between two plates with some pressure applied on them. The fish is wrapped in plastic or packed in cardboard boxes for easier handling and because of market requirements, but this slightly reduces the heat transfer from the fish. Despite this, contact freezing is an efficient freezing method. Evaporators in R-717 systems typically have a temperature of about -33 °C, but with a R-744 system, the temperature can reach -50 °C. There is a risk of dry ice formation if the temperature is reduced further. Verpe et al. (2018) aimed to experimentally investigate the freezing time of different systems. They reported that the freezing time of the fish is shorter with lower evaporating temperatures and therefore the R-744 system reduces the freezing time by 25-50% compared to an R-717 system. However, R-744's COP, ranging between 1.8 and 3.0, was 11% and 6% lower than that of an R-717 and a R-717/R-744 cascade system, respectively (Verpe et al., 2018).

2.5. Freezing of seafood in air blast freezers

Air blast freezers are common in land processing plants, but some fishing vessels also have such systems, which enables the crew to single freeze the fish quickly after slaughter, resulting in well preserved product quality. The evaporator temperature in the blast freezers is typically between -35 °C and -52 °C, and air fans circulate air through the evaporators and ensure high air velocity across the products. The product freezing time is normally between 12 and 48 h (Dempsey and Bansal, 2012). Temperatures in the lower range (-50 °C) are possible with refrigerant R-744, for example in a cascade system (Fernández-Seara et al., 2012).

3. Developments in R-744 refrigeration technology

The recent interest in R-744 refrigeration and heat pump systems have been triggered by (1) the improvements in the system components, for instance the development of high-efficient heat exchangers and compressors, (2) the development of high-capacity compressors by several manufacturers (applicable for marine installations, too), (3) the achievements in energy-efficient measures with adapted system architectures such as parallel compression and the expansion work recovery applying multi-ejectors (ME), and (4) heat recovery opportunities, the excellent applicability of R-744 refrigeration systems to all-in-one installations, which also meet hot water and space heating/cooling demands, as required on many fishing vessels. The holistic effect of all these improvements has led the R-744 refrigeration system to find a wide range of application areas, including fishing vessels, in all climate regions.

To the best of the authors' knowledge, there are very few studies dealing with the development of the R-744 refrigeration systems specifically for fishing vessels. Nevertheless, the developments are mostly applicable to all areas, including fishing vessels.

3.1. Improvements in system components

The increasing number of R-744 refrigeration systems has urged researchers and manufacturers to develop highly efficient components for different application types. This subsection includes recent improvements in the main components of the system, which includes compressors, gas coolers and evaporators. The latest advancements made by the manufacturers will also be highlighted, as these advancements valuably contribute to widening the R-744 application range.

3.1.1. Compressors

A compressor is the heart of a refrigeration system; however, it is also the main energy-demanding unit and therefore its performance has a direct impact on the capacity and COP of the system. Academia and industry intend to develop energy-efficient and capacity controlling R-744 compressors with high capacity, which are also usable and required in harsh marine environments. In the limited space as it is case in fishing vessels, it is only possible to reach needed higher cooling capacities by using R-744 which has lower evaporation temperature (as low as -50°C). In the need for higher cooling capacities, the COP of the system, which has secondary priority in this case, decreases.

As for traditional compressors, the R-744 compressors should be resistant to dynamic load changes and high pressure levels, and offer high efficiency and cooling capacity, low cost, compactness, low weight and leakage rates, reliable oil supply, low oil movement into the system and easy maintenance (Fröschle, 2012, 2011).

The number of scientific studies for R-744 compressors is limited and these have been conducted considering different types of compressors, such as semi-hermetic reciprocating (piston) (Hafner et al., 2013, 2012; Javerschek et al., 2019, 2017; Javerschek and Yi, 2019; Ma et al., 2011), rotary rolling piston (Ooi, 2008), rotary vane (Chinen et al., 2014), rotary scroll (Zheng et al., 2020), and oil-free (Hafner et al., 2011; Kurtulus et al., 2014; Kus and Nekså, 2013a, 2013b).

On the other hand, the compressor manufacturers are making great progress in R-744 compressor development. One major Italian manufacturer claims that CO_2 will be one of the few regulatory-proven, long-term alternatives to synthetic refrigerants (McLaughlin, 2017; Stausholm, 2021), especially to R-22, which is currently the dominant refrigerant in refrigeration systems of the global fishing fleet. According to the information collected from compressor manufactures, semi-hermetic reciprocating CO_2 compressors are most often applied compared to the rotary rolling piston, rotary vane and rotary scroll compressors for smaller capacity units. Due to the semi-hermetic structure, there is no leakage through the shaft seal (Ma et al., 2011).

In Table 1, the data range of several specifications for commercially available R-744 compressors is listed (only the data shared by the manufacturers are shown in the table). There are now semi-hermetic

Table 1
Key data for commercially available R-744 compressors at 50 Hz.

Specification	Units	Subcritical	Transcritical
Number of cylinders		2-4	2-6
Displacement	m^3/h	1.33 - 64.9	1.12 – 98.58
Operating pressure	bar	~65	~150
Maximum cooling capacity	kW	~65 (at T_c/T_e=10/-35 °C)	~130 (at T_{gc}/T_e=35/-10 °C, P_{gc}=90 bar)
EER*	-	3.67 – 4.28 (at T_c/T_e=5/-35 °C)	1.82 – 1.91 (at T_{gc}/T_e=35/-10 °C, P_{gc}=90 bar)

* EER values collected from GEA BOCK.

type compressors with six cylinders, an energy efficiency ratio (EER) of 1.91 (transcritical system at T_{gc}/T_e=35/-10 °C, P_{gc}=90 bar, provided by Gea Bock), displacement of up to approximately 100 m^3/h and operating pressure of up to 150 bar (Bitzer, n.d.; Bock, n.d.; Copeland, n.d.; Dorin, 2021; Frascold, n.d.). The R-744 compressor manufacturers have achieved higher isentropic and volumetric efficiencies, higher cooling capacities (as required for marine applications), less operating costs, lower noise levels, less vibration, and improved oil management (enabling on-board installations and less oil carry-over to the system). These are key advancements particularly for the R-744 installations in fishing vessels that face high dynamic forces. The higher efficiencies and capacities in semi-hermetic piston compressors have been achieved through an increase in the number of cylinders along with optimised components of the compressor, capacity control over changing load conditions, lower oil carry-over to the system, and improved compressor thermal management (Fröschle, 2012, 2011; Javerschek et al., 2019, 2017; Javerschek and Yi, 2019).

3.1.2. Heat exchangers

Gas coolers and evaporators are core components like compressors that are necessary for the system operation. In transcritical R-744 systems, the heat rejection takes place in a gas cooler. The heat is removed from the refrigerated space via evaporators. Internal heat exchangers are used to recover heat within the system. In the development of heat exchangers, the fundamental target is basically to increase the overall heat transfer coefficient and reduce the pressure drops. Due to the restrictions and requirements, effort is needed to find the optimum design for the heat exchangers implemented for different applications.

When designing a gas cooler, the goal is to achieve the lowest possible high temperature side pressures and achieve a minimal temperature difference between the refrigerant exit temperature and the heat sink temperature (Yin et al., 2001). Through these, the power demand of the compressor is reduced, and the system's cooling capacity is increased. Various types of existing gas coolers were under investigation: tube-in-tube (Yu et al., 2014, 2012), helical coil-in-fluted, finned, water-coupled microchannel (Fronk and Garimella, 2011), air-cooled microchannel (Yang et al., 2019) and water-coupled microchannel (Zilio and Mancin, 2015). Regarding R-744 evaporators, in a few studies, the researchers investigated the heat transfer coefficient and pressure drop for an evaporator with vertical smooth and micro-fin tubes (Kim et al., 2008) and for an air-cooled finned evaporator (Bendaoud et al., 2010; Larbi Bendaoud et al., 2010).

The number of scientific studies on gas coolers and evaporators utilized in the R-744 unit for fishing vessels needs to be increased to meet certain requirements for the robust and safe operation of the R-744 unit under harsh sea conditions. In most fishing vessel applications, seawater is used as a heat sink or refrigerated medium (to cool down the fish), hence, it is critical to design them while taking into consideration the properties of seawater.

3.1.3. Heat exchanger improvements by the manufacturers

As with the development of R-744 compressors, significant development progress has been achieved by the manufacturers of R-744 heat exchangers (gas cooler, evaporator, sub-cooler, etc.) (Koegelenberg et al., 2020). The manufacturers are encouraged by the rapid growth in the R-744 market areas and consequently motivated to invent cost-efficient and innovative design solutions to gain a high market share in the future.

According to the manufacturers' information, heat exchangers specifically designed for R-744 are currently commercially available with an operating pressure of up to 140 bar and a cooling/heating capacity of up to 1000 kW. The design targets in heat exchangers are high performance/efficiency at high operation pressure, cost-effectiveness, low-pressure drop, reliability, durability, safety and compactness (space-saving) (Laval, 2021; Carrier, 2021; Kaori, 2021; Kelvion, 2021; Lu-ve, 2021). These specifications are required by end-users. Specifications such as robustness, reliability, durability and safety of the heat exchangers become more important in terms of fishing vessels operating under turbulent sea conditions. The heat exchangers used in fishing vessels must also be resistant to corrosion.

3.2. Enhancements in system energy efficiency

The layout and *P-h* diagram of a basic transcritical R-744 refrigeration system with two different evaporation temperature levels, also known as a "Basic booster system (BBS)", is shown in Fig. 2. Downstream of the high-pressure control valve (HPV), there is a liquid vapour separator and a flash gas by-pass valve (FGBV) maintaining the pressure level in the separator. These booster systems represent the base system applicable in fishing vessels operating in cold regions such as in Norway where the maximum seawater temperatures are below 20°C all throughout the year (World Sea Temperatures, 2020). In order to apply the R-744 systems to the vessels operating in hot climates, further energy-efficient solutions, heat recovery and thermal energy storage as mentioned in the following sections must be implemented.

3.2.1. Parallel compression

An R-744 BBS might face energy efficiency challenges in regions with elevated heat sink temperature levels, as an elevated sink temperature leads to a significant increase in flash gas and requires higher gas cooler pressure levels. A transient model was developed by (Brodal et al., 2018) for an R-744 RSW system to analyse the effect of seawater temperature on the system performance. They reported that the COP and cooling capacity of the system decreases with rising seawater temperatures. The COP was five for the Barents Sea (Northern Europe) while it was between three and 3.5 for the Mediterranean Sea. With the help of parallel (auxiliary) compressors (PCs), the pressure level in the separator is maintained and the vapour is directly compressed to the high-pressure side (Gullo et al., 2018; Karampour and Sawalha, 2018). This makes the system with parallel compression more efficient than the R-744 BBS (Chesi et al., 2014; Javerschek et al., 2016). This enhanced system configuration can also enable the application of transcritical R-744 refrigeration systems for fishing vessels operating in warm seawater regions.

An example of a PC application in an RSW chiller is shown in Fig. 3 (shown by dashed blue line). This system was investigated by Bodys et al. (2018) and they reported up to 12% and 17% increase in the COP of the chiller at the Mediterranean and East-Asian seawater temperature conditions, respectively, with the parallel compression solution.

3.2.2. Integration of multi-ejectors

Advanced ejectors, called multi-ejectors (MEs)[1], have been developed for various R-744 refrigeration systems. MEs control the high temperature side pressure and at the same time expand the refrigerant from the high-pressure side to intermediate pressure. They also transfer the refrigerant from the medium pressure to intermediate pressure level in the phase of either liquid or vapour, as shown for an R-744 RSW cooling system in Fig. 4 (Hafner et al., 2014). In this way, a significant amount of load is shifted from the so-called base compressors to the PC, leading to a lower total compressor power demand and therefore to an increased system energy efficiency/COP.

The *P-h* diagram of two R-744 RSW systems developed for fishing vessels is presented in Fig. 5. In the *P-h* diagram, the expansion of high-pressure flow and the pressure lift, achieved by the ME, can be seen by green dashed lines (Bodys et al., 2018).

One of the main ejector performance indicators is ejector efficiency, and it strongly depends on geometrical design and operating parameters (Smolka et al., 2016). According to the results of various studies, the maximum achieved ejector efficiency is recently measured at up to 40%

[1] MEs: Several fixed geometric ejectors with integrated check valves.

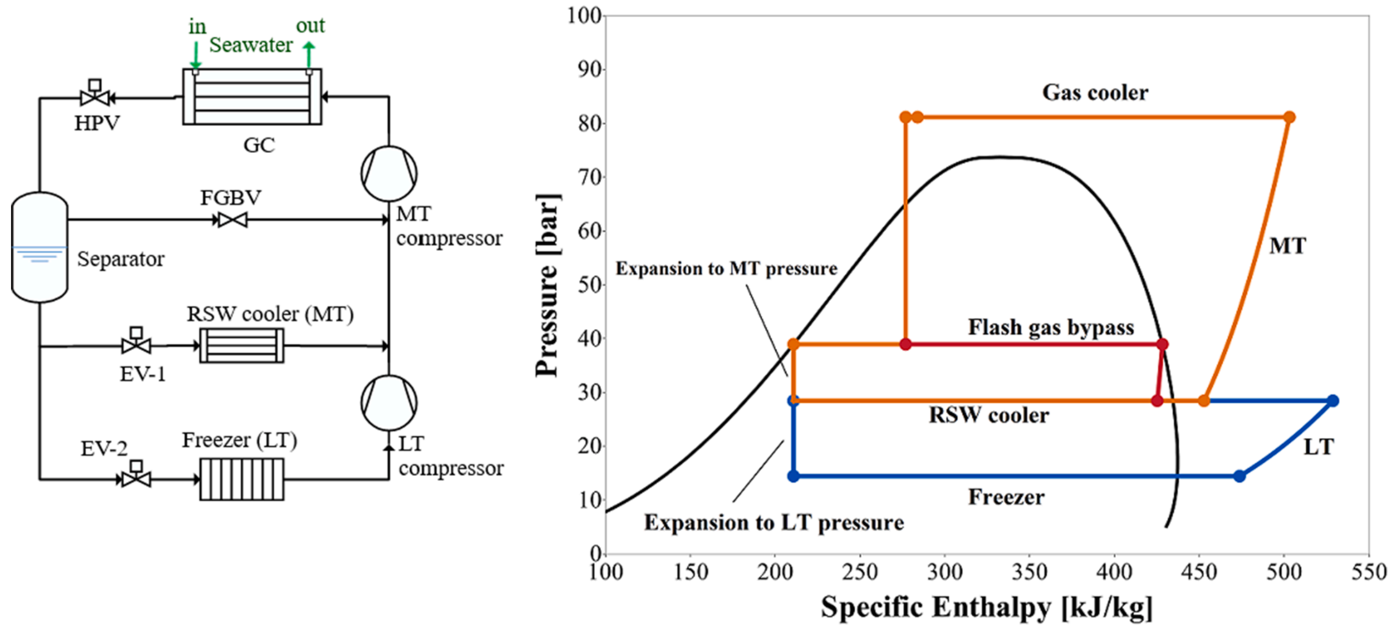


Fig. 2. Basic booster system's layout and its *P-h* diagram.

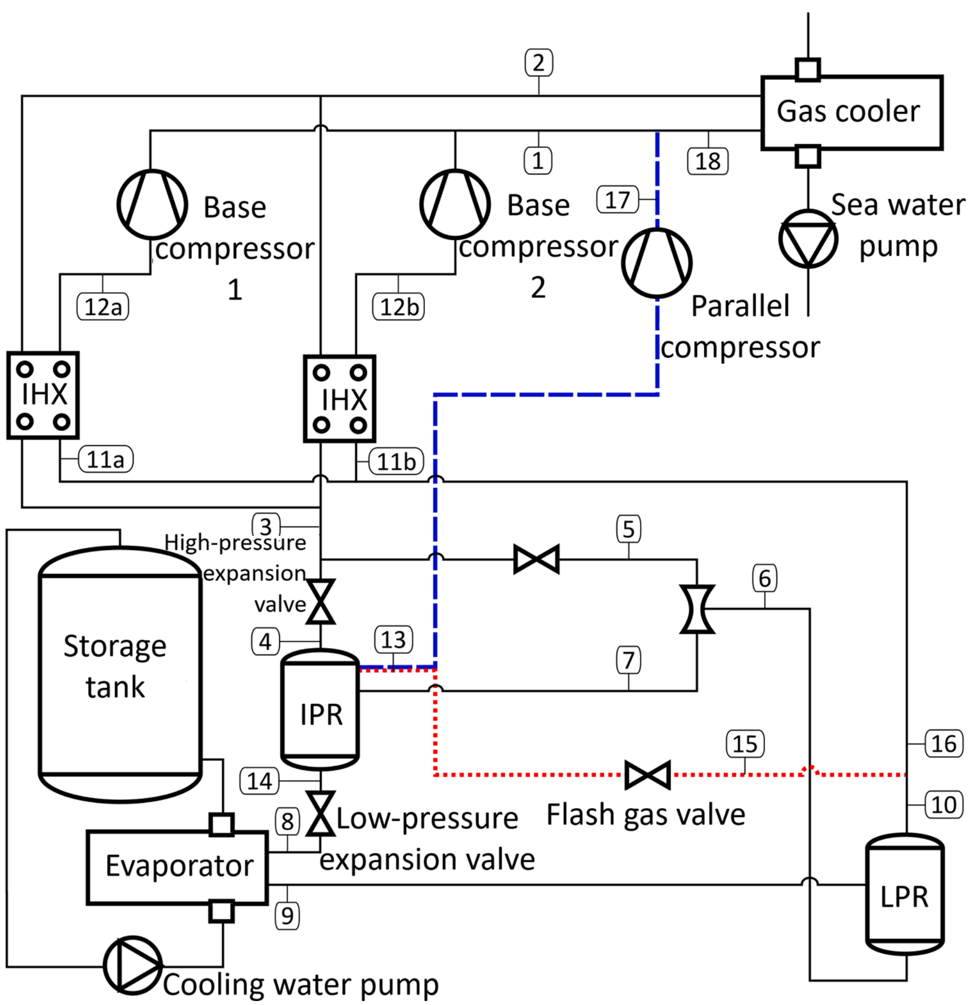


Fig. 3. The layout for R-744 booster system for RSW with PC. The processes for PC and FGBV are shown in blue and red colours, respectively, with the permission of Bodys et al. (2018). The flow direction is clockwise. 12a-1 and 12b-1: base compression, 1–2: heat removal through the gas cooler, 3-4: Expansion to the intermediate-pressure receiver by expansion valve, 5-7: throttling and mixing in the ejector, 8-9: evaporation, 9-10: vapour refrigerant from the evaporator to the low-pressure receiver, 10-11a and 10-11b: vapour refrigerant from low-pressure receiver to the base compressors, 14-8: expansion to the evaporator by expansion valve, 13-15: flash gas from intermediate-pressure receiver to low-pressure receiver13-17: compression of intermediate-pressure vapour refrigerant to high-pressure by the parallel compressor.

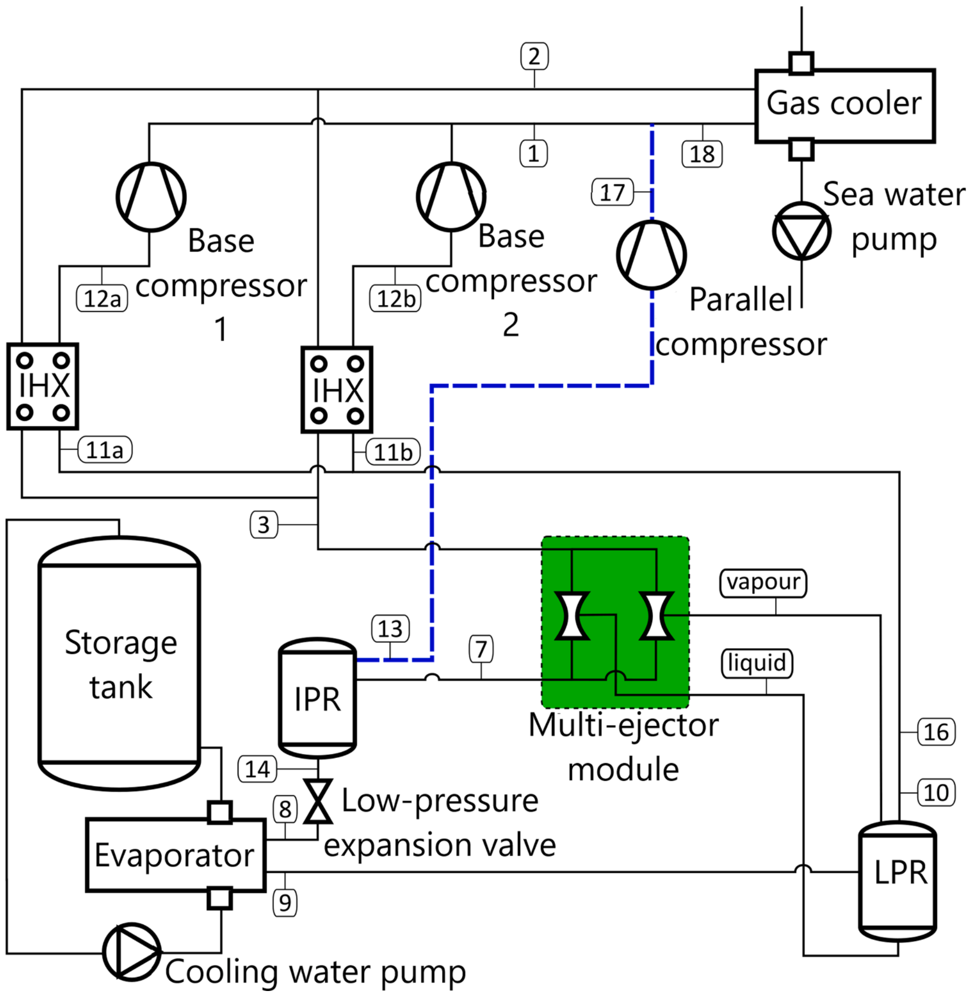


Fig. 4. . The layout of R-744 booster system for RSW with ME with the permission of Bodys et al. (2018). The flow direction is clockwise. 12a-1 and 12b-1: base compression, 1–2: heat removal through the gas cooler, 3-7: throttling and mixing in the multi-ejector, 8-9: evaporation, 9-10: vapour refrigerant from the evaporator to low-pressure receiver, 10-11a and 10-11b: vapour refrigerant from low pressure receiver to the base compressors, 14-8: expansion to the evaporator by expansion valve, 13-17: compression of intermediate-pressure vapour refrigerant to high-pressure by the parallel compressor.

(Bodys et al., 2016; Palacz et al., 2017; Smolka et al., 2016). Moreover, the system with the ME has between 7-9% higher COP compared to the system with parallel compression (Section 3.2.1) (Boccardi et al., 2016; Haida et al., 2016). Bodys et al. (2018) analysed the different proposed configurations to enhance R-744 refrigeration systems applied to fishing vessels operating in the regions with hot climates - the Mediterranean (the seawater temperature varies from 18 °C to 21 °C) and East-Asian climates (the seawater temperature varies from 30°C to 33°C), via the mathematical model that they developed. The results of their study are summarised in Table 2 for maximum COP of various systems. The highest COP was achieved by the system with ME, as compared to BBS and BBS+PC, with a value of between 2.98 and 3.22, and between 2.35 and 2.58 for the Mediterranean and East-Asian climates, respectively. In other words, the system with ME has up to 21% and 8% higher COP compared to BBS and BBS+PC, respectively, in the Mediterranean climate. In the East-Asian climate, the difference is up to 56% and 34% compared to BBS and BBS+PC, respectively.

In more recent studies, the results have also shown that ME improves the energy efficiency/COP of the system. Liu et al. (2021) investigated a CO_2 supermarket refrigeration system with different configurations in various climatic zones. By implementing ME, the increase in energy-saving was just above 25% and the increase in seasonal energy efficiency ratio was around 35% in all climate zones (Liu et al., 2021). Expósito-Carrillo et al. (2021) presented that an ejector can increase the COP of a two-stage CO_2 refrigeration unit by up to 13% compared to the system without an ejector, at 25 °C of outdoor temperature (Expósito--Carrillo et al., 2021). Elbarghthi et al. (2021) experimentally proved that the ejector could recover almost 37% of expansion losses in a R-744 refrigeration system (Elbarghthi et al., 2021).

3.2.3. *Effect of Internal heat exchanger (IHX)*

An internal heat exchanger is an important component for enhancing the energy efficiency and secure sufficient superheat upstream of the compressor suction in a transcritical R-744 refrigeration and heat pump system. It transfers heat from the high-temperature side of the system to the suction line of the compressor. In addition, the IHX subcools the high-temperature refrigerant before entering the expansion valve (thus, reducing the amount of flash gas and reducing the expansion losses) (ASHRAE, 2018). Refrigerant exiting the evaporator in the liquid phase may have in some cases over time a detrimental effect on the compressor, and without an IHX it is not simple to secure the superheat and comply with the warranty requirements of the compressor manufactures.

Aprea and Maiorino (2008) experimentally evaluated the effect of a coaxial IHX in a transcritical R-744 refrigerator. They compared R-744 evaporating and suction temperature, refrigerant mass flow, COP, and refrigeration capacity with and without IHX. They reported that the COP (10% higher) and refrigeration capacity of the system with IHX were significantly higher compared to measurement results for the system without IHX (Aprea and Maiorino, 2008). An experimental and numerical study aiming to analyze the effect of an IHX (helical double tube coils) used in a single-stage transcritical R-744 cycle was performed by Rigola et al. (2010). The numerical model, founded on a global algorithm, was validated by measurements. Both experimental results and numerical predictions showed that an IHX enhances the COP by around 20% and 30% at an ambient temperature of 35 °C and 43 °C,

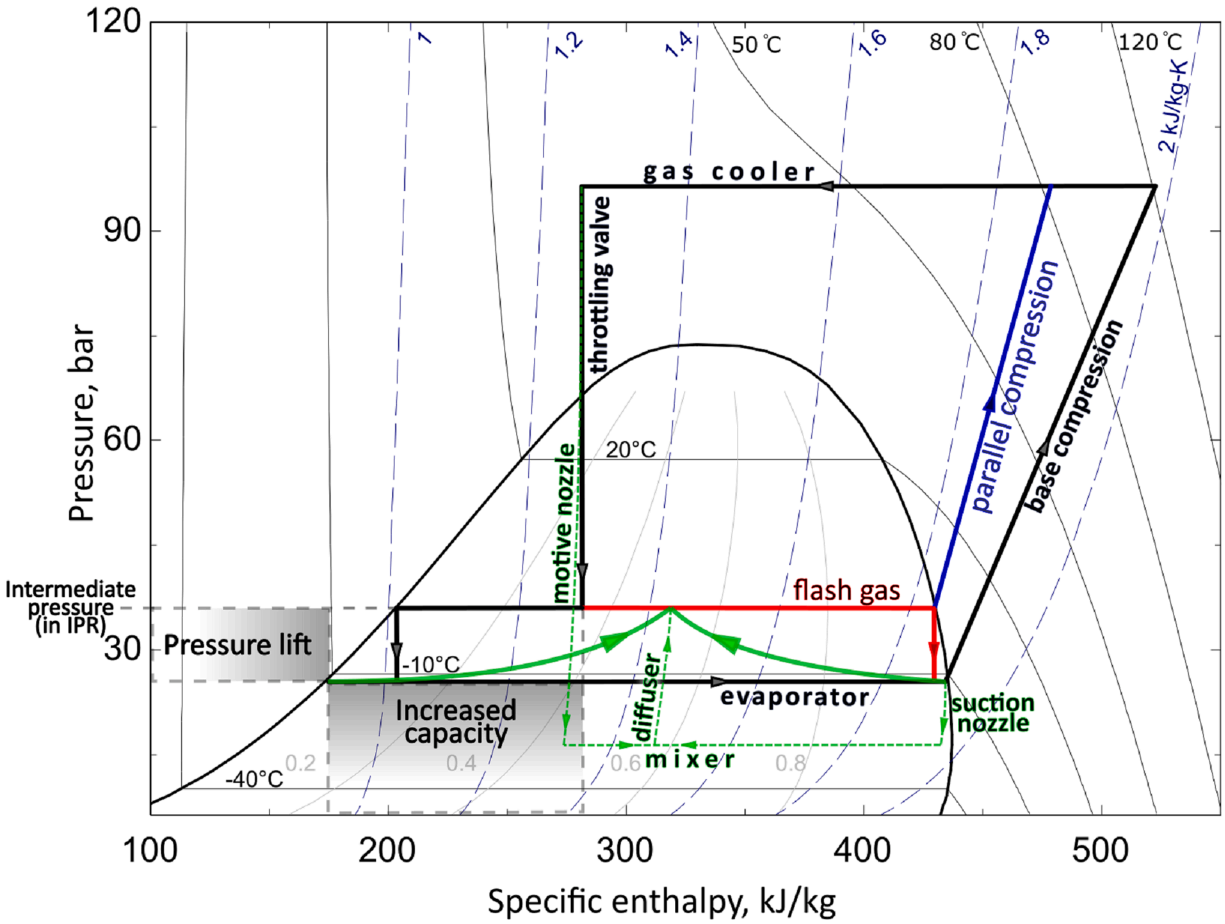


Fig. 5. *P-h* diagram of the R-744 booster system for RSW with PC, FGBV and ME. The processes for PC, flash gas bypass and ME are shown with blue, red and green colours, respectively, with the permission of Bodys et al. (2018). For the application shown in Fig. 3, there is no ME, hence the diagram must be without green lines. For the application shown in Fig. 4, there is no flash gas.

Table 2
Overview of the COP of different systems (Bodys et al., 2018).

System	Intermediate pressure	Mediterranean Highpressure	COP	East-Asian Highpressure	COP
	bar	bar		bar	
BBS	35 - 45	65	2.55 – 2.66	97.3	1.61 – 1.65
BBS + PC	35 - 45	65	2.84 – 2.98	92.5	1.90 – 1.93
BBS + PC +ME	34 - 38	65	2.98 – 3.22	94.6	2.35 – 2.58

respectively (Rigola et al., 2010). The performance of a counterflow IHX with a copper single-pass double-pipe was experimentally evaluated by Torrella et al. (2011). They conducted in total 90 tests (44 tests with IHX) and considered various parameters such as evaporating temperature, gas cooler outlet temperature and high side pressure. The experimental results show that both cooling capacity and COP of the system are increased by 12% with IHX (Torrella et al., 2011).

3.3. Heat recovery and thermal storage (integrated R-744 systems)

The unique properties of R-744 enable the recovery of heat from the high and intermediate temperature stage of the refrigeration system in order to produce domestic hot water (DHW) (up to 85°C) (Stene, 2004) and to cover AC demands all year round and provide space heating (SH) (up to 45°C) when required. Furthermore, integrating thermal energy storage (TES) solutions into the system brings flexibility and further benefits (IRENA, 2020). The thermal storage can be either cold storage (Selvnes et al., 2021) or hot storage depending on the system and demands on the end-user sides. Basically, the required load for both cooling and heating can change within the day. Thermal storage is a smart solution to reduce the peak loads and manage the shift loads within time periods. Consequently, it enables more stable operating of the refrigeration equipment while at the same time reducing the total energy consumption. Space requirements can be challenging, especially in marine applications. Saeed et al. (2021) numerically investigated an RSW system with TES for a fishing vessel to reduce the total chilling time of the system. They achieved a decrease in chilling time (Saeed et al., 2021).

Verpe (2018) numerically investigated the performance of an industrial plate freezer with R-744 including a thermal storage in which CO_2 is utilized as phase change material. He developed a numerical model for the freezing time of fish blocks and verified the model's predictions through experiments with 3% deviation. He reported that it is possible to reduce the freezing temperature to as low as -50 °C with R-744, which resulted in short freezing times and increased production capacity. Further reduction in freezing times and increase in product capacity up to 3% was achieved through applying cold thermal storage devices (Verpe, 2018).

3.4. The benefits of R-744 developments for fishing vessel applications

Even though the developments mentioned in the previous sections have not been entirely targeted for R-744 refrigeration systems in fishing vessels, these developments provide some benefits that will likely help R-744 systems to be applied to fishing vessels. The reason is that, beside safety aspects, the energy-efficiency enhancements have increased the competitiveness of transcritical R-744 refrigeration systems over conventional HCFC, HFO and R-717 based systems applied to the vessels. R-744 becomes a competitive option for fishing vessels operating in all climate regions, with an increasing number of installations together with studies proving its benefits and reliability. On the other hand, the design and energy efficiency-related improvements have made the R-744 system a safe, compact, natural refrigerant-based, eco-friendly alternative to conventional F-gas systems or other flammable refrigerants on fishing vessels. For instance, R-744 compressor capacities have been increased, enabling contractors to build more compact systems with a reduced number of compressors. In addition, the integration capability of R-744 refrigeration when refurbishing vessels and its ability to utilize heat recovery in a compact design shows that the R-744 installation occupies a smaller space compared to the previous/traditional separate systems. The compactness of the system is vital for fishing vessels that usually have limited space for installation. The most important benefit when applying R-744 equipment in fishing vessels is that the equipment can provide freezing at temperature levels below -50 °C. This is not possible with other conventional fluids and enables significantly reduced freezing times when processing the valuable catch and securing fast storage at low temperatures to maintain quality and obtain a maximum price further down in the value chain.

An integrated R-744 refrigeration system has been proposed for a fishing vessel that is designed to provide RSW, freezing, AC cooling, space heating and DHW, as shown in Fig. 6 (Semaev, 2021). Most of the energy-efficient solutions, together with heat reclaim and thermal storage opportunities, are implemented within the system. These kinds of R-744 systems have received global attention, meaning more such systems will be built in the near future. The current status of R-744 refrigeration technologies in fishing vessels will be described in the following section.

However, it should be noted that there is still a need for advancements in R-744 systems applied to fishing vessels. This will be discussed in Section 5 and suggestions will be made by the authors.

4. Status of R-744 refrigeration technologies in fishing vessels

In 2016, the UNEP task force report on alternatives to refrigeration systems for fishing vessels (Pachai et al., 2016) concluded that systems with R-717 and/or R-744 present feasible options to replace R-22 for almost all the possible applications. Hafner et al. (2019) reviewed refrigeration equipment onboard marine vessels, including fishing vessels, with a focus on Nordic countries and the achievements made with systems applying natural refrigerants. For fishing vessels, it was shown that all new installations in Norway apply R-717 or R-744 for the RSW systems, and that R-717/R-744 cascade freezing systems are also commonly applied.

This section summarises the current status of R-744 systems on fishing vessels. Again, since the number of scientific studies is limited, some commercially available systems, as presented by the manufacturers, are also highlighted.

4.1. Cascade systems with R-717/R-744

In 2001, the ever first R-717/R-744 cascade system was introduced as a replacement for R-22 systems onboard a fishing vessel. Since then, several fishing vessels have been built with or converted to such systems, among them all Dutch trawlers (Pachai, 2017). Fig. 7 shows a principal sketch of a cascade system using R-744 in the low-temperature (freezer) cycle and R-717 in the higher temperature cycle, while Table 3 gives an overview of some installations of such systems onboard trawler vessels.

The first system, installed on a Norwegian purse seiner/trawler had a total refrigeration capacity of 1350 kW at an R-744 evaporation temperature of -48 °C. The R-744 low-temperature side consisted of 11 vertical plate freezers, one vertical flake ice machine and natural air convection coils in three cargo holds. Due to the low evaporator temperature, a 40% reduction in product freezing time was achieved, compared to R-22 systems at -40 °C (Nielsen and Lund, 2003).

Some subsequent implementations of R-717/R-744 cascade systems (Table 3), applied for vertical plate freezers, are presented by Pachai (2017) and (GEA, 2019a). To serve as a buffer, the vessels are generally also equipped with RSW systems cooled by one or two R-717 screw compressors.

Pachai (2017) highlighted the compactness of R-717/R-744 cascade systems compared to conventional R-22 systems and two-stage R-717 systems. The compressor volume flows and weight, as well as pipe dimensions of LT suction and discharge lines, were compared for the LT stage, at a capacity of 100 kW at evaporation temperature of -40 °C and condensation temperature of -5 °C. The R-22 and R-717 compressor require about 10 times larger suction volume flow than the R-744 compressor (9 and 11 times respectively), and three times larger discharge and suction line dimensions. The R-744 compressor weight is only 288 kg (2×144 kg), compared to 1100 kg for the R-22 compressor and 2170 kg for the R-717 (2×1085 kg) compressor. The COP for the LT side (at -50 °C /-5 °C) is 2.9 for the R-717/R-744 cascade system and 2.2 for the two-stage R-717 system.

The state-of-art commercial R-717/R-744 cascade system for fishing vessel applications is reported to give a 25% higher freezing capacity within the same floor space, compared to a two-stage R-717 plant. In addition, at low evaporation temperatures down to -45 °C, COP is increased by up to 15% (Controls, 2021).

4.2. R-744-only systems

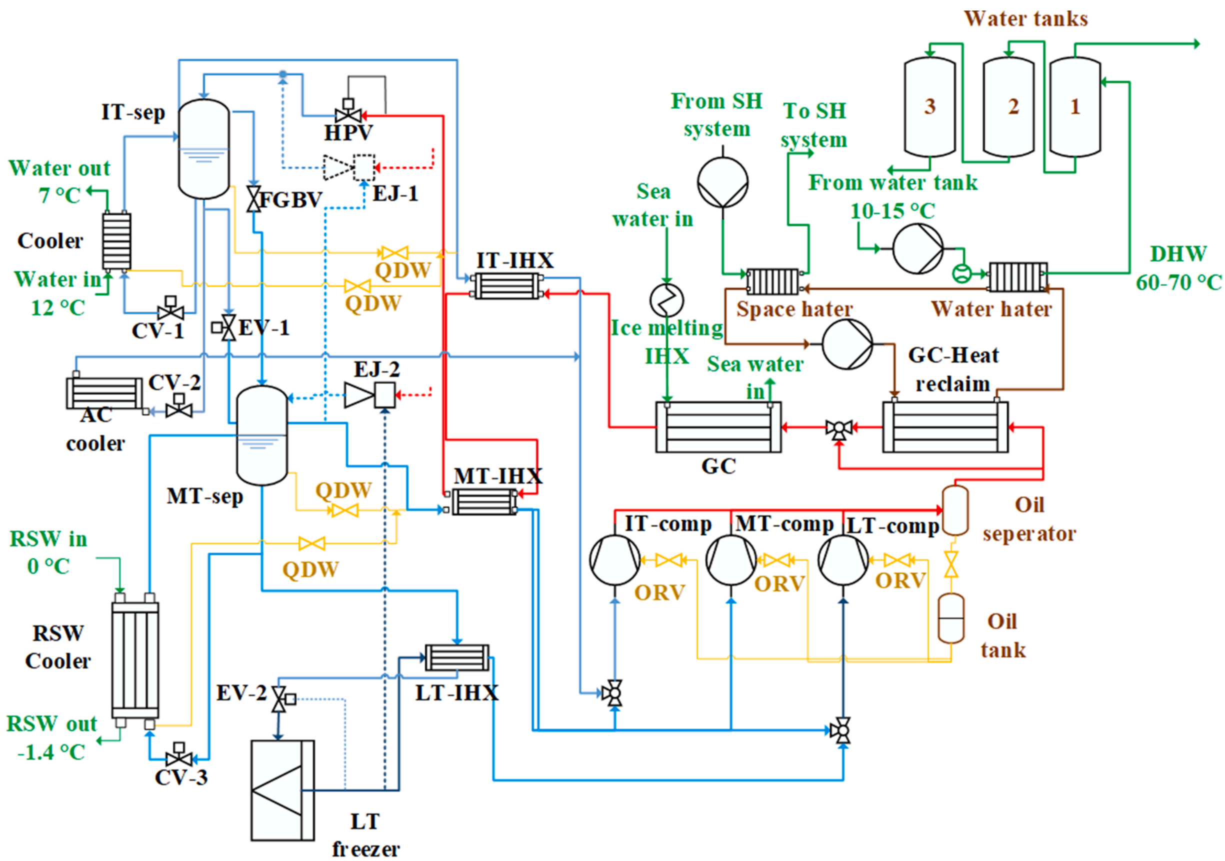
While cascade systems utilize the different properties of two refrigerants in two separate systems, an R-744-only system may have some advantages with regard to space requirements and maintenance efforts, especially for smaller size fishing vessels (Pachai et al., 2016). R-744-only systems are available both for RSW cooling and for freezing applications, as summarised in Table 4, and further described in Sections 4.2.1 and 4.2.2.

4.2.1. RSW plants

In Norway, RSW systems have been used to chill fish onboard for more than 50 years, especially for pelagic fish. These systems mainly use R-717, but the number of systems applying R-744 is increasing. Much of the research and development on R-744 RSW systems has been conducted in Norway, as described in (Andresen et al., 2011; Bodys et al., 2018; Brodal et al., 2018; Grimsmo et al., 2016; Nekså et al., 2010; Nordtvedt and Ladam, 2012; Rekstad et al., 2015).

The first RSW R-744 prototype, installed on a Norwegian trawler in 2012 consists of four transcritical compressors, a shell-and-tube condenser with R-744 on the tube side, and a flooded evaporator. The system has worked as expected, also with varying ambient temperatures and under tough weather conditions. Measurements for one week of operation, with seawater temperatures of around 4°C, showed COP values of seven (Widell et al., 2016). To reduce cost, charge, weight and size some improvements were made, including the development of a new plate heat exchanger of "dimple type design" for both the evaporator and the condenser. The upgraded system was demonstrated in 2014 on a Norwegian purse seiner, replacing the R-22 system. It consists of two separate systems, each with a cooling capacity of 150 kW. The compressors are frequency controlled and can operate between 40% and 100%. Reported experiences are more stable operation, keeping an RSW temperature of -1.3°C, as well as less noise and vibration from the compressors (Rekstad et al., 2015).

Since these first prototypes were launched, further R&D work has been done and more than 50 units of this type have been installed on



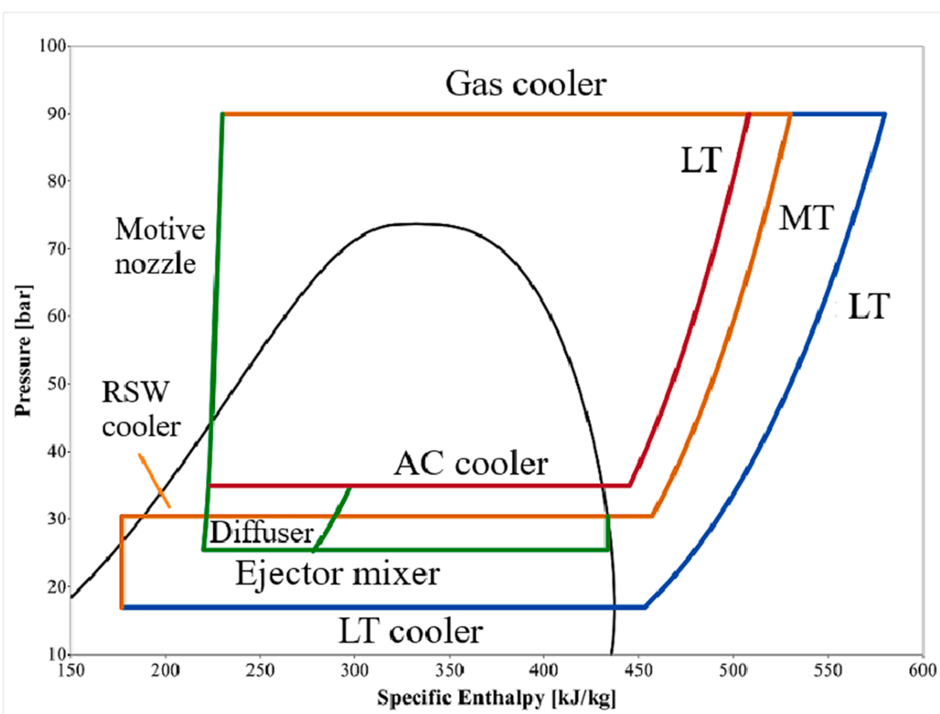


Fig. 6. The proposed system to meet cooling and freezing needs in fishing vessels, particularly RSW demand: CO_2 only, fully integrated refrigeration system for fishing vessels (Semaev, 2021). The flow is in the counter-clockwise direction. CO_2 is compressed by the compressors. The heat is utilized from the gas coolers, which are cooled down by the seawater, to supply DHW and SH. RSW cooler is a gravity-fed flooded evaporator. For AC cooling needs, a flooded evaporator (AC cooler) is utilized. The LT freezer operates on direct expansion conditions which means a section of the evaporator was used to superheat the refrigerant before entering the LT compressor. Depending on the operation mode, the CO_2 is throttled by HPV or ejector. There is a separator at the IT and MT stages to separate liquid and vapour phases.

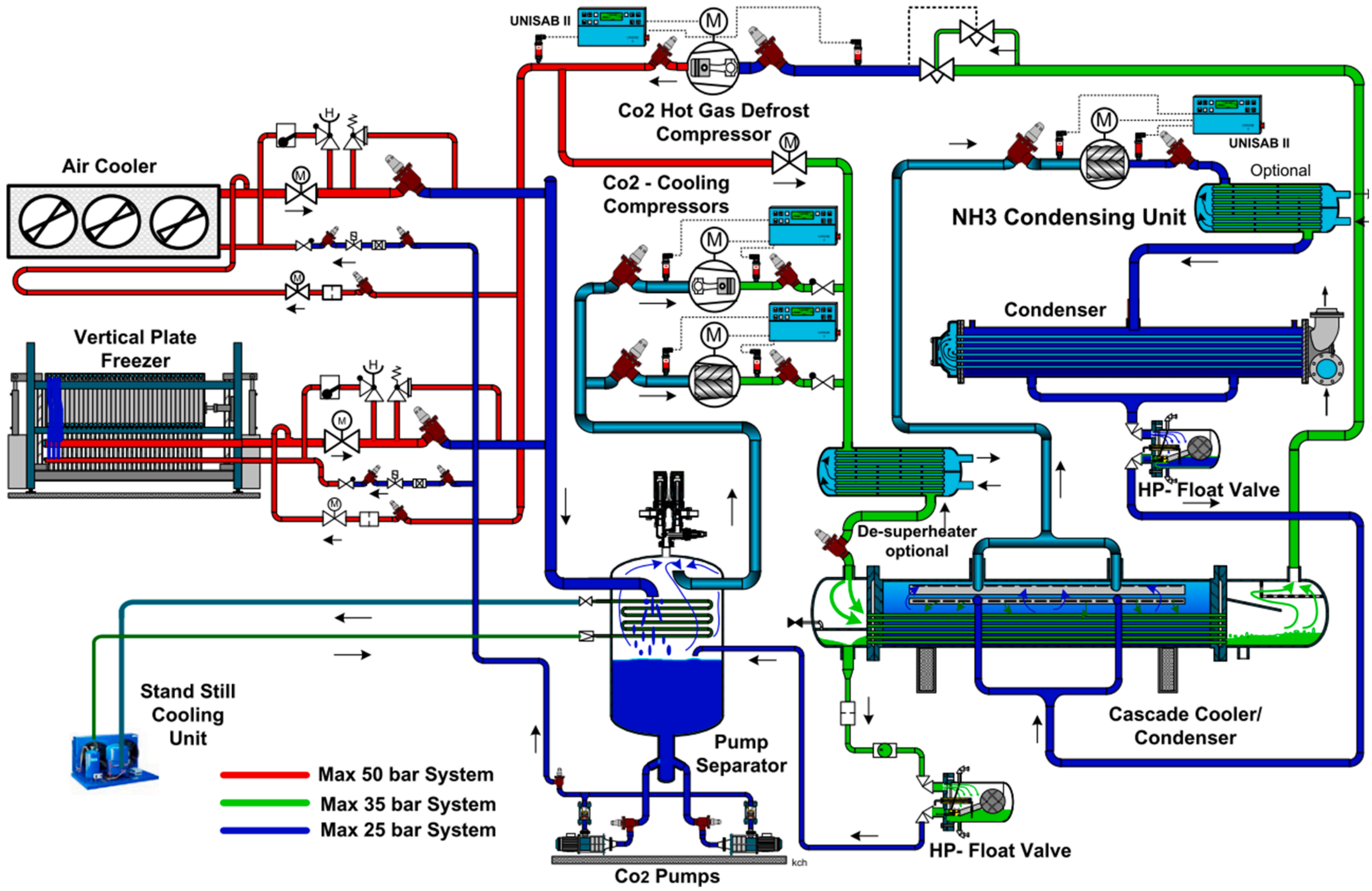


Fig. 7. An example of an R-717/R-744 cascade system for a marine application, with the permission of the author (Pachai, 2017). NH_3 cycle (on the right-hand side): The high-pressure NH_3 is sent from the screw compressor to the condenser via an optional de-superheater. The NH_3 is condensed as heat is rejected to the cooling water circuit. The liquid NH_3 is expanded by the HP-float valve to the evaporation pressure of the cascade heat exchanger in which NH_3 gains heat and evaporates. The evaporated NH_3 condenses the vapour CO_2 of the low-temperature stage and returns back to the NH_3 screw compressors. CO_2 cycle (on the left-hand side): The CO_2 compressors (screw- and piston type) maintain the pressure/temperature level inside the CO_2 separator. The HP-float valve of the CO_2 circuit supplies the liquid CO_2 to the separator. Pumps are circulating the liquid CO_2 to the various expansion valves where the liquid CO_2 is further throttled to the low temperature level of the air cooler and freezers. The fish products are cooled by the air coolers (storage) and vertical plate freezers (freezing of blocks). A dedicated CO_2 hot gas defrost arrangement is implemented with a separate CO_2 compressor (shown on the top) utilizing vapor of the cascade condenser to deliver heat towards the air coolers and the freezers when defrost or a release of the frozen block is required. A small capacity stand still cooling unit maintains the pressure level inside the CO_2 loop in case of standstill of the main unit by recondensing the boiloff CO_2 vapour.

Table 3
Examples of R-717/R-744 cascade systems installed on fishing vessels.

Year	Vessel length [m]	Nationality	Freezing capacity[tons/ day]	Number of compressors	
				R-717 screw	R-744 reciprocating
2001	75	Norway	201	2	4
2004	86	Denmark	180	6	3
2014	115	Russia	240	2	6
2019	142	Dutch	250		

fishing vessels, still mostly on Norwegian vessels. Today's model (PTG, 2021a), the transcritical unit "SeaCO₂ol", offers cooling capacities from 50 kW up to 450 kW, cooling seawater from 8°C to temperatures close to the freezing point. The system is equipped with ejectors and heat exchangers with titanium tubes. Further development is focused on larger capacity compressors. A similar system is the "CO₂PRO RSW" unit (TheExplorer, 2021) which has been installed on more than 10 existing Norwegian vessels, down to 10 m in length and is normally equipped with ice or an ice slurry system. Replacing it with an R-744 RSW plant prolongs the time at sea, but without the need for large re-builds often associated with R-717 retrofits on smaller vessels.

Table 4
Summary of R-744 only systems for fishing vessel applications.

Plant type (year)	Refrigeration capacity kW	tons/ day	Evaporation temp. [°C]	No. of compressors
First RSW (2012)	250		-5	4
Today's RSW (2021)	50 - 1000		-5	1 - 5
First Freeze (2014)		40	Down to -50	11
Today's Freeze (2021)	50 - 300	10 - 60	Down to -50	3 - 10

The increasing interest in R-744 has resulted in the market introduction also outside of Norway. In 2019, the R-22 RSW plant on an Alaskan 45-meter trawler, built in 1979, was replaced by an R-744 plant (GEA, 2019b). The system, which has a cooling capacity of 500 kW for keeping up to 340 tons of pollock fresh on the several days' journey back to port, was easily fit into the existing space (8×1×2 m). Three compact semi-hermetic compressors, all equipped with frequency converters, enable highly-efficient operation also at part-load and provide extra capacity if operated on 70 Hz. The system mostly operates in the sub-critical range, however, is designed for transcritical operation with a non-superheated evaporator. Following this installation, the Seattle based company offers refrigeration capacities from 100 kW to 1000 kW, based on GEA bock compressors and with the systems up to 200 kW using a single compressor (R744, 2019).

4.2.2. Freezing plants

The first prototype of a R-744 freezing plant was installed on a Norwegian trawler in 2014. Compared to the existing R-22 system, the R-744 plant allowed for an increased freezing capacity from 30 to 40 tonnes/day, a 20% lower space requirement, as well as 25% reduced deep-freezing time resulting in documented higher quality than conventional freezers (Hafner et al., 2019). The system is based on a booster two-stage pump-circulated system, with an air-cooled gas cooler. The pressure classification on the high, medium and low-pressure side is 120 bar, 80 bar and 52 bar, respectively. Due to the limited availability of large-capacity R-744 compressors, the number of reciprocating compressors is high – eight on the low-pressure side and three on the high-pressure side (Widell et al., 2016). Since 2016 more than 10 similar units have been installed. The prototype has developed into today's standard model, SuperFreeze, which is a transcritical pump-circulated unit with a gas cooler that is either seawater or air-cooled… It can be connected to plate, tunnel and Individual Quick Freezers (IQF) as well as cold stores. The significantly reduced freezing time not only improves the quality of the delivered fish, but also helps to remove the bottleneck that was previously related to freezing (Ladam, 2021; PTG, 2021b).

5. Prospects for R-744 refrigeration technologies in fishing vessels

This review shows that the number of transcritical R-744 units in fishing vessels is increasing, especially in cold-climate countries like Norway where seawater temperatures are low, below 20 °C (World Sea Temperatures, 2020). This is triggered by the thermodynamic and transport properties of R-744 which allow for more energy efficient operation of the cooling and freezing units in subcritical operations compared to other refrigerants. In cold climates, especially when there are freezing applications onboard, the R-744 systems are the preferred refrigeration technology. In comparison to R-717 systems, where the freezing temperatures are limited to around -40 °C (Mønsted, 2011), the more compact R-744 systems enable freezing temperatures down to -50 °C thereby significantly reducing the freezing time and the required suction pipe diameters. In some fishing vessels where the dominant cooling load is due to RSW cooling, R-717 is a viable and applied option too.

When operating the fishing vessels in higher seawater temperatures (around 30 °C), there are several design considerations depending on the main cooling demand. If chilling/RSW is the dominant part, R-717 is the most energy efficient solution. In the case of additional onboard freezing demands, a cascade R-717/R-744 unit may be considered, as the freezing temperatures can be as low as -50 °C in the R-744 part. For many ship owners, the energy efficiency of these systems has a lower priority than the freezing time, preservation of valuable food and the space required by the cooling/freezing equipment. In addition, in many regions, the transition from R-22 towards a flammable refrigerant is complicated and mostly unaccepted (DNV, 2011). For these regions and end-users willing to phase out synthetic working fluids, R-744 systems can be a viable alternative if the system architecture is adapted for high heat-rejection temperatures (Bodys et al., 2018; Semaev, 2021).

The cost of ownership for the refrigeration equipment depends heavily on the skills of the vendors. If they are able to design, implement, commission and service these R-744 systems, the end-user will decide what kind of system will be implemented in their next fishing vessel. In the case of the Nordic countries, where vendors have learned how to successfully implement R-744 systems in many sectors, some of them being able to provide successful onboard installations, the result is that several ship owners have decided to convert their entire fleet to R-744. This proofs that the R-744 refrigeration systems are providing them the lowest total cost of ownership.

There are certain requirements for fishing vessels that necessitate further developments. To begin with, refrigeration systems for fishing vessels require adapted compressors. As of today, there are no large-capacity semi-hermetic compressors for R-744 refrigeration units on the market, hence the implementation of integrated systems with a capacity of several megawatts is often not possible due to space requirements. This applies to both low-temperature (freezing below -50 °C) screw compressors and high-pressure compressors that allow the system to operate in a transcritical cycle. In regard to heat exchangers, seawater-cooled heat exchangers are crucial components for energy efficient systems. The temperature difference between seawater and refrigerant is directly related to the performance of the system. New designs are needed to reduce service and maintenance costs as well as downtime. Transcritical R-744 refrigeration units can be applied in large capacity applications when high-pressure heat exchangers are developed. Well-designed counterflow gas coolers can achieve a temperature difference of 1 Kelvin due to heat rejection at gliding temperatures, compared to the few Kelvin required when applying a condensing liquid inside the unit (Hafner et al., 2019).

In today's vessels, excess heat from the propulsion engines can be used for space and tap water heating, but this source may not be sufficient for other processes onboard, for example enzymatic hydrolysis, used for the utilization of marine raw material. Also, the development towards hybrid or fully electrified systems strongly limits the availability of surplus heat. An R-744 refrigeration system with heat recovery and/or an R-744 heat pump option solves this issue by upgrading surplus heat from the refrigeration system.

6. Conclusions and further work

The goal of this study is to gain an overview of the status and recent developments of the R-744 refrigeration systems in fishing vessels.

R-22 is today the most used refrigerant in the refrigeration systems of the global fishing fleet. In the age of rising concerns over climate change, there is a need for substituting harmful synthetic refrigerants, particularly R-22, with natural, environmentally benign alternatives. The R-717 is the prime natural refrigerant that is currently used in refrigeration systems onboard fishing vessels.

R-744 is another eco-friendly option. Depending on cooling and freezing demands, R-744 based refrigeration systems can meet the requirements of certain applications in which R-717 is not a feasible solution. The applications in which R-744 can be utilised are (1) as an R-744-only solution: the systems on fishing vessels operating in low seawater temperatures, (2) as an R-744-only solution: the systems which include a freezing function and require a higher freezing capacity, on the vessels operating in low seawater temperatures and (3) the systems which need additional freezing capacity, on the vessels operating in higher seawater temperatures, such as an R-717/R-744 cascade.

There is a particularly increasing trend in the number of R-744 units on fishing vessels in cold-climate countries, where more than 50 R-744-only units have been installed on fishing vessels since 2016. It is also a realizable alternative for the hot-climate countries if flammability is a serious concern and/or there is a need for a higher freezing demand. This achievement is triggered by improvements in the components and enhancements in system efficiency. For a wider application in hot climates, component-based improvements and the number of energy-efficient solutions needs to be further increased.

It should be noted that there is a lack of scientific efforts/studies related to R-744 systems applied on fishing vessels. The main research and development activities have recently been made by some of the manufacturers of system components and contractors. The number of scientific studies and open access publications can be significantly increased in collaboration projects with industry and dedicated public funding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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