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Abstract
This report aims to describe synergy effects of LNG driven vessels with onboard refrigeration and fish processing. An overview of conventional onboard refrigeration technologies is described, together with possibilities of utilizing "free cooling" from LNG driven vessels and the use of cold thermal storages. Given the variety of fishing vessels and thus onboard refrigeration/processing equipment, the structure of this report distinguishes between the different processes (air conditioning, chilling, freezing). Furthermore, a chapter on fuels and propulsion technologies is included as it defines boundary conditions for thermal energy management. Two sources of heat recovery are described, exhaust gas and refrigeration systems, together with possible areas where this heat can be utilized. Lastly, other options for increasing energy efficiency in fish processing is included, and this report is concluded with a suggestion on the way forward.

Executive summary

To satisfy the ever-increasing demand for food in a sustainable fashion, it is essential to reduce food losses and waste, and is specifically addressed by the UN trough their sustainable development goal number 12. The global fishing fleet is an important provider of fish and seafood, and therefore an area where improved use of energy resources would contribute towards a more sustainable food chain. All vessels have methods for keeping the fish cold for preservation reasons, either through storing on ice, chilling in refrigerated seawater or freezing in blocks. The use of onboard mechanical refrigeration systems should be increased for reducing food losses, but at the same time the energy efficiency of such systems should be improved as they can be large consumers of electricity which is often produced by fossil fuelled generators. Doing so would be beneficial with respect to reducing greenhouse gas emissions, as energy use of such systems accounts for two-thirds of these. The remaining third could be mitigated by cutting leakage of high-GWP refrigerants, i.e. transitioning towards natural refrigerants (UNEP, 2018). Besides the environmental concerns, there is obviously an economic incentive for shipowners to invest in energy efficiency measures which would reduce the overall energy use.

The main consumer of energy is however the propulsion system of a vessel, and there are several different actions for reducing its energy consumption. Recently a transition towards low-carbon fuels and improved propulsion technology has started, and this will in part alter the premises for onboard refrigeration. For example, some fishing vessels are planning to use LNG as fuel, which creates the possibility to recover "free cooling" to cover some of the refrigeration demands. Such recovery concepts exist for LNG-fuelled passenger vessels to cover parts of AC cooling demand, but there is a need to develop concepts adapted to fishing vessels given their differing operational conditions and patterns. Another under-utilized feature that is described in this report is the use of cold thermal storages, which can be used to offset the temporal mismatch between supply and demand, but also introduce increased technical flexibility, energy efficiency and improve the overall chilling process.

Recovering waste heat is another important measure to improve overall energy efficiency, and this reports focus on two sources for heat recovery, namely from the exhaust gases and from the refrigeration system(s). Heat from exhaust gases has, in general, a high quality and varying quantity dependent on load of engine, and can be used for covering e.g. hot water production, rest raw material processing or power generation (ORC). Heat from the refrigeration systems can be used to cover other demands such as room heating or snow melting, dependent on temperature levels.

Lastly, this report covers other options for increasing energy efficiency in the fish processing industry as a whole. The Norwegian land-based industry has during the last decades had an increasing focus on reducing energy consumption, and it is natural to extend this work to the fishing fleet, as many of the described measures applies for fishing vessels as well.

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1 Introduction

An estimated 15 % to 50 % of all food is lost or wasted, meaning it is produced but never eaten by humans. The FAO estimates that 35 % of fish and other seafood are lost, 30 % of cereals and 45 % of fruit and vegetables (Gustavsson et al., 2011). The UN sustainable development goals address this problem, mainly in target 12.3, which says "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses". Food loss and waste is also linked to other targets in SDG 12 and other goals, such as SDG 2 (zero hunger), SDG 6 (water management), SDG 7 (efficient energy use), SDG 8 (economic growth), SDG 9 (infrastructure), SDG 13 (climate action) and SDG 15 (life on land) (United Nations, 2020).

One important measure to reduce food losses is to use refrigeration, either chilling or freezing, which prevents food from degrading. Comparing with higher storage temperatures, reducing food temperatures keeps the product quality better and gives longer shelf life because it reduces microbiological activity, as well as chemical and physical changes (Magnussen et al., 2008; Singh, 2011; Visser, 2006). Since refrigeration requires electricity to operate compressors, pumps, and fans, increasing the volume of refrigeration systems worldwide would also lead to increased energy consumption, unless there is a simultaneous focus on increased energy efficiency for both new and existing systems. Worldwide, the refrigeration sector consumes about 17 % of the total electricity used, including air conditioning (International Institute of Refrigeration, 2015). Increasing refrigeration during food production, transport and storage will reduce losses, but those systems can also benefit greatly from energy reduction measures. Compared to the cost of developing new energy production plants, increasing energy efficiency is often far less expensive. Focusing on reducing energy consumption in these systems could not only affect total energy use, but also greenhouse gas emissions, both directly (by cutting leakage of high GWP refrigerants) and indirectly (from energy use). The direct greenhouse emissions account for less than one-third, while indirect greenhouse gas emissions account for more than two-thirds of these emissions (UNEP, 2018).

The Norwegian fishing fleet has a large potential of reducing both the total energy consumption and the emissions, because it consists of many vessels and many have a high average age. The propulsion system is the main energy user and there are several different actions for reducing its energy consumption. However, the refrigeration systems also consume a great part of electrical energy, which is produced onboard, but with less research focus until now.

This report gives suggestions of possible synergy effects with onboard processing. In chapter 2 it describes cooling and freezing onboard and utilization of cold. Chapter 3 gives a short overview of fuels and propulsion systems and suggested utilization of heat. Chapter 4 gives an overview of other options for increasing energy efficiency. Chapter 5 gives conclusions and suggestions for further work.

2 Cooling and freezing onboard

The fishing fleet of Norway consists of a range of different types of vessels, ranging from small boats to large fish factories, in total 5 978 at the end of 2019 (Directorate of Fisheries, 2020). All vessels have methods for keeping the fish cold, to preserve fish quality and shelf life. There are mainly three different methods: Store the fish on ice (which is brought from land or produced onboard), chilling in RSW (refrigerated sea water) tanks, and freezing in blocks in plate freezers. A few vessels also have quick freezers for single frozen fillets or other products. More details are given in section 2.2. Keeping the fish cold is necessary to avoid food degradation and losses, but these systems are substantial electricity consumers and would almost always benefit from efficiency improvements. The Norwegian land-based industry has, during the last decades, had an increasing focus on reducing energy consumption and it is necessary to extend this work to the fishing fleet to improve competitiveness in the world economy. One possibility is to better use the surplus heat and cold generated, which is discussed in this report. There are also other possibilities in improving energy efficiency, described in section 4. (Ates et al., 2017; Indergård et al., 2018; Stonehouse and Evans, 2015; Verpe et al., 2018; Walnum et al., 2011; Widell and Eikevik, 2010)

Some fishing vessels are planning to use LNG (Liquefied Natural Gas) as fuel for a more environmentally friendly propulsion. LNG is stored at about -162 °C and when using it as fuel it is possible to utilize the evaporation heat from the gasification of LNG to cover some portion of the cold needed to chill or freeze the fish. There exists a concept developed for cold recovery on LNG-fuelled passenger vessels, used for covering parts of the AC cooling demand. However, since the cooling demand, operational conditions and operation pattern for a fishing vessel differs in many ways from that of a passenger vessel, there is a need for developing concepts adapted to fishing vessels. Section 2.3 describes possibilities with utilizing cold from LNG.

2.1 Refrigerants and refrigeration systems

The refrigeration system capacity and temperature levels, along with the operational range, are important factors for determining which refrigerant is most suitable with respect to energy efficiency and total cost of ownership. There is no one perfect refrigerant, although ammonia has been successfully used in industrial refrigeration systems in Norway and many other countries for more than one hundred years. Systems with ammonia are energy efficient and there are large sized components available on the market. In general, refrigerants that have a high critical point compared to the system temperatures, good transport and heat transfer properties, low molecular weight and low viscosity will help improve the energy efficiency of the refrigeration system (Forbes Pearson, 2003). More details about ammonia systems are given in section 2.1.2.

Today's refrigerants in the market can be divided into three groups: saturated, unsaturated and natural working fluids. The saturated CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons) affect the climate and the environment. Therefore, they are part of phase-out programs (see F-gas regulation). The unsaturated HFCs are flammable and have toxic decomposition products (even without a fire) when leaking. Consequently, the more sustainable alternative refrigerant are the natural working fluids. Table 1 gives an overview of some refrigerants, with ODP (Ozone depleting potential) and GWP_{100} (Global warming potential, calculated over 100 years).

Table 1. Information about different refrigerants. (The Linde Group, 2020)

Formula (name)	Type	ODP	GWP_{100}
R12 (freon)	CFC	1 (high)	10 900
R22	HCFC	0.055 (medium)	1 810
R404a	HFC	0	3922
R410a	HFC	0	2088
R134a	HFC	0	1 430
R32	HFC	0	675
R1234yf	HFC / HFO	0	4
R1234ze	HFC / HFO	0	6
R717 (NH3/ammonia)	natural	0	0
R744 (CO_2)	natural	0	0
R290 (propane)	natural	0	3

2.1.1 Refrigerant phase-out plans

The Montreal protocol was initially signed by 26 countries, to regulate the use and production of chemicals that contribute to the Ozone layer depletion. Some countries have already phased out CFCs, and are phasing out HCFCs, but other countries have a longer period to implement this. The Kyoto protocol was signed in 1997, to control the negative impact on the global warming effect and it regulates the emissions of HCFCs. This was not enough, so there are newer regulations to further reduce emissions, the EU F-gas regulation from 2015 and the Kigali amendment, which came into effect in January 2019. The aim of the Kigali amendment is to reduce the HFC related GHG emissions by 80 % before 2047.

Tokle et al. (1993) investigated the usage of different refrigerants in various sectors. The fishing fleet of 600 ships reported to use 91% HCFCs, utmost R22 and the remaining 9% CFCs, most likely R12. Haukås (2007) reported a change, 82% used HCFCs (R22), 4% HFCs and a new trend towards natural refrigerant ammonia 14%. (Hafner et al., 2019). R22 is globally still the most widely used refrigerant onboard fishing vessels according to International Institute of Refrigeration (Larminat, 2018). There are less harmful hydrofluorocarbons with relatively low global warming potential (GWP) values, but these fluids are classified as flammable and require risk assessments and special safety mitigations measures. The newly introduced HFOs have a very short atmospheric lifetime due to their chemical structure, the double bond. Short atmospheric lifetime is the main reason for the low GWP values of HFOs. However, this takes neither the greenhouse gas emissions from the production into consideration, nor the environmental impact of the decomposition products. The risks related to the use of HFOs and their blends when it comes to human health, safety and the environmental impact of decomposition products are not fully understood yet (Fleet et al., 2018). It has been reported that HFO's can decompose into life-threatening substances like Trifluoroacetic acid and hydrogen fluoride. There are numerous examples in the past of apparently safe chemicals have turned out to be environmentally unacceptable, sometimes even in quite small quantities. (Hafner et al., 2019)

It is necessary for the people onboard marine vessels and to secure the investments, by converting the current refrigeration units from HFCs directly to natural working fluids, as a precautionary approach. New orders should only request for units applying natural working fluids (not just specifying for low-GWP options).

Thereby, avoiding both costly retrofit actions in the future and higher operational costs, when applying non-natural working fluids. The energy efficiency of refrigeration units applying natural working fluids is higher when comparing the performance with traditional HFC and HFO based units. (Hafner et al., 2019)

2.1.2 Ammonia system

Ammonia is a natural refrigerant with good thermodynamic properties. It has no impact on either the ozone layer or the global warming. Ammonia is well used in the land-based food processing industry in Norway, which means that there are often good handling procedures. The toxicity can create problems if there is a leakage onboard and it is therefore necessary that the system is situated in a separate room, that personnel is well trained and has appropriate safety equipment available. It is important to avoid copper components because ammonia and water will corrode copper, zinc, and their alloys. For example, ammonia and water will destroy the copper windings of the electrical motor in a hermetic compressor. Ammonia has very high latent heat and the refrigeration capacity per unit mass flow is the highest of all refrigerants used in traditional vapor compression systems. Because ammonia has low molar mass it can have much higher particle velocity than all other refrigerants and therefore small pipe sizes can be used. (Pearson, 2008a; Stoecker, 1998)

In Norway, many vessels for pelagic fishing have two independent large ammonia systems. This will ensure refrigeration even if there are some issues with one of the systems. Examples of ammonia systems onboard were described by (Widell and Ladam, 2013). There has also been some development towards smaller systems, containing less ammonia.

2.1.3 CO_2 system

Carbon dioxide (CO_2) is a natural refrigerant which is until now used for chilling and freezing onboard only a few fishing vessels in Norway. It is reliable and efficient, but not yet well known to this industry, and especially abroad in other fishing regions. An advantage of CO_2 systems is the possibility of integrating cooling and heating systems. One example is given in Figure 2.1, which is a CO_2 booster refrigeration system, working in a transcritical circuit at elevated heat rejection temperatures. It is adapted from one of the commercial refrigeration system of perfect temperature group (PTG) and modified from sub-critical to trans-critical operation to evaluate the potential of heat recovery. The low-pressure side can have a temperature down to -50 °C (6.8 bar) and the high-pressure side operating at 90 bars (maximum 130 °C). The refrigeration load is removed in the plate freezers at the lowest evaporation temperatures. The vapour fraction of the refrigerant in the return line to the low temperature (LT) separator depends on the load in the plate freezers. If the refrigeration capacity is less than the load, super-heating of refrigerant at the end of plate freezer will happen and result in temperature increase in LT separator. In the opposite scenario, vapour fraction will be less than 1. The LT separator ensures liquid flow into the plate freezer, resulting in flooded evaporators and high heat transfer rate. This system was simulated by Saeed (2020) to show working conditions. The low pressure (LP) compressor lifts the pressure from 6.8 bar to around 26 bar. The medium temperature (MT) cooler rejects heat to water and cools the refrigerant. The refrigerant from the MT cooler is then mixed with the vapour coming from the MT separator. The temperature of the vapour coming from the MT separator is around -10 °C (~26 bar). The high pressure (HP) compressor lifts the pressure of the refrigerant from 26 bar to 90 bar. The system can operate in sub-critical or transcritical mode, but this depends on the heating requirement or the ambient conditions. The gas cooler cools the refrigerant, and it is afterwards expanded in the high pressure control valve and enters the MT separator.

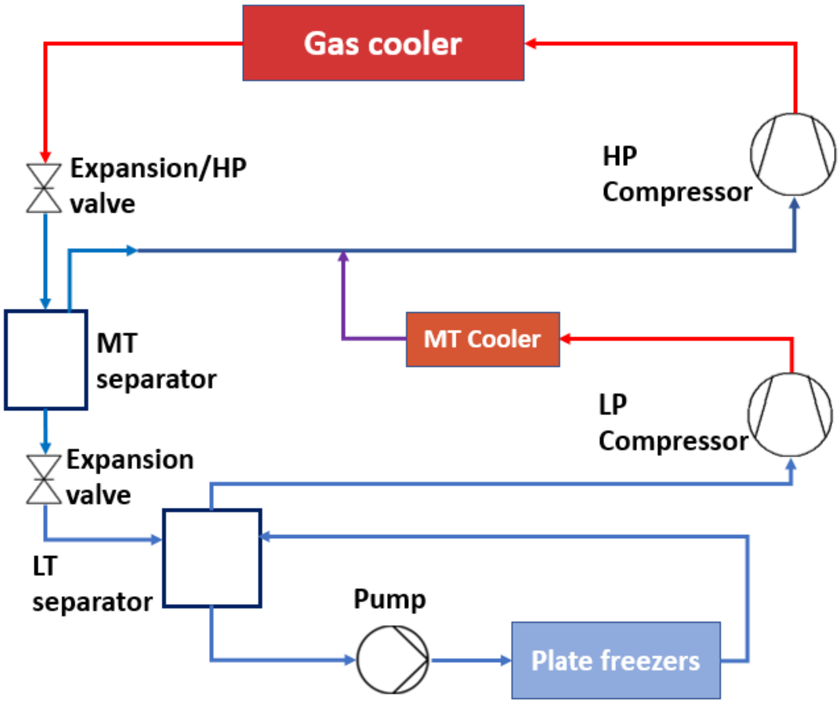

Figure 2.1. A transcritical CO_2 booster refrigeration system. (Saeed, 2020)

An alternative to a one- or two-stage ammonia system is a cascade system with ammonia on the high-temperature side and carbon dioxide on the low-temperature side. This approach can be more efficient in high ambient temperature conditions and more cost effective than one-stage ammonia systems. It can also have lower evaporation temperatures (below -50 °C), which can provide lower product temperatures and faster freezing, resulting in better product quality. Another benefit is that the working fluid in the evaporator would be the less harmful refrigerant CO_2, which increases the safety of people working close by.

Several cascade systems that rely on NH_3 and CO_2 are described in the literature, but all for land processing plants. Getu and Bansal (Getu and Bansal, 2008) analysed the effect of subcooling, superheating, condensing and evaporating temperatures and isentropic efficiency on COP and mass flow ratio. Rezayan and Behbahaninia (Rezayan and Behbahaninia, 2011) optimized different parameters for a cascade system and used annual costs as the objective function. This resulted in a total cost reduction of 9.34 % compared to a base case. Bingming, et al. (Bingming et al., 2009) used a test rig for experimental investigations on how different parameters (evaporating temperatures, condenser temperatures, and degrees of superheating and subcooling) affected system performance. They showed that the COP of a cascade system was always higher than in a single-stage ammonia system, and was also performing better than a two-stage ammonia system when evaporation temperatures were below -40 °C. Visser (Visser, 2010) described a trans critical two-stage CO_2 system, which replaced several systems for cooling and heating and reduced specific electrical energy use by 33 %.

2.2 Conventional cold utilization onboard

Fish and seafood are sensitive to high temperatures during processing, which means that chilled or frozen handling is often necessary. In countries with higher water temperatures, the degradation is slower than in cold waters like those outside of Norway.

Ice is commonly used for the conservation of fresh fish, maintaining temperature slightly above 0 °C. There is a great dependence between the size of ice pieces and cooling time. Keeping the fish in ice boxes is very common, although it is usually not an effective method because the correct proportion of ice is rarely used. Another option is ice made from seawater, with a lower melting temperature than freshwater ice. However, it is physically unstable, thereby the overall temperature decreases, and temperature is not properly controlled.

The ice can be brought from land (most common) or produced onboard. A theoretical analysis was performed by Saini et al (2019) to see if there is potential to have a small refrigeration system onboard to keep the ice cold. The intention was not to produce ice, but only to have enough cooling capacity to cover the heat ingress from the outside. A single stage NH3-H2O vapour absorption system was found to be suitable. Heat was derived from the engine jacket exhaust and it was cooled with seawater. This system can give the fishermen more predictability and better product quality. Payback time was calculated to be 1 year and 4 months.

2.2.1 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, pumps and valves, in which seawater is mechanically refrigerated and circulated. Herring and mackerel are species that is typically transported in RSW tanks, while species like Blue whiting are stored in refrigerated fresh water. These fish are used for fish oil and meal production, and using fresh water lowers salt uptake in the fish(Grimsmo et al., 2016; Olsen and Norum, 2010).

Herring and mackerel (pelagic fish) are transported in tanks with refrigerated seawater (RSW), with a vapour compression refrigerator system. Other types of fish, such as blue whiting, are stored in refrigerated fresh water. These fish are used for fish oil and meal production, and fresh water storage lowers salt uptake in the fish. (Grimsmo et al., 2016), (Olsen and Norum, 2010)

Chilling systems onboard fishing vessels have improved over the years, but they are far from optimal. Uneven cooling, especially in large tanks (300 m3), 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 occurred earlier, but 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 water has been shown to act both as a preservative and prevent lumping. (Grimsmo et al., 2016; Widell and Nordtvedt, 2016)

Few research papers address the topic of chilling of fish onboard using RSW systems. Thorsteinsson et al. (2003) performed a dynamic simulation to assess the feasibility of a hybrid RSW/CSW system. Wang and Wang (2005) have described different types of refrigeration systems onboard, including absorption. (Larminat, 2018) also gives an overview of refrigeration systems in fishing vessels and different use of them. Some reports have been published in Norwegian, mainly supported by the Norwegian Seafood Research Fund[1], which has as a focus area the production of top-quality fish. Norway has used RSW systems to chill fish onboard for more than 50 years, especially for pelagic fish. These refrigeration systems use natural refrigerants, mainly ammonia, but a few also use CO2. Much of the research on CO2 RSW systems has been conducted in Norway. The development of CO2 RSW systems has been described in a range of articles. (Andresen et al., 2011; Bodys et al., 2018; Brodal et al., 2018; Neksa et al., 2010; Nordtvedt and Ladam, 2012; Rekstad et al., 2015; Widell et al., 2016)

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[1] www.fhf.no

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2.2.2 Fish freezing plate freezers

On board trawlers, whole 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, packed fillets or small trunks are frozen by contact between two plates with some pressure applied on them. Nowadays, the market requires a lot of packaged frozen fish, this is wrapped in plastic, but it should be noted that this practice results in a decrease in energy efficiency. This is due to the drop in heat transmission coefficient due to the air that remains in the package, considerably increasing the time required for freezing.

2.2.3 Freezing of seafood in blast freezers

Freezing tunnels are defined as any refrigerated space which gets a temperature range of -25 / -32 °C and it is used for fast freezing of a product. It may be continuous, where the fish is moved along the freezing chamber in a direction opposite to the forced flow of cool air, or discontinuous, in which the chamber is filled and emptied completely in cycles. This latter type is more versatile and less expensive, but it requires more labour and energy consumption is higher. This type of freezer is common in land processing plant, but not onboard.

2.3 Utilizing cold from LNG

Liquefied natural gas is stored in onboard cryogenic tanks. The storage temperature and pressure depend on the type of engine. The typical LNG storage pressure for sea-going vessels with low-pressure engines is 5 bar, and the corresponding saturation temperature is -138 °C (Chorowski et al., 2015). It is necessary to heat and vaporize the LNG before it is used as engine fuel. The cold energy from this vaporization can be used for different onboard applications which can reduce total fuel consumption and improve overall energy performance.

Libas is the world's first LNG and battery-driven fishing vessel and it is owned by the Norwegian fishing company Liegruppen (Gabrielii and Jafarzadeh, 2020). The dual fuel main engine can operate on both LNG and diesel but will be 95% powered by LNG, supplied from a 350 m3 cylindrical vacuum-insulated tank. An auxiliary engine, which also can switch between LNG and diesel, complements the main engine during some work tasks and in bad weather (Seaman, 2018). The original plan was to deliver it in 2020. Onboard cold recovery for HVAC was previously implemented on the ferry Viking Grace, which operates on the trans-Baltic route between Stockholm and Turku (Cemre Shipyard, 2020). A patent covers the cold recovery solution for this ferry (Karlsson, 2015).

The cold recovery can be computed under adiabatic conditions with the following equation:

$$Q_{recovery} = m_{LNG}(h_{out} - h_{in})$$

Where h_{in} and h_{out} are the inlet and outlet enthalpy of LNG in the cold box (heat exchanger). In this report, different LNG cold recovery applications have been analysed for fishing vessels.

The cold recovery potential is a dynamic factor, and the fluctuations are often very high. LNG cold recovery was also estimated for a fishing vessel with a 4.5 MW engine and onboard data was used for validations. The logged data for diesel consumption was converted to similar data for LNG and the data was then used for calculating LNG vaporization energy. The data was hourly and for a period of one month. The fuel consumption unit of the data was unknown but best prediction was made. The recovery potential is presented in Figure 2.2. The vessel is stationary, or the engine is not in operation when the recovery values are zero. The estimation was done with the identical inlet/outlet conditions of reference chilling vessel. The results of the LNG cold recovery were within the range reported by literature and engine manufacturers. (Saeed, 2020)

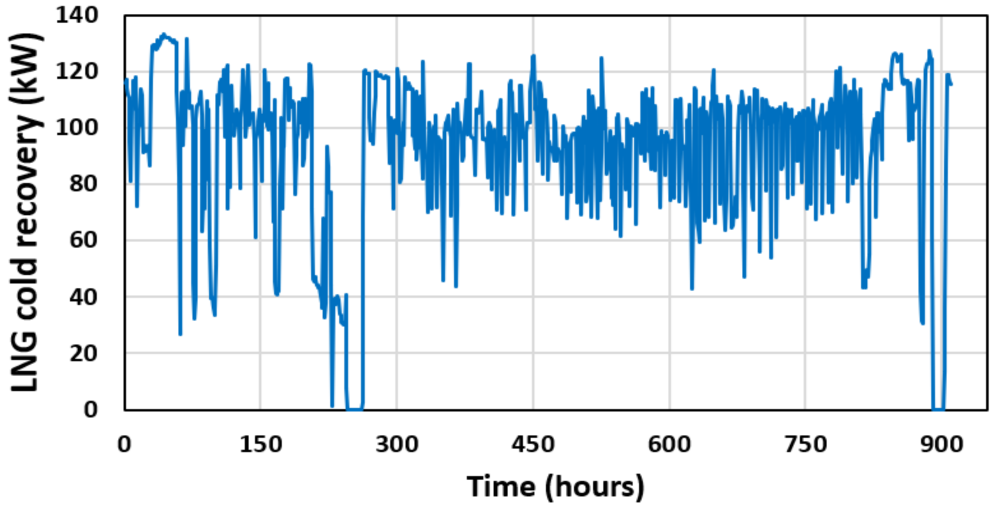

Figure 2.2. Theoretical estimation of LNG cold recovery potential of a fishing vessel with a 4.5 MW motor (Saeed, 2020)

2.3.1 For Air Condition

Air conditioning on fishing vessels is for crew cabins, common areas, and electronic systems. Fishing vessels have specific indoor regulations for the control room and other spaces. The standard design conditions of temperature are 22-25 °C and 45-55% for relative humidity. The designed indoor environmental regulations for fishing vessels are outlined in a report by DNV GL (Germanischer Lloyd, 2007). Air conditioning and ventilation control temperature, humidity, and air quality. The cooling power required for this purpose can be substituted by LNG cold recovery. The current implementation of cold recovery for HVAC in marine vessels uses an intermediate water-glycol system (Baldasso et al., 2020). The water-glycol loop extracts cold energy from the cold box and delivers to the air conditioning or air handling unit. The layout of the system is shown in Figure 2.3.

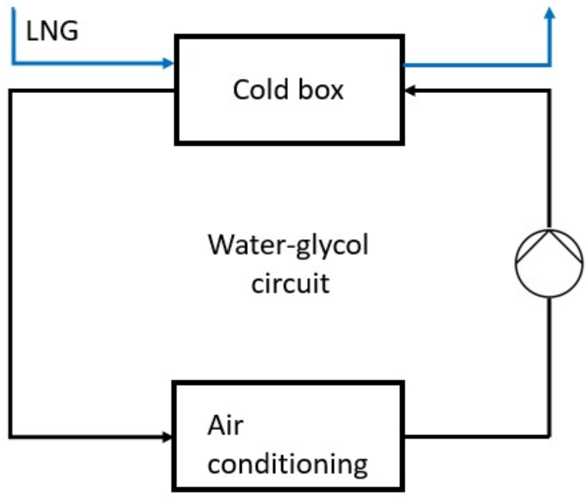

Figure 2.3 LNG cold recovery integration for air conditioning, adapted from Wärtsilä (Sipilä and Levander, 2011)

2.3.2 For chilling (RSW)

A costal demersal trawler with a 760 kW engine was used as reference case for simulation of utilization of cold from LNG vaporization by Saeed (2020). A chilling load profile was designed from the properties of Mackerel, although these systems can be used for other species as well. It was assumed that the trawler was equipped with a CO_2 refrigeration system and that the ambient temperature was 15 °C. Some different modes for utilization of the cold were tested. One mode was to integrate LNG cold with thermal energy storage and to utilize for peak loads. The LNG cold was also investigated for cooling of chilling tank. It was a simple approach without any complex circuits. The further details of these configurations are reported by (Saeed, 2020)

LNG cold for sub-cooling of refrigerant is shown in Figure 2.4. The chilling load varied from 35 kW to 250 kW, and the sub-cooling was found to be 8-10 kW with average fuel flow (typically when the fishing vessel is in transport mode). Results showed an increase in refrigeration COP by 15.2 % compared to simple chilling system. The variation in refrigerant mass flow was negligible with and without sub-cooler. The reason for higher COP is both that the evaporation pressure increased and that the vapor fraction after expansion valve was lower. This trend was clearer at lower refrigeration loads than at higher loads.

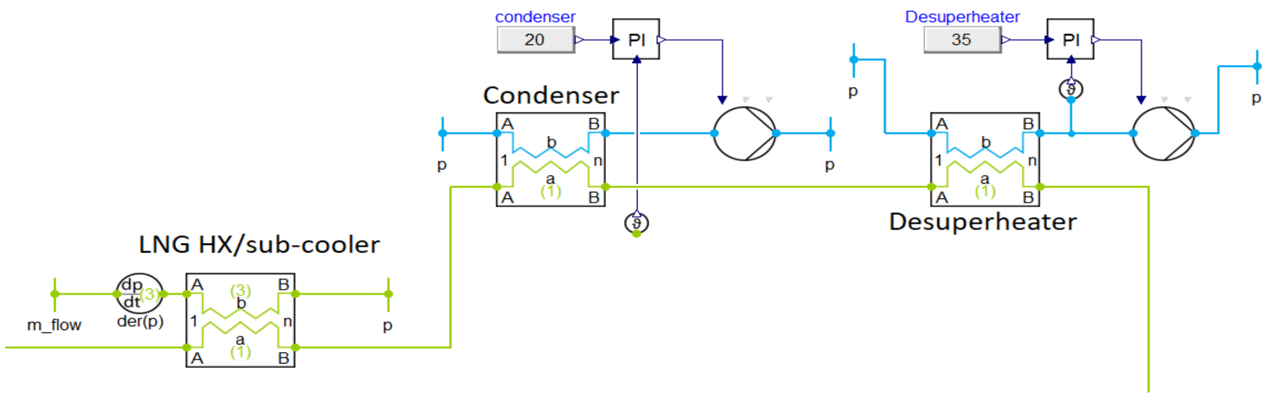

Figure 2.4 LNG cold as sub-cooler in chilling system (Saeed, 2020)

2.3.3 For freezing

In the freezing system, the LNG sub-cooler was introduced after the medium temperature separator. The layout of the system can be seen in Figure 2.5. The freezing load varied from 270 kW to 60 kW, and the sub-cooling effect with average fuel consumption was 9.8 kW. The result showed that the COP increased by 6.4 % with the LNG sub-cooler. The sub-cooler impact is reduced flash gas in a low-temperature separator, which resulted in less compression work of both compressors and hence high COP. The combined (freezing and heating) COP increased by a factor of 2.8 compared with only freezing COP.

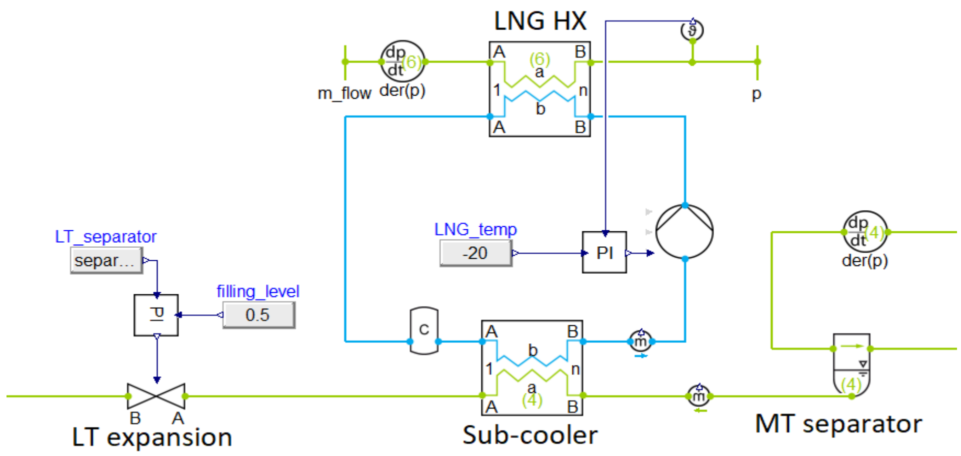

Figure 2.5 LNG cold as sub-cooler in freezing system (Saeed, 2020)

2.4 Cold thermal storage

CTES is a supplemental feature which allows for saving of cold thermal energy for later use. One of the main reasons for implementing such a feature in a cold process is to offset the temporal mismatch between supply and demand but can also improve the overall chilling process in terms of technical flexibility, energy efficiency and economic benefits.

A sensible storage operates in principle no differently than a domestic hot water storage tank and is named so since thermal energy is stored by increasing water temperature. A latent storage uses a phase-change material (PCM) as a storage medium and allows for a more compact design because it can store more energy per volume compared to the sensible type. There is a wide range of different types of PCM and design of equipment for latent heat storages, with current research focused on increasing the heat transfer rates. A trivial example of a PCM is water/ice, with a phase change temperature of 0 °C and a phase change enthalpy of 333 kJ/kg. For temperature requirements below 0 °C eutectic mixtures of water and salt are typically used (Mehling and Cabeza, 2008)

A latent storage is most feasible for use onboard fishing vessels given the compact nature of such a system. For LNG driven vessels, a possible application is to store recovered cold energy in surplus periods and use it in peak periods.

In chilling vessels, the fish is stored at -1 °C in RSW tanks. To boost the refrigeration capacity during peak loads, water/ice thermal storage can be an effective choice. At peak demands, there is always enough temperature difference between water stream from RSW tank and ice storage to initiate heat transfer. The properties of water as PCM are phase change temperature 0 °C, density 999 kg/m3 at 0 °C (liquid), specific heat capacity solid phase 2.1 kJ/kg.K and specific heat capacity of liquid phase 4.218 kJ/kg.K. The charging of thermal storage was performed with two flow conditions of glycol, i.e., 2 kg/s and 6 kg/s. The charging is shown in Figure 2.6. The charging of 1 m^3 TES with 2 kg/s (-5°C inlet to TES) was completed in 318 minutes (5.3 hours). The time required for fully charged TES with 6 kg/s was 235 minutes (3.9 hours). A fully charged TES of size 1 m^3 corresponds to 838 kg ice, including the internal heat transfer area.

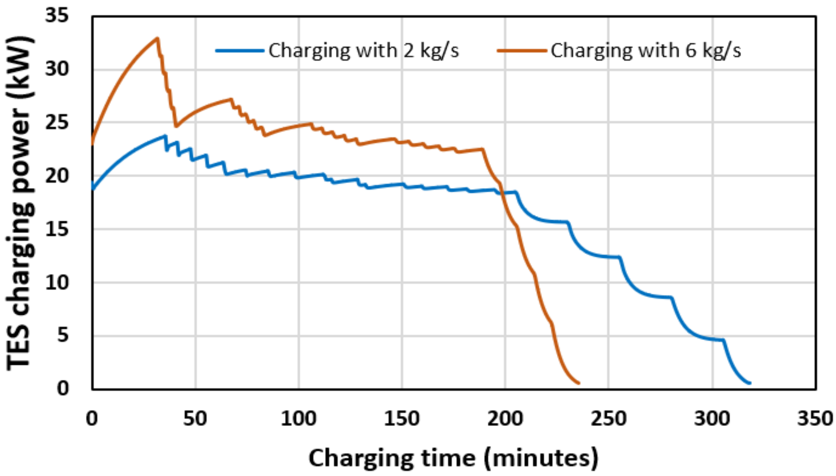

Figure 2.6 Water/ice thermal storage charging (Saeed, 2020)

TES discharging was analysed by varying the inlet RSW temperature from 10 °C to 8 °C in 1 hour. The maximum and minimum discharging power in the start and end was 57.4 kW and 19.6 kW, respectively. The TES discharging is shown in Figure 2.7.

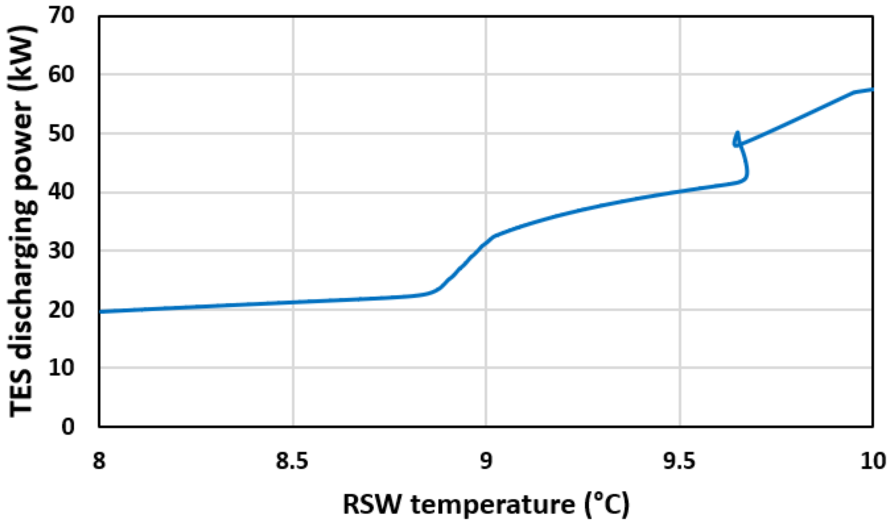

Figure 2.7 Water/ice thermal storage discharging (Saeed, 2020)

The charging of big water/ice thermal storage is feasible during initial chilling of RSW tanks before actual fishing. For fast discharging, it is efficient to have multiple small thermal storage in parallel. To set up indirect charging and discharging loop for water/ice thermal storage, two additional heat exchangers are required including one seawater/RSW heat exchanger. A plus argument is that water is sustainable as compared to other phase change materials. Another choice is a suitable and environment friendly PCM on the refrigerant side. This will eliminate the need of an extra heat exchanger and additional thermal losses.

2.4.1 For freezing system

CO_2 as a phase change material is a great option for freezing options, due to its suitable storage temperature and negligible GWP. CO_2 as PCM was investigated for integration with the freezing system. The purpose of this thermal storage was to boost the refrigeration capacity at peak loads and reduce the processing time of each cycle. Each m^3 of space on a fishing vessel is very important. So, a size of 1 m^3 (including internal pipes) was analyzed. It was estimated that the charging time for PCM between freezing cycles is 40 minutes and discharging was required for 10 minutes to cover the peak load. The storage conditions of PCM were 8 bar and -56.6 °C. The dry ice accumulation is on the shell side and charging and discharging of the storage is with the refrigerant in the tubes. The storage was integrated with the refrigeration system described in Figure 2.1 The charging condition of thermal storage was 3 bars (-68.3 °C). The charging was done by deploying an additional expansion valve and compressor after LT separator. Thermal storage charging was also performed with an ejector to have free pressure lift from 3 bar to 6.8 bar.

After 40 minutes of charging with a flow rate of 0.07 kg/s, the amount of solid CO_2 was 171 kg. The thermal storage charging with ejector showed a stable condition at 3.55 bar and -64.8 °C. The mass of dry ice at the end of the simulation was 116 kg, with a charging flow of 0.041 kg/s. The discharging of thermal storage was simulated with a constant super-heat of 8 K for 10 minutes according. The maximum discharging value was 51.4 kW. The total melting of dry ice in 10 minutes was 112 kg. The discharging rate of thermal storage is a combination of three factors, i.e., refrigerant flow, super-heat, and TES heat transfer area. The charging and discharging scenarios are shown in Figure 2.8.

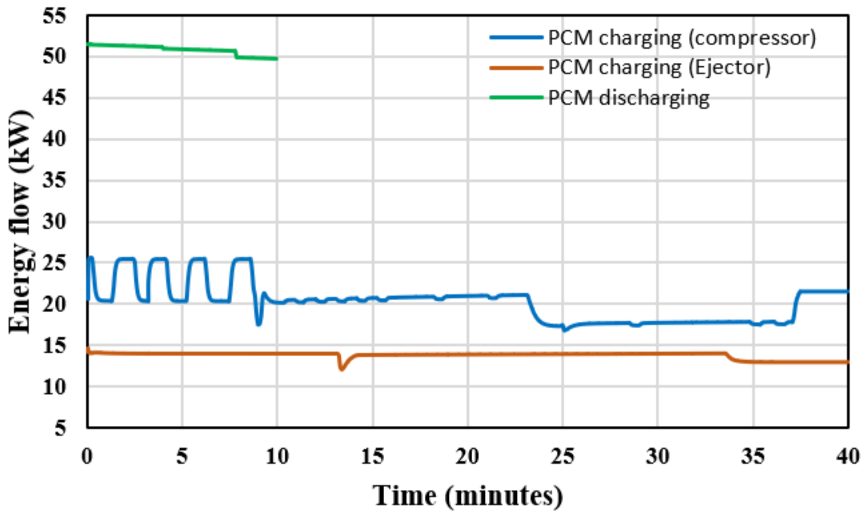

Figure 2.8 CO_2 thermal storage charging and discharging (Saeed, 2020)

Hafner et al. (2011) modelled a cold thermal energy storage (CTES) in a cascade system that used ammonia and carbon dioxide. The storage was a tube-and-shell heat exchanger tank where pressurised liquid carbon dioxide was subcooled on the shell side by the refrigerant (also CO_2) in the tubes. The results showed a 30 % reduction in electricity use compared to an equal system without CTES.

3 Heat generation and utilization onboard

In today's fishing vessels, excess heat from the propulsion engines can be used for space and tap water heating but may not be enough for other processes onboard, for example enzymatic hydrolysis, used for utilization of marine raw material.

For future propulsion systems, such as hybrid or fully electrified systems there are less or no surplus heat available. To provide the required heat, it is possible to utilize surplus heat from the refrigeration system. The surplus heat is normally available at lower temperature levels and the installation of a heat pump, to lift the temperature level, is needed. Heat pump systems with the refrigerant CO2 are well suited for these cases, since these are compact units and the refrigerant is detectable and therefore not dangerous if there are leakages. These systems are utilized by most Norwegian supermarkets and some industrial process plants but must be adjusted for fishing vessels. For example, the variation in operating conditions and operation profile between different types of fishing vessels are much larger than between supermarket installations.

Furthermore, a refrigeration plant onboard a fishing vessel generally differs from a land-based installation in the following ways;

- the electricity is most often produced in fossil-fuelled generators onboard
- there are higher refrigerant leakage rates due to the harsh environment
- over-dimensioned components/systems and limited space
- more stringent safety regulations regarding e.g. flammability

3.1 Fuels and propulsion systems in fishing vessels

The increasing demand for fuel efficiency and reduced emissions, together with the diverse operational pattern of different shipping segments, such as cargo vessels, cruise ships and fishing vessels, have led to the development of various propulsion system solutions. Moreover, within each shipping segment, there can be large variations in the operational profile, such as between coastal and deep-sea fishing vessels.

Propulsion solutions are often categorised in mechanical, electrical or hybrid propulsion. The ships' electrical power demand can be supplied by combustion engines (generators), fuel cells, energy storage (batteries) or a combination (hybrid power supply). In this section, diesel is assumed as fuel for the combustion engines and/or generators, but it could also be alternative fuels, such as LNG, which is described in section 3.1.5. More details about operating modes for hybrid ships are given in a report by Gabrielii and Jafarzadeh (Gabrielii and Jafarzadeh, 2020).

3.1.1 Diesel-mechanical propulsion

The conventional propulsion system onboard fishing vessels is the mechanical diesel-fuelled engine with auxiliary engines for electric power supply, shown in Figure 3.1. The main diesel engine (1) drives the propeller (3), either directly or via a gearbox (2). Diesel generators (7) supply power to a separate alternate current (AC) network (6), distributing electric power to auxiliary loads (5) such as HVAC (heating, ventilation and air conditioning), refrigeration and diverse frequency-controlled equipment (4).

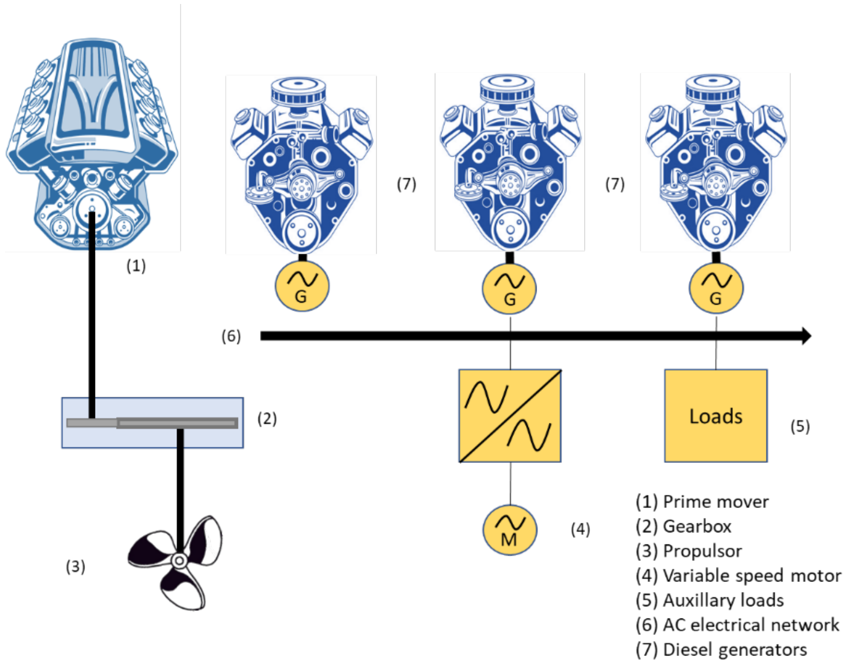

Figure 3.1. Example layout of a conventional mechanic propulsion (adapted from [17])

Mechanical propulsion is particularly efficient at design speed, which is normally between 80% - 100% of top speed. Therefore, for "transport ships" operating at a constant speed a mechanical propulsion system together with waste heat recovery (WHR) might be the preferred solution for reducing fuel consumption and emissions. However, for speeds below 70% of top speed the fuel efficiency is poor since fuel consumption is significantly increased below 50% of rated power. For many ship types, a mechanical propulsion system implies operation at low engine load during certain periods, resulting in high specific fuel oil consumptions (SFOC) and related emissions. For these ships, an electric or hybrid propulsion might instead be the most efficient solution (Geertsma et al., 2017).

For small ships, the conventional machinery is one small diesel engine supplying both the propulsion, with a direct propeller drive, and the electric power demand, via an alternator. The ship often has a large thermal energy surplus since the engine operates also when the ship is at zero or low speed (Aarsaether, 2017).

3.1.2 Diesel-electric propulsion

Figure 3.2 shows a "typical" layout of a diesel-electric propulsion system. Multiple diesel generators (1) supply power to the AC electric network (2). From there, electric power is distributed, via transformers (3) and/or variable speed motors (4) to electric propulsion motors (5), and to auxiliary loads and motors (6) (Geertsma et al., 2017).

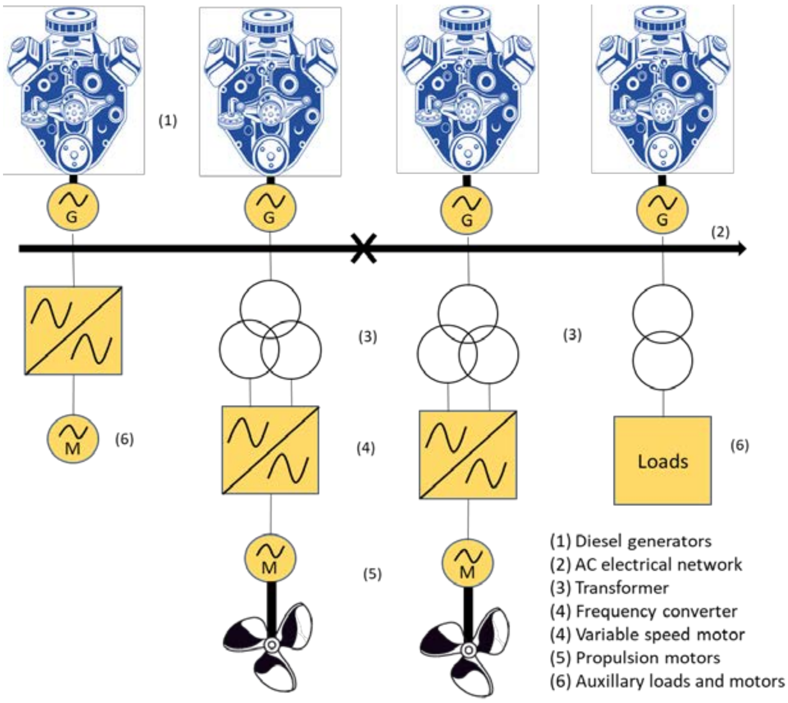

Figure 3.2. Example layout of an electrical propulsion system (adapted from Geertsma et al (Geertsma et al., 2017)**)**

Diesel-electric propulsion is especially fuel-efficient when the utility (auxiliary) load constitutes a significant fraction of the propulsion power demand (e.g. cruise ships) and for ships with a large variation in their operation profile. A power management system ensures the engines to not operate on part-load, but instead matches the number of engines in operation for covering the combined propulsion and auxiliary load. With such a concept, the diesel generators operate closer to their design point and at rated speed, leading to higher fuel efficiency and lower emissions (especially NOx). A disadvantage is the higher conversion losses due to the additional conversion stages (between electrical and mechanical energy), implying a high specific fuel oil consumption (SFOC) especially near the top speed (Geertsma et al., 2017). In fishing vessels, diesel-electric propulsion is increasingly considered for fishing ships having large load variations, while maintaining a constant load for a relatively long time, such as ocean-going bottom-trawling and long-line vessels (Aarsaether, 2017).

There are many possible arrangements of a diesel-electric propulsion system. Examples of layouts used on large fishing vessels are a twin-screw propulsion including four electric motors of varying size, four generators and two main switchboards. The generators start and stop automatically as the electrical load varies (total demand of propulsion and auxiliary systems). The electric motors drive the propeller(s) providing highly reliable and efficient operation. The concept has been delivered to Norwegian purse seiners and around 30 fishing vessels in other parts of the world. Reported advantages from ship-owners include fuel savings, reduced noise levels and reliable operation (Slettevoll, 2019).

3.1.3 Hybrid propulsion

A hybrid propulsion system enables the vessel to be propelled in two ways, namely electrical (diesel-electric and/or battery) and mechanical (direct diesel-drive). These systems are especially fuel-efficient for ships with varying speed conditions and a relatively small auxiliary load. Figure 3.3 shows a mechanical-electrical hybrid propulsion system. A mechanical diesel engine (1) provides direct propulsion for high speeds, with a high efficiency. An electric motor (2), which is coupled to the same shaft through a gearbox (3) or directly to the shaft driving the propeller, provides propulsion for low speeds. Thus, running the main engine inefficiently in part load is avoided. The electric motor could also be used as a generator, supplying power to the ship's auxiliary electrical network (4). When the mechanical main engine is running, the system allows generating power for ship's auxiliaries either from the main engine, via the electric generator (2), or from the generating sets (5). In other words, the control strategy allows transferring electrical power from the mechanical drive to the electric network and vice versa (Geertsma et al., 2017).

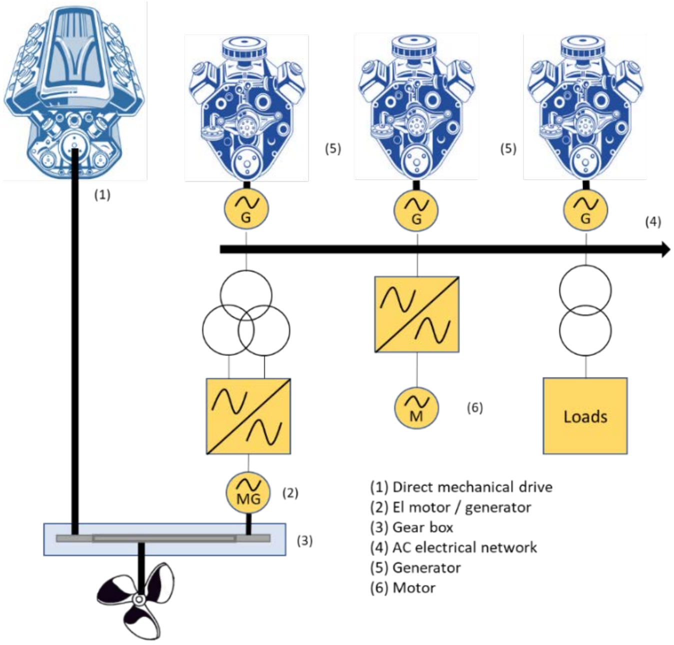

Figure 3.3. Example layout of a hybrid (mechanical-electrical) propulsion system (adapted from Geertsma et al. (Geertsma et al., 2017)**)**

For fishing vessels requiring high propulsion capacity, a hybrid solution could be favourable since a diesel-electric solution can be relatively expensive. Typical operation is diesel mechanical for steaming to and from fishing field, while a typical operation for the electrical propulsion is transit at lower speeds and fishing operations. In occasions with heavy steaming, a parallel operation can be applied. This enables optimized fuel economy for all operation modes. Generally, economic benefits are to be expected if the fishing vessel operates below 15% propulsion power, equivalent to 40% of top speed, for a significant amount of time (Geertsma et al., 2017).

If one of the generators in Figure 3.3 is exchanged with a battery pack instead, we get a hybrid propulsion system with hybrid power supply. The battery pack can be designed to handle power fluctuations and peak-shaving. It will also be possible to swich off diesel generators and engines for shorter periods, to have zero emission operation and significant noise reduction. This will be most beneficial for ships with varying power demand and much low-load operations, but also for large electric power demands when the ship is in port. Additional benefits with battery onboard is that it gives the possibility of using renewable power production onboard (solar, wind) and it also enables storing of regenerated energy from heavy winches for fishing gears.

3.1.4 Pure electric propulsion

A pure electric propulsion refers to a ship operating solely on batteries, which are charged exclusively with shore power. In this case, the ship's onboard emissions are reduced to zero. To achieve "true" zero emission operation, the shore electricity must be produced from renewable sources, nuclear power or by using CCS (Carbon Capture & Storage) technology. The amount of electricity that can be transferred from shore to ship depends on the shore electrical grid capabilities, the battery charging facilities and the time spent at berth.

Short-sea shipping has naturally the highest potential for pure battery operations, specifically ships on short routes, with regular schedules and operating on long-term contracts. Deep-sea shipping can install batteries for energy optimisation during cruising, or as low-emission solution when operating in sensitive areas or near harbours. The main barriers are cost, infrastructure, and space requirements (DNV GL, 2019).

3.1.5 LNG as fuel

The global use of LNG is assumed to increase significantly, especially in coastal shipping. Main drivers for such a development include regulations (e.g. MARPOL, Annex VI), potentially low gas prices compared to oil and diesel, as well as positive profit related to sustainability and more environmentally friendly operation. Using LNG as fuel enables compliance with all known future regulations for NOx and SOx emissions without the need for exhaust gas treatment. It will also contribute to reducing the carbon footprint from ships. The reduction in CO2 emissions compared to diesel/gas oil is typically 20% but can be somewhat counteracted by methane slip from certain engines. In an LCA perspective, it is also important to include GHG emissions from LNG production and transport. LNG-fuelled ships emit 90 % less NOx, 25 % less CO_2, and almost no SOx as compared to heavy hydrocarbon fuels (Fiskebåt, 2018; Jafarzadeh et al., 2017)

Despite having many advantages, LNG is scarcely used in the fishing sector. There is scepticism relating to bunkering opportunities, safety issues, investment costs as well as space required for installation. Another possible disadvantage connected to LNG operation of fishing vessel is that a dual-fuel engine, operating on both LNG and diesel, has a longer response time than a diesel engine. This can be a challenge during fishing and manoeuvring when fast load control is needed. However, a hybrid propulsion system including a battery package enables “boosting” via an electric motor, which eliminates the response time problem (Eknes and Halvorsen, 2020).

3.2 Heat recovery

Excess heat generated onboard is mainly from the engine and the refrigeration system.

3.2.1 Heat recovery from engine

Heat recovery from an engine onboard a fishing vessel was estimated by Saeed (2020). It was assumed that a 760 kW trawler engine was an internal combustion four stroke piston engine. The stochiometric air fuel ratio for gasoline engine is 14.7:1 (Zhai et al., 2012) and 17.2:1 for gas engines. This is an ideal air fuel ratio and far away from real case. The marine gas engines operate on lean mixtures and typically the air fuel ratio is around 30:1 (Baldasso et al., 2020). The exhaust gases of such engines leave at a range of 380 °C to 410 °C under variable speed and load. (Wärtsilä, 2018). For heat recovery estimation, specific heat capacity values of air (Engineering Toolbox, 2001) were utilised for exhaust gases. It was assumed that the heat recovery from flue gases was used for water heating from 15 °C to 80 °C (tap water heating). The energy flow of the exhaust gases was calculated from three conditions (m_1, m_2 and m_3), with different parameters shown in Table 2. The fuel consumption is represented by m_1, when the vessel is moving towards fishing ground, m_3 during trawling and m_2 on the way back to shore.

Table 2. Characteristic values for heat recovery from flue gases. (Saeed, 2020)

Fuel flow (kg/s)	Air flow (kg/s)	Total flow (kg/s)	Exhaust gas temperature, (°C)	Heat capacity air, (kJ/kgK)
0.0095 (m_1)	0.289	0.298	375	1.062
0.0135 (m_2)	0.412	0.425	410	1.071
0.0176 (m_3)	0.537	0.555	380	1.064

Equation (1) was used for setting up the energy balance.

$$\dot{Q} = \dot{m} * Cp * \Delta T \text{ [kW]} \quad (1)$$

where Q, m, Cp, ΔT are the heat recovery, total flow of exhaust gases with three fuel flow conditions, heat capacity of air and temperature difference of flue gases, respectively. The sulphur content in LNG is very low as compared to diesel fuel, which is a plus point to recover more energy from exhaust gases without acid formation. In this case, exhaust gases were cooled up to 120 ℃. Heat recovery from the flue gases of the engine were found to be in the range of 81 kW to 153 kW. The heat recovery had a potential to cover an onboard average 117 kWh hot tap water demand.

3.2.2 Heat recovery from refrigeration system

A heat recovery analysis was performed for the chilling unit. A CO_2 refrigeration system working in the sub-critical state with ambient temperature conditions of 15 °C has low temperature heat recovery potential at 30-35 °C in a desuperheater. Heat recovery from the desuperheater was found to be in the range of 8 kW to 68 kW. It had a capacity to cover an average 38 kWh space heating demand, but this would be at low temperatures (30-35 °C). It was observed that by installing a desuperheater, chilling-COP of the system decreased by 6.3 % at maximal load and 17.4 % at minimal load (correlated to simple refrigeration unit) and the reduction was due to increased pressure after compressor. However, combined (chilling and heating) COP increased by 24 %. (Saeed, 2020)

Heat recovery evaluation was also performed for freezing system in trans-critical operation. Heat was recovered from two stages, one from MT cooler (low temperature) and other from gas cooler (high temperature). The heat recovery potential from the refrigeration system depend on the load profile and operational condition, where heat recovery potential increases with increased load. The average recovered heat was 298 kWh and was investigated to use for rest raw material processing.

A CO_2 refrigeration system working in the sub-critical state with ambient temperature conditions of 15 °C has low temperature heat recovery potential at 30-35 °C in a desuperheater. Heat recovery from the desuperheater was found to be in the range of 8 kW to 68 kW. It had a capacity to cover an average 38 kWh space heating demand, but this would be at low temperatures (30-35 °C). It was observed that by installing a desuperheater, chilling-COP of the system decreased by 6.3 % at maximal load and 17.4 % at minimal load (correlated to simple refrigeration unit) and the reduction was due to increased pressure after compressor. However, combined (chilling and heating) COP increased by 24 %. (Saeed, 2020)

3.3 Other uses of heat

On board a fishing vessel there are several possible heat demanding operations, such as room heating, tap water heating, snow melting, and processing.

3.3.1 Room heating

Room heating on the fishing vessel is mainly for the comfort of the crew members and the heating demand is dependent on ambient conditions. At present most of the installed systems are based on electric heat. It would be expensive to change those, but for new ships it could be consider. Thermal heat is available from the refrigeration system and propulsion, but it would require piping and that could be expensive and demand space and would gain weight to the boat.

3.3.2 Tap water heating

A more suitable use of the heat could be for tap water heating. Using the available heat from the refrigeration system will not require extra piping and would save energy.

3.3.3 Snow melting

For ships operating in artic regions snow and ice is a problem. Rashid et al. (2016) described icing accumulation and de-icing methods. Thermal system exist and use of accumulated water is an option.

3.3.4 ORC

Heat from the propulsion engine could be utilized in different Organic Rankine Cycles (ORC) to produce electrical power. Durakovic and Nikolaisen (2019) evaluated different cycles. These could be implemented on a ship but the demand for electricity should be analysed before investing in such system.

3.3.5 Processing of fish and rest raw material

Rest raw materials from fish processing (heads, viscera, bones, etc.) give valuable ingredients for feed, human consumption and more specialized products, such as pharmaceuticals. In earlier days, most of this resource went to waste, but today more and more is utilized in large rest raw material factories. Most is still used for feed ingredients, but an increasing percentage is going to human consumption and higher value products. Currently, there are three main methods of processing rest raw material industrially:

Ensilage: Adding acid and letting endogenous enzymes dissolve the substrate before separation, dewatering and stabilization. To separate oil and protein, heat must be added. This method is suitable for feed and fish oil production.

Thermal treatment: Traditional method for producing meal and oil from pelagic fish and from rest raw material where available in large volumes. The process includes heating and drying to separate oil and solids. Suitable for feed and with some refining human consumption (to a certain degree). In thermal treatment, rest raw material is first crushed in mincer to make it easy to pump. It is then heated in heat exchanger up to 90°C. The temperature of the rest material can be less than 90 °C (for example, 60, 70, 80 °C) but it may affect the quality and production rate. After heating, RRM is treated in a tri-canter. It is a special component that separates the stick water (water phase), sludge (solid phase) and oil. Tri-canter is also called three phase separator. After tri-canter, the oil phase is further treated in polishing centrifuge to remove the impurities (Carvajal et al., 2017)(After tri-canter, the oil phase is further treated in polishing centrifuge to remove the impurities (Carvajal et al., 2015).

Hydrolysis: To hydrolyze means to break apart chemical bonds by the addition of water, to make something water soluble. In enzymatic hydrolysis of fish protein, enzymes cut protein chains so that the protein and fat are easier to separate, thereby obtaining better yield in both fat and protein fractions. This process is relatively fast, and yields purity, quality and stability far superior to other processes. Hydrolysis processing is utilized in large scale on rest raw materials from salmon slaughteries, and on krill at sea. In hydrolysis process, the rest raw material is heated up to 50 to 60 °C after mincer. After heating, the RRM treat in hydrolysis tank. In hydrolysis tank, the RRM mixed with equal amount of water (1:1) and with addition of chemicals or enzymes. Common enzymes of treatment are Papain and Bromelain. Normal processing time of RRM treatment in enzymatic hydrolysis tank is 1 hour. Inactivation of enzyme is necessary at 90 °C for 10 minutes after hydrolysis process (Carvajal et al., 2015).

The process set up may vary for all three methods. In most configurations, these are large factories with (a) an evaporator dewatering the product and producing condensate at about 85 °C and (b) at least one temperature increasing step in the process. Regulations state that the product, regardless of processing method, should be held above 90 °C for 10 minutes to destroy bacteria. Most processing configurations also include other heating steps.

Before processing, the rest raw material is cold (usually below 10 °C, sometimes as low as -3 °C). Therefore, a significant amount of heating is required to process the rest raw material. Today, this heating is mainly performed by diesel engine powered steam generators. For such heating, energy efficiency is poor and both environmental impact and carbon footprint significant, and it is also very expensive.

There is a huge potential for utilizing heat pumps in these processes. Open and closed-cycle MVC processes with steam are applied for instance for industrial wastewater treatment in food and fish industries; and various evaporation processes in the food and fish industries. Compression/absorption (hybrid) heat pumps using ammonia /water as the refrigerant pair are applied for instance for drying processes by fish and dairy industries. Transcritical CO_2 systems are suitable for the direct production of steam out of the gascooler, due to heat rejection at the gliding temperature. Vapour compression systems are the most mature technology for using surplus heat for industrial utilisation.

Saeed (2020) suggested a system for fish oil production. The recovered heat is used for processing of rest raw material for onboard fish oil production. In this system design, the freezing refrigeration capacity and per day fish production is known from commercial system.

The rest raw material from processing of fish for each cycle of 150 minutes corresponded to 3000 kg. The amount of heat, which was needed to raise temperature from 10 °C to 90 °C is shown in Figure 3.4. The equations which were used to calculate thermal properties of Mackerel are valid in the range of -40 °C and 40 °C. Since the heating behaviour of fish was linear, interpolation was used to calculate properties up to 90 °C.

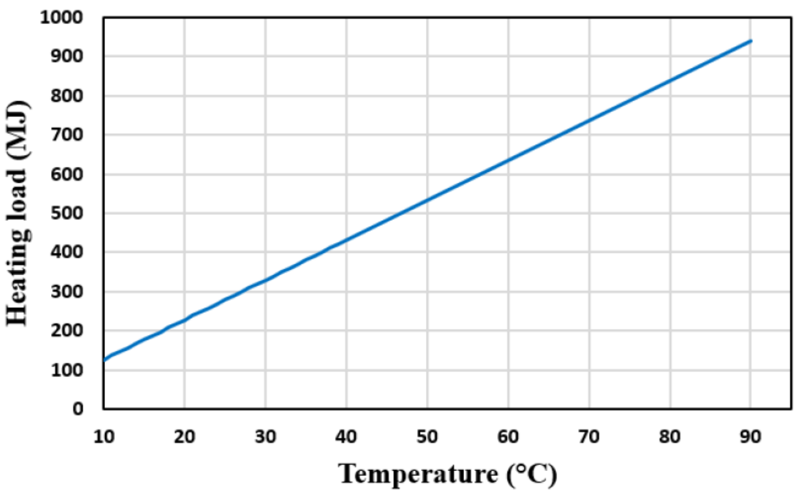

Figure 3.4. Heat load of rest raw material heating (Saeed, 2020)

4 Other options for increasing energy efficiency in fish processing

Different fish processing systems pose different challenges, but the methods for finding possible improvements are similar. Energy management is central to improving efficiency, by energy auditing, raising awareness and proper operation of the equipment. Some energy-saving measures are low cost and can be rapidly implemented, such as cleaning condensers, changing defrost regimes, and preventing leaks in vacuum and air systems. Other measures, such as installing frequency converters on compressors and other motors, are more costly, but can also result in greater improvements in efficiency. Reducing energy consumption is not only a benefit for the industry, but also for society, the climate, and the environment. As populations grow worldwide, so does energy demand. Increasing energy efficiency is often less expensive (and less politically charged) compared to developing new energy production plants.

Briefing Note A from the UNEP (2018) lists potential energy savings from different actions (not additive), for refrigeration, air conditioning and heat pump systems:

- Minimizing cooling load (30-60 %)
- Equipment control (30-70 %)
- Operation and servicing (15-30 %)
- Refrigerant selection (5-10 %)

Although the fish industry has focused on increasing energy efficiency in recent years, many opportunities for improvement remain. Refrigeration systems are not always dimensioned correctly, or operations may have changed over the years, so a first step towards improvement could be to undertake measurements, calculations and other analyses. More uniform use of energy during the day could result in lower power peaks and reduced costs. Other investments include better regulation of compressors and other components, the use of surplus heat in processing, and the installation of heat pumps and thermal storage. (Aprea et al., 2007; Evans et al., 2014).

4.1 Energy management

The first step in managing energy use is to catalogue actual usage, which often requires extensive use of measuring equipment. However, numbers make it possible to see the effect of a change, which can provide motivation for further improvements. Energy auditing and visualisation for everyone in the processing industry raises awareness and will help reduce unnecessary energy consumption.

A central operating system can result in lower energy consumption compared to several separate smaller systems. The operating system can be set to optimize compressor operation to avoid unnecessary partial load operation. It should also be set up with alarms and notifications and to allow visualisation of vital parameters and variables.

Visualising benchmark numbers for employees could raise awareness of energy efficiency. However, the decision as to which numbers and how they should be visualised is a discussion that needs to be held locally, with representatives from central management.

The efficient use of space, especially in rooms subject to chilling or freezing temperatures, is also a part of good energy management.

Another low-cost initiative that could lead to energy savings is to shut off equipment not in use and starting equipment only when necessary.

It has been shown that impingement freezers have shorter processing times than conventional belt tunnel freezers, resulting in higher production capacity with the same refrigeration load (Salvadori and Mascheroni, 2002). Selecting the right equipment during the design phase is also important for increasing energy efficiency.

Depending on the measures taken, the potential savings from improving energy management range from 5-35 %. Several of the following suggestions can also be considered energy management.

4.2 Reducing heat loads

It is important to start by reducing heat loads in existing systems. This is heat that the refrigeration system must remove. Reducing heat loads reduces cooling demand and consequently, energy consumption. A survey of different contributors to the heat load will reveal which can be reduced. The main heat load comes from the products and it is therefore important that product temperatures are kept at stable low temperatures before they are refrigerated. If loading is inefficient, it could lead to unnecessary heating of the products, which should be avoided. A low final temperature is best for good food quality and long shelf life. Insulating the walls, floor and ceiling will reduce heat ingress from the outside, but a complete vapour barrier is even more important in preventing moisture and ice formation inside insulation, since both can damage it. The largest heat leaks are commonly by doors, so they must be properly constructed. Moist air inside a refrigerated room will accumulate on the evaporators, which will reduce heat transfer and increase the need for defrosting.

The size of the refrigerated rooms (freezing tunnels, freezing, and cooling storage) should be matched with production volumes. If a room is too large, it requires more refrigeration capacity than necessary because of heat leakage and the possibility of uneven temperature distribution. If a room is too small, products may not be cooled or chilled quickly enough.

4.3 Contaminants

At an evaporation temperature below -33.4 °C for ammonia, the pressure becomes sub-atmospheric. This will allow leakage of air into the system if the system is not completely sealed (which is common for larger systems with many components and pipes). Air inside a system will accumulate in the high-pressure side and increase condenser pressure (Welch and Wright J., 2008). This can lead to both higher energy use and more wear on mechanical parts, because of the higher temperature. The oxygen in the air increases corrosion of pipes and vessels (Ficker, 2009). Manual or automatic air purgers can be used to remove the air. If air gets into the system, it will also introduce water vapour, which will have an additional negative effect on system efficiency. Water accumulates on the low-pressure side of the system and a water filter should be installed there. Water content should be less than 1 %. Copper components must always be avoided in ammonia systems, because ammonia and water corrode copper, zinc, and their alloys. Oil is another contaminant that can come from compressors. It should be removed by an oil separator that is installed after the compressor. Oil is used in the compressors to reduce friction and improve the seal between moving and static parts. However, even if compressors are equipped with oil separators to ensure oil return, some of the oil will always follow the refrigerant. An oil film on the inside of the evaporator will reduce heat exchange. Extra oil drain valves in the lower parts of the systems should also be used. Oil is lower density and will therefore accumulate in the lowest parts of the system. (Koster, 2009; Lorentzen, 1988; Pearson, 2008a, 2008b; Widell, 2012a)

4.4 Temperature levels

The temperature/pressure levels that a compressor works between are important in determining the energy efficiency of the system. Larger differences result in lower efficiency. For reciprocating compressors this is solved by employing compressors at different stages.

Selecting the evaporator temperature is crucial in determining compressor energy use. The temperature in the evaporator should be kept as high as possible to ensure the lowest possible temperature lift in the compressor. The energy use of the compressors can be reduced by 2-4% for each Kelvin that the temperature/pressure is increased in the evaporators or decreased in the condensers.

Product temperatures should be low, but an evaluation of temperature needs may reveal that a higher evaporator temperature will nevertheless result in the same desired product temperature.

4.5 Capacity regulation

Reciprocating and screw compressors are the most common compressor types used in industrial ammonia systems. Reciprocating compressors require more service but can have greater energy-efficient capacity regulation and operation (at low cooling capacities) than screw compressors (Pearson, 2008b). Screw compressors are more common when larger cooling capacities are required. They are also more reliable and can work across larger pressure differences. One screw compressor working across the same pressure difference as two reciprocating compressors in series requires lower investment costs.

Figure 4.1 shows a graphic of a compressor that is regulated with a slide valve. Slide valve regulators have been the most common way of varying the capacity of a screw compressor. Opening the slide valve will vent some of the gas from inside the compressor to the suction port. This can provide smooth regulation to about 10 % of full capacity, but the energy efficiency of the compressor will be reduced due to friction in the gas and a reduction in volume ratio (Stoecker, 1998). A small opening in the slide valve results in a larger capacity drop, since the relation between the slide position and the capacity is not linear, see Figure 4.2. The benefits of using an economizer will be lost if the capacity is reduced below about 80 %. In industrial refrigeration systems, more than one compressor may be operating at a partial load during production. It is better to run the compressors at full load or turn them off and only have one operating at a partial load.

A more common way of varying the cooling capacity is to use a frequency converter (variable speed drive, VSD), which varies the speed of the compressor motor. It is normally operated between 30 and 60 Hz, allowing the operator to increase the cooling capacity above the design value at peak loads (for 50 Hz) if the compressors are built for this. (Pachai, 2014; Widell, 2012b)

Other motors can also have frequency converters, such as the seawater pump for chilling condensers. If a motor is low efficiency, the payback time for replacing it with a high-efficiency electrical motor can be short. Operational costs are typically 98 % of a motor's life costs, while investment costs are only 2 %.

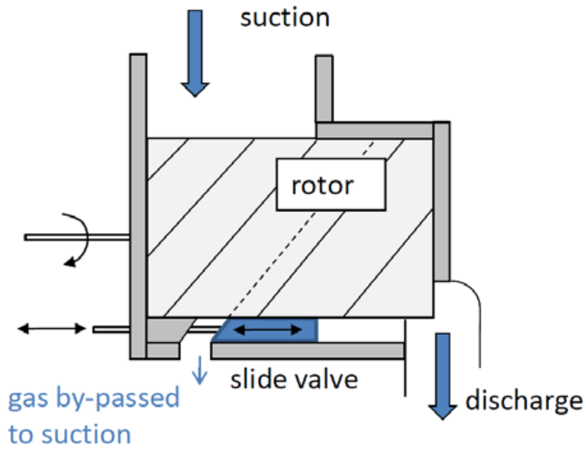

Figure 4.1. Compressor with slide valve in operation. The dash line indicates where compression starts at part load operation (Widell, 2012)

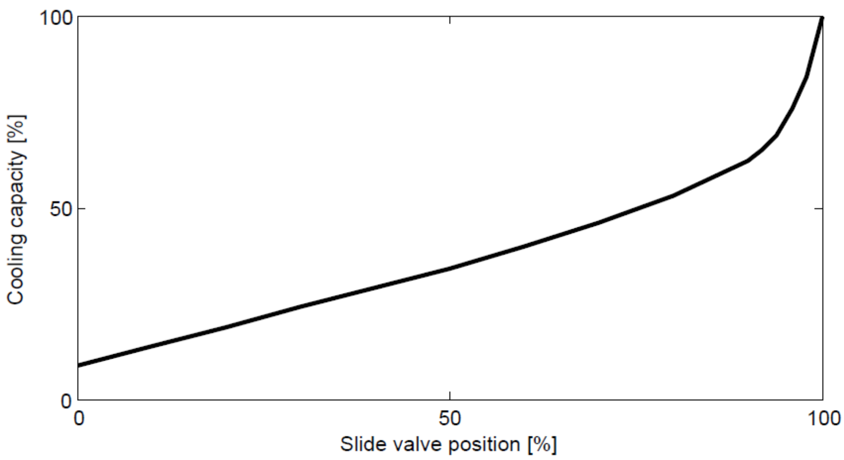

Figure 4.2. Theoretical curve showing cooling capacity as a function of compressor slide valve position (Widell, 2012)

4.6 Condenser considerations

It is necessary to maintain a low condenser temperature to keep the compressor pressure lift as low as possible. This can be done by ensuring high heat transfer rates and low cooling media temperatures (Forbes Pearson, 2003). Because of higher heat transfer coefficients, condensers chilled by water are more effective than air-cooled condensers.

Since condensers in this industry often are chilled with seawater, they are consequently subject to fouling. The local environment around the water outlet of seawater-cooled condensers is beneficial for biological growth. Sessile invertebrates such as mussels, barnacles and sea anemones must be removed regularly to ensure a high mass flow and high heat transfer through the heat exchanger.

As described in section 4.3, air inside a refrigeration system will accumulate in the high-pressure section and increase the condenser pressure. This will make the compressor work at a higher pressure, leading to higher energy usage, but also more wear on mechanical parts because of the higher temperature. The air inside the system can be removed manually (which must be detected and undertaken by the operators) or with an automatic air purger, which is easier.

Compressor energy use can be reduced by 2-4 % for each Kelvin that the temperature/pressure is reduced in the condensers.

5 Conclusions and the way forward

Electricity used onboard fishing vessels is entirely produced by fossil fuels, so improved energy efficiency is important for shipowners – both for the climate, but also for operational costs. Global warming can be intensified by the release of harmful refrigerants, which is inevitable from industrial refrigeration systems. Harmful refrigerants such as R22 are being phased out, but they need to be replaced by natural refrigerants that have known long-term insignificant effects on the environment. Ammonia has been used continuously since the beginning of industrial refrigeration in large refrigeration systems, and these systems can be very efficient. Ammonia is also safe to use if the required precautions are taken. CO_2 are also good alternative working fluids, although they are not now widely used in industrial refrigeration.

The main consumer of energy is however the propulsion system of a vessel, and there are several different actions for reducing its energy consumption. Recently a transition towards low-carbon fuels and improved propulsion technology has started, and this will in part alter the premises for onboard refrigeration. For example, some fishing vessels are planning to use LNG as fuel, which creates the possibility to recover "free cooling" to cover some of the refrigeration demands. Such recovery concepts exist for LNG-fuelled passenger vessels to cover parts of AC cooling demand, but there is a need to develop concepts adapted to fishing vessels given their differing operational conditions and patterns. Another under-utilized feature that is described in this report is the use of cold thermal storages, which can be used to offset the temporal mismatch between supply and demand, but also introduce increased technical flexibility, energy efficiency and improve the overall chilling process.

Recovering waste heat is another important measure to improve overall energy efficiency, and this report focus on two sources for heat recovery, namely from the exhaust gases and from the refrigeration system(s). Heat from exhaust gases has, in general, a high quality and varying quantity dependent on load of engine, and can be used for covering e.g. hot water production, rest raw material processing or power generation (ORC). Heat from the refrigeration systems can be used to cover other demands such as room heating or snow melting, dependent on temperature levels.

An eight-year centre for renewable energy named HighEff[2] that began in 2016 aims to reduce specific energy consumption in Norwegian industry by 20-30%. The centre is led by SINTEF and has many other research institutes and industries as partners. One of the industry sectors that is being examined is the food industry, where activities include energy auditing of refrigeration systems aboard fishing vessels, high-temperature heat pumps for steam production, integrated energy systems for food production and developing technology for natural refrigerants.

CoolFish[3] is another project which covers several aspects of this report. CoolFish will develop technologies and concepts for more integrated, energy-efficient and climate friendly cooling, freezing, and heating onboard fishing vessels. It will also increase the knowledge transfer between research and industry, both nationally and internationally.

Increasing the edible yield and use of by-products can also lead to lower emissions. Processing more seafood before export is advantageous because of better possibilities to make use of by-products and decreased need for transportation when exporting products rather than whole fish. In CoolFish, there will be more activities within this field in 2021.

On the long-term, it is desirable to increase the knowledge of the impact of individual measures in fisheries management to be able to optimize the management system also from an environmental point of view.

[2] https://www.sintef.no/projectweb/higheff/
[3] https://www.sintef.no/en/projects/coolfish/

Taking carbon footprint and energy efficiency into account in the design of the fisheries management systems of the future would help making seafood production an even more sustainable and less resource-demanding business.

Seafood products studied are on the right way towards sustainability and have many of the essential elements of sustainable production in place already. However, there are many actions both on the short and long term that can improve the situation further and it is very important to deal with these questions in a proactive way to produce sustainable products.

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