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Cryogenic cold utilization and system integration possibilities for LNG-driven fishing vessels

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ABSTRACT

Liquified natural gas (LNG) fuelled vessels are increasing in the fishing industry due to its reduced environmental footprint as compared to vessels using heavy hydrocarbon fuels. Cryogenic tanks are used to store LNG on ships, and the LNG vaporization can be done with different technology before used for engine fuel. The refrigeration system is essential to maintain the quality of fish. The operational power for the cooling system is produced by the engine. The challenge is to utilize the evaporation cold of the LNG efficiently, to reduce the overall energy consumption and to boost the cooling capacity. An objective of this paper is to describe different options for integration with the refrigeration system of the fishing vessel and to analyse their actual cold recovery potential from vaporizing LNG. Results show that for a 760 KW engine capacity coastal demersal trawler, 10.45 kW cold recovery is estimated under specified conditions.
Keywords: LNG Cold, Fishing Vessels, Cold Recovery, Chilling System, Refrigeration, Cryogenics, Thermal Storage.

1. INTRODUCTION

Fishing vessels are the most significant energy consumer, which holds them responsible for high emissions among the seafood product value chain (Jafarzadeh et al., 2017). In 2015, the fishing sector was responsible for 1.9 % of total Norway's emissions. Efforts are ongoing to reduce emissions and improve the overall energy efficiency to make the business more sustainable. Norway's ambition is to become a low emission society by 2050. Several steps are considered to achieve this. One effort is increased CO_2 tax (currently 508 NOK/tonnes) to incentivize businesses towards more sustainable solutions (Norwegian ministry of climate and environment, 2018). The European commission transport white paper (2011) set a target of 60 % lower carbon emissions by 2050 compared to 1990 and 70% compared to 2008 with the aim towards zero energy emissions (Sihvonen, 2018).
Transportation industry will require a change from mineral oil to electric batteries, hydrogen, or gas. Liquid natural gas (LNG) or gas use in the EU is encouraged by regulations, tax breaks, and subsidies (Sihvonen, 2018). LNG is gaining more attraction in the marine industry due to its high energy density, availability, and fewer emissions. LNG has a higher hydrogen-to-carbon ratio than diesel. LNG-fuelled ships emit 90 % less NO_x, 25 % less CO_2, and almost no SO_x as compared to heavy hydrocarbon fuels (Jafarzadeh et al., 2017).
LNG fuel is stored onboard in cryogenic tanks, and the storage pressure of LNG in the tank depends on the design of the system. The saturation temperature of LNG at 1 bar is -162 °C. The density of LNG is 450 kg/m^3 which is small in comparison to diesel density, which is 860 kg/m^3 (Jafarzadeh, 2017). Due to the high calorific value of LNG, the required mass flow rate of LNG is less than the diesel engine for the same power, which is an advantage for LNG. The density difference between LNG at 1 bar and compressed natural gas (CNG) at 200 bar is 275 kg/m^3, which means LNG fuelled vessel can travel 2.5 times more as compared to CNG vessel for the same volume of a fuel tank (Arteconi et al., 2019).
There is extensive research on different methods of vaporization at LNG regasification terminals, but a few data on onboard LNG regasification. Astolfi et al., (2017) studied the organic Rankine cycle (ORC) with various working fluids to enhance the effectiveness of LNG regasification terminals. Seawater used as a heat source and different condensing temperatures analysed for gasification. The expansion energy recovered from the ORC was converted to electricity. They summarized that this technology could be suitable for

onshore regasification terminals because specific energy consumption was less than other methods. Tan et al., (2010) examined the cold recovery from LNG refrigerated vehicles. Thermal storage investigated as an option to recover cold in the internally finned tube heat exchanger with LNG inside the tube and water as a phase change material outside the tube. Better results were found for internally finned tubes for thermal storage in comparison to a plain tube heat exchanger. Koo et al., (2019) studied the evaporation of LNG using ORC and its integration with the engine cooling system on ships. LNG gasification was done with heat energy from the condenser and cold energy from the evaporator utilized for the engine cooling circuit. High exergy efficiency and net power output were reported. Other literature on the cold recovery of LNG fishing vessels and its application for refrigeration system integration has not been found.

2. SYSTEM DESIGN

2.1. LNG on fishing vessels

LNG fuelled ships use dual-fuel engines that operate both on diesel and natural gas. Natural gas used as primary and diesel as a backup fuel. Dual fuel engines can be classified as low, medium, and high-pressure engines. Low-pressure engines operate at approximately 5-6 bar, medium pressure engines at 17 bar and high-pressure engines at 300 bar at the inlet fuel conditions to the engine (Jafarzadeh et al., 2017), (Koo et al., 2019).

A Norwegian coastal demersal trawler equipped with a 760 kW engine capacity is a study case. The inlet fuel conditions to the engine were set at 6 bar and 40 °C. LNG cold energy is dependent on the fuel consumption of the engine. The fuel consumption of the fishing vessel is not constant throughout the journey. It is different during fishing, towards the fishing ground and returns and the fuel consumption pattern is highly dependent on the fishing method and the type of vessel. Due to the variable fuel supply, cryogenic cold energy will also fluctuate. There can be many applications for the LNG cold, but for this paper, it is utilized for three separate options, sub-cooling of refrigerant in a refrigeration system, direct chilling of a fish tank and thermal energy storage. The 760 kW trawler was designed to use diesel as a fuel and the diesel consumption converted into LNG consumption by using characteristic values and equation. Yearly diesel consumption of this engine is 407,030 litres in 280 operational days. The round trip of one fishing journey was assumed six days. Two days each for moving towards the fishing ground, during fishing and return, with a total diesel consumption of 8.72 m^3 and estimated energy of 35.17 MWh by using Eq. (1). Specific fuel consumption of an 845 kW gas engine was used for LNG estimation due to its availability in the market. By using Eq. (1), LNG fuel consumption for 760 kW trawler in one trip is 15.55 m^3 (Jafarzadeh et al., 2017)

$$E = \frac{F * \rho}{Sfc} \text{ [kWh]} \qquad \text{Eq. (1)}$$

Where E, F, ρ, Sfc are energy, fuel consumption, density, and specific fuel consumption, respectively. The values used for calculation purpose are shown in Table 1.

Table 1. Characteristics values for calculation (Jafarzadeh et al., 2017)

Parameters	**Values**
Diesel engine power (kW)	760
Sfc diesel engine (g/kWh)	213.30
Diesel density (kg/m^3)	860
Gas engine power (kW)	845
Sfc gas engine (g/kWh)	198.99
LNG density (kg/m^3)	450

Based on the above calculations and data, the average mass flow rate in six days journey is 0.0135 kg/s or 0.0291 litres/s. For trawling vessels, the highest fuel consumption is during trawling (Gulbrandsen, 2012). It was assumed that during trawling fuel consumption is 30% higher than average (0.0176 kg/s and corresponding engine power 760 kW), 30% less than average when moving towards fishing (0.0095 kg/s and engine power 532 kW) and return fuel flow equal to average (0.0135 kg/s and engine power 372 kW). LNG fuel flow from the cryogenic tank to the LNG vaporizer (cold box), and then to the engine can be done by using a pump before the cold box or by compressor after the cold box. Both cases are studied in the simulation software.

2.2. Refrigeration system

The natural refrigerant CO_2 was used as a working fluid in the refrigeration system. Refrigeration capacity is in the range of 170 kW to 250 kW with a total chilling tank volume of 300 m^3, the estimation was adapted from the interpolation of available data from Skipsteknisk (2003) and Nordtvedt et al. (2019). The performance of the refrigeration system is measured by the coefficient of performance (COP). COP is a ratio of evaporator output and compressor input and it is a unitless number.

2.3. Simulation model

A steady-state thermodynamic analysis of the LNG cold recovery was performed on Aspen HYSYS V10. Peng Robinson equations were used as a fluid package. For simplification, LNG was assumed as 100 % Methane at 3.5 bar and bubble point (-144.1 °C) in the LNG fuel tank. In the simulation, the fixed parameters were evaporation and condensation temperature -6 °C and 20 °C, respectively, compressor adiabatic efficiency 0.75 for both compressors, pump adiabatic efficiency 0.75, the temperature difference in the heat exchangers 5 K and the outlet temperature of methane from sub-cooler -6 °C. When a pump used to drive fuel, then the vaporization pressure of the methane in the sub-cooler was fixed to 6 bar, and 3.5 bar in the compressor case. The compressor increases both pressure and temperature. If the system is using a pump, then heating of fuel is necessary after the sub-cooler to meet the inlet fuel conditions of the engine. The flow diagram of the complete system is shown in Fig. 1.

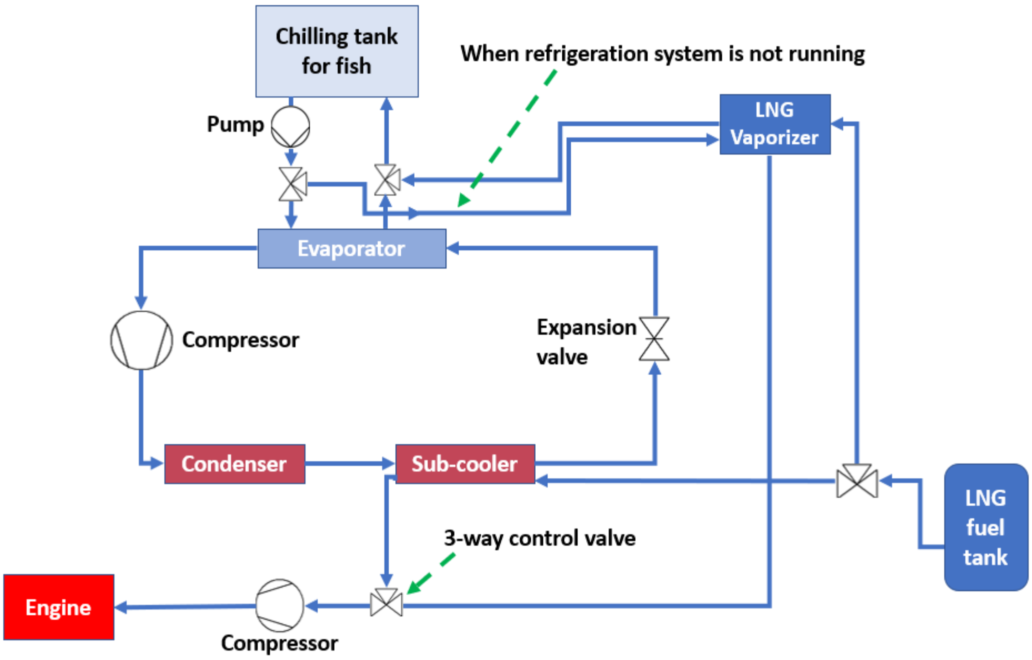


Figure 1: System layout

3. DIFFERENT OPERATING MODES/SCENARIOS

3.1. Sub-cooling of refrigerant

In the refrigeration system, sub-cooling of the refrigerant after condenser increases the volumetric refrigeration capacity. High refrigeration capacity with the same amount of work by compressor results in high COP. A shell and tube heat exchanger (HX) was used as a sub-cooler in the refrigeration system with methane inside the tube and refrigerant on the shell side. The inlet temperature of the refrigerant to the LNG HX was fixed to 20 °C and liquid phase. Sub-cooling of refrigerant in LNG HX after condenser is analysed in this scenario.

3.2. Direct chilling of fish tank

Direct chilling of the fish tank with LNG cold is an option when the fish tank has a minimal load (only thermal losses). The simulation for direct chilling was also performed in the shell and tube heat HX with methane inside the tube and water on the shell side. It was assumed that inlet water temperature in the HX is 2 °C, with no freezing of water at -1 °C due to the utilization of seawater in the fish tank. The flow rate of the seawater circuit was estimated with constant C_p and constant temperature difference of 3 °C in the heat exchanger.

3.3. Thermal storage

Cooling demand in the fishing vessels varies with time and need. Thermal storage with LNG cold is a suitable option when the refrigeration system is not running, or the chilling tank has no load. A water-based (eutectic) phase change material (PCM) with a phase change temperature of -6 °C was used for analysis. The PCM properties were density 1110 kg/m^3, specific heat capacity 3.83 kJ/kg.K, and latent heat 300 kJ/kg (PCM products, 2018). The initial temperature of the water was assumed at an ambient temperature of 15 °C. Thermal storage of three sizes 0.5 m^3 (58.65 kWh), 1 m^3 (117.30 kWh), and 1.5 m^3 (175.95 kWh) were analysed with LNG cold potential without thermal losses of a storage tank.

3.4. Cold recovery potential at different fuel tank pressures

The storage pressure of fuel in the LNG tank is important for cold recovery potential. High pressure in the tank elevates the bubble point. Cold recovery potential at different LNG pressure is also studied and the corresponding results are presented in section 4.

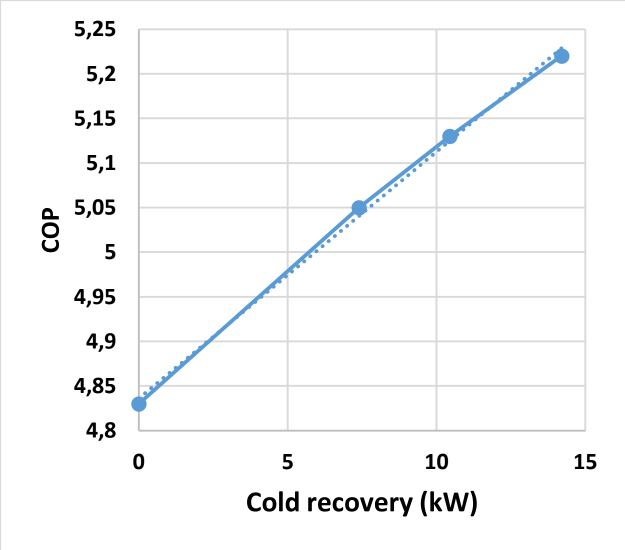
4. RESULTS AND DISCUSSION

Cold recovery potential from the simulation results both with compressor and pump is presented in Table 2. The required power for fuel flow by a pump is less as compared to the compressor but it should be noted that compressor is mature technology than a cryogenic pump. An additional heat exchanger is also required after sub-cooler in case of a pump to meet the inlet fuel temperature of the engine.

Table 2: Cold recovery potential from simulation results

Trawler mode	Fuel flow (kg/s)	Engine power (kW)	Cold Recovery with pump flow (kW)	Cold recovery with compressor flow (kW)	Pump power (kW)	Compressor power (kW)
Towards fishing	0.0095 (m_1)	372	7.3	7.4	0.008	0.99
Return	0.0135 (m_2)	532	10.4	10.45	0.011	1.42
During fishing	0.0176 (m_3)	760	13.55	13.63	0.015	1.85

The simulation results show an increment in COP of the refrigeration system, with LNG cold recovery in the sub-cooler at a refrigeration load of 173 kW. The highest COP is observed at the maximum LNG cold recovery, which is 5.22 at full capacity (760 kW) of the engine. Fig. 2a shows this relation.
The sub-cooling effect with LNG cold is very high at low loads. At small refrigerant loads, the refrigerant mass flow is low, which leads to a significant temperature difference in the sub-cooler at maximum LNG cold recovery. At the maximum refrigeration load, the sub-cooling effect is minor but still contributes to increased COP as compared to a system without sub-cooler. Fig. 2b shows the temperature difference between in and out of the sub-cooler with the three LNG fuel flow conditions.



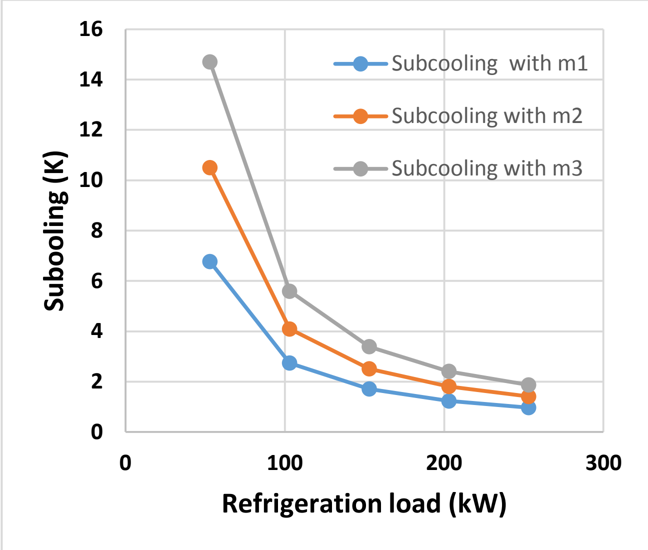


Figure 2a: LNG cold recovery versus COP **Figure 2b: Refrigeration load versus sub-cooling**

Direct chilling of fish tank with LNG cold shows a small temperature gradient in the HX. The temperature difference in the LNG HX for fish tank water is dependent on the flow rate of water (load dependence), which is high in the case of water due to the involvement of only sensible heat. However, the temperature difference of refrigerant in the LNG sub-cooler is high due to small refrigerant flow in the refrigeration system.

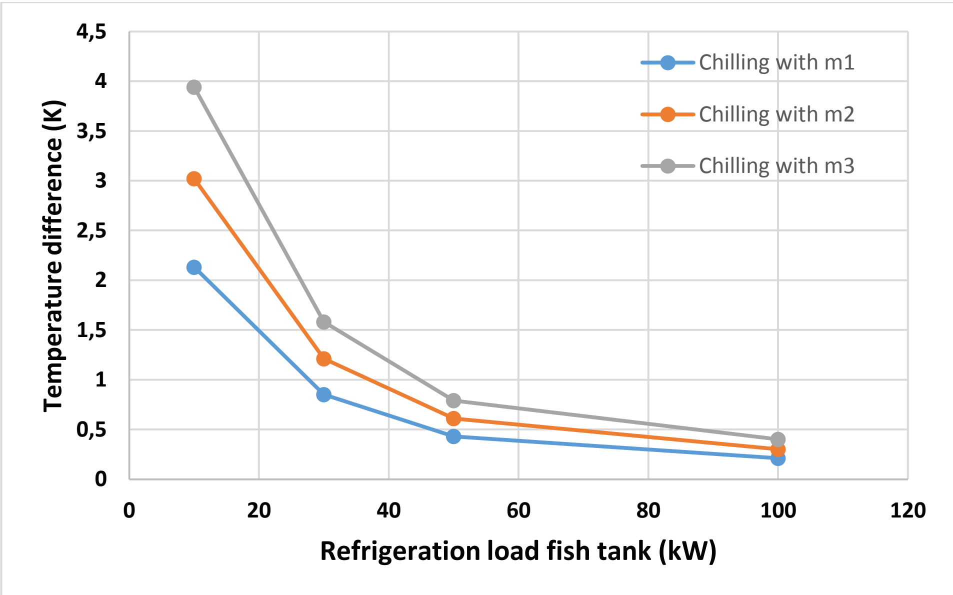


Figure 3: Water chilling at different loads in LNG heat exchanger

Direct chilling with LNG cold was studied at different refrigeration loads. At higher loads, it is not possible to attain a water temperature of -1 °C after LNG HX but the option looks suitable for low loads. The chilling water temperature difference between in and out of the heat exchanger with their corresponding LNG cold recovery is visualized in Fig. 3.

Thermal energy storage is an interesting feature that can increase system performance by assisting the refrigeration system at peak demands. The available storage energy is an offset between refrigeration demand and available LNG cold. The size of the thermal storage tank is a balance between the available cold energy, free space, and refrigeration load profile of the vessel. The shortest time to store energy is observed with 13.63 kW at m_3 (fuel flow) and the highest time with 7.4 kW. If thermal losses are considered, the required cooling time will increase. The results are shown in Fig. 4.

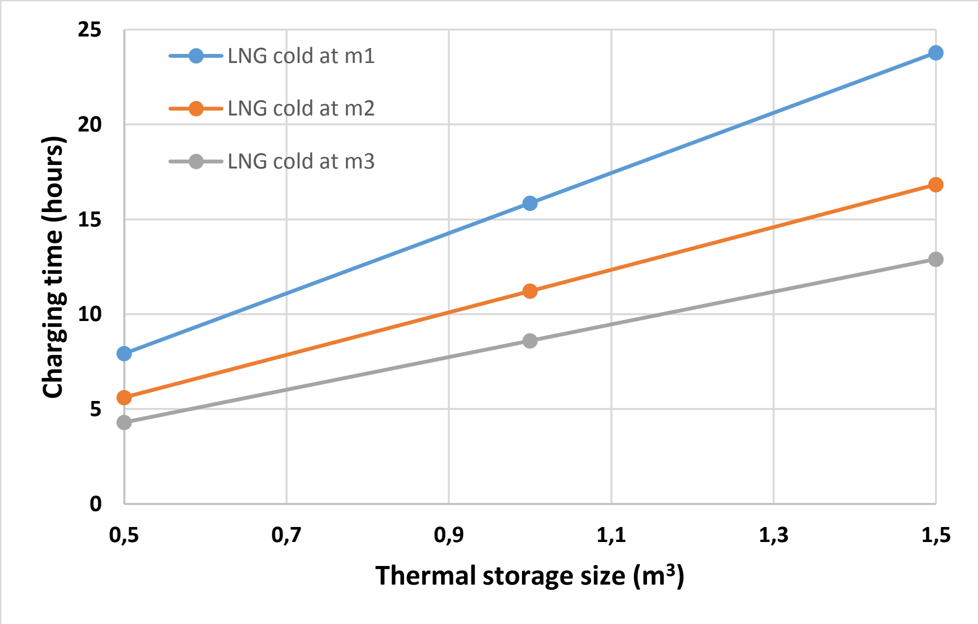


Figure 4: Storage size versus required charging time with LNG cold

The increased pressure in the LNG tank shows a reduction in the cold recovery potential. This is due to the high boiling temperature of methane at high pressures. High pressure also leads to a decrease in the density of fuel, which means less fuel in the same volume of the storage tank. Less amount of fuel can create issues for long journey fishing vessels. On the other hand, the high pressure of fuel can assist the medium or high-pressure engines by reducing the pressure lift in the pump or compressor. The cold recovery potential at different pressure levels in the tank is more visible at the maximum flow rate (m_3) of fuel, but the effect is small at a low flow rate (m_1). This is shown in Fig. 5.

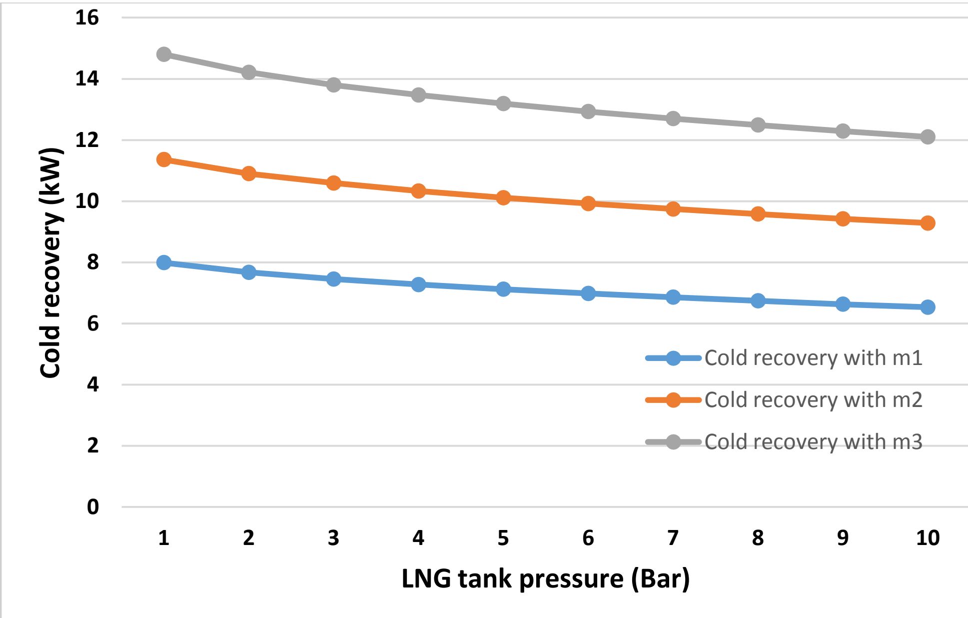


Figure 5: LNG tank pressure versus cold recovery potential

The compactness and robustness of the systems are very important on the fishing vessels. Each m^3 of space onboard costs a lot. Either it's the installation of LNG vaporizer, thermal storage tank, and LNG fuel tank, it should be a competitive choice in terms of size, investment, and sustainability. The life cycle and economic assessment are necessary before implementing any solution.

4.1. Future work

The cold recovery potential is sensitive to the fuel consumption of the engine, and the fuel consumption pattern is a dynamic factor. A small change during the trip leads to alter the fuel supply. More detailed data is a need for full dynamics. The fuel flow varies a lot for different fishing vessels and fishing methods, which makes it difficult to generalize the technology.

LNG heat exchanger or LNG vaporizer is very important to design smartly. Refrigerant load and fuel supply to the engine are independent parameters. LNG superheat in the heat exchanger is difficult to control due to its independent behaviour. It is recommended to use a secondary circuit between the LNG cold box and the cold recovery application for better monitoring and safety of the system.

There is a potential to extend this work with another case study to the onboard processing of fish, mainly big trawlers. Onboard processing includes filleting and freezing of fish. Waste material (small pieces and bones) from fish filleting demands further processing to produce fish oil, fish meal, and other nutritional products. This waste material processing requires a lot of heat energy. Heat recovery from the flue gases of the engine, desuperheater of the refrigeration system and their integration with other arrangements can make the fishing vessels more sustainable, climate-friendly, and energy-efficient.

5. CONCLUSIONS

In this paper, an innovative approach for LNG cold recovery potential on a fishing vessel was carried out on the software Aspen HYSYS V10. As a first application, LNG cold was utilized for the sub-cooling of the refrigerant in the CO_2 refrigeration system. Results show an increment of COP by 8 % at maximum and 4.5 % at minimum cold recovery potential at a constant refrigeration load of 173 kW. Other potential applications, direct chilling of a fish tank, and thermal storage with LNG cold were also analysed. For the direct chilling of a fish tank, a small temperature difference in the heat exchanger was observed for chilling water. The results predict that the option is viable for small refrigeration loads. It is perceived that the size of thermal storage relies on the available LNG cold and the length of a fishing journey. Optimum design pressure of fuel in the LNG tank can save the space on the vessel and capital investment. Dynamic simulations of the complete fishing trip are requisite for precise prediction of LNG cold applications.

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