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Integrated thermal storage and heat recovery of the CO_2 refrigeration system for fishing vessels

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ABSTRACT

The natural refrigerant CO_2 is gaining an attraction for fishing vessels due to its compact units, negligible global warming potential (GWP), and non-toxic behaviour. Chilling and freezing onboard are energy-consuming processes but are necessary to ensure high-quality products. Cold thermal storage is a smart feature that assists the refrigeration system at peak loads, and such setups are working efficiently on the onshore facilities. CO_2 thermal storage is suitable for fish freezing with which you can store cold energy as low as -57 °C. Heating is also necessary onboard, for warm water, snow melting, and processing of fish rest raw material. Currently, the onboard refrigeration system challenges are low coefficient of performance (COP) at part load operations and insufficient capacity at peak loads. This paper investigates the integrated CO_2 thermal storage and heat recovery from the gas-cooler of the CO_2 refrigeration system to improve the total system performance.

Keywords: Refrigeration, Thermal Storage, Carbon Dioxide, Fishing Vessels, Integration, Heat Recovery, Energy Efficiency.

1. INTRODUCTION

Modern refrigeration systems are integrated heating and cooling systems. Natural refrigerant CO_2 is a fair choice, with excellent thermophysical properties, non-flammability, and compact systems due to high volumetric capacity (Hafner et al., 2019). Thermal energy storage is a method to store energy in times when refrigeration load is less and utilize during peak load to reduce the chilling or freezing time. Thermal energy storage in the form of dry ice is the right choice for freezing systems operating at an evaporation temperature of -50 °C. The phase change temperature of CO_2 from liquid to solid is -56.6 °C at 5.18 bar. Storing cold energy in solid form is possible by charging the thermal storage system with CO_2 refrigerant pressure less than 5.18 bar (Niu et al., 2011), (Hafner et al., 2011).

The short journey fishing vessels store fish in refrigerated seawater (RSW) systems. The long journey vessels who spend weeks in the sea, freeze the fish to have a long shelf life. These vessels often have onboard processing units in which they produce fillets from the whole fish. The fish is processed and frozen after the catch and then stored in low-temperature cargo storage. In this way, the vessels can remain at sea until the cargo storage is full. The leftover from the processing of main fish product (fillets) are head, bones, skin, trimmings, and guts; typically called rest raw materials (RRM) in Norway. The RRM is not as valuable as fillets but can be processed further to value added ingredients. According to FAO (2014), globally, 80 million tonnes of fish are processed for filleting, canning, or curing, of which rest raw materials account for 50 to 70 % that are not fully utilized (Ølsen et al., 2014). RRM is a source of fish oil (omega-3) production, which is the highest profitable product among other additional by-fractions.

Refrigeration systems are designed to cover an average load, but they must also be able to cover some peak loads (Valentas et al., 1997). If the refrigeration capacity is lower than the product load, it will prolong the freezing time, and this problem happens during the start of the freezing cycle. In plate freezers, one reason for having a high starting refrigeration load is due to defrosting of the plates after each period.

This study aims to investigate the implementation of CO_2 thermal storage as dry ice to cover the peak loads. The charging and discharging potential of CO_2 thermal storage are evaluated for integration with the existing refrigeration system for fish freezing. The unused refrigeration capacity at part load operations is an option to utilize and store cold thermal energy for later use. The heat recovery from the refrigeration system is also analyzed for fish oil production to improve the energy performance of the total system.

2. SYSTEM DESIGN AND SIMULATIONS

2.1. Dynamic modelling software

To simulate the dynamic energy model, Dymola software (Dymola, 2020) with components and refrigerant libraries from TLK- Thermo GmbH (TLK, thermo 2020) were used. TIL media is a model library for refrigerants and secondary fluids, while TIL for components like heat exchangers, compressors, and valves. The software has built-in components with a high degree of control on the input parameters and boundary conditions. It also has an add-on library for thermal storage, which combines with the designed refrigeration systems in TIL and Dymola.

2.2. Refrigeration system and freezing load

The reference refrigeration system for this paper is a two-stage CO_2 booster system working in the trans-critical state with a freezing capacity of 240 kW. The operating conditions of the unit are -50 °C evaporation (6.8 bar in low temperature (LT) separator) and 90 bar in the gas cooler. The medium temperature (MT) separator temperature and pressure are -10 °C and 26.4 bar, respectively. The temperature after the gas cooler and MT cooler is 15 °C. Both coolers are assumed water-cooled heat exchangers with an inlet seawater temperature of 10 °C. The source of refrigeration load is plate freezers in which fish is freezing from 10 °C to -20 °C (center temperature). The simplified sketch of the refrigeration system is shown in Fig. 1a. The fish freezing load is shown in Fig. 1b and it is adapted from the operational plate freezers for fish. Fish freezing is a transient process. At a temperature close to the initial freezing point, thermal properties change to a great extent, mainly the specific heat capacity, which prolongs the freezing time. In Fig. 1b, the peaks depict the new cycle of freezing after 40-45 minutes. Each peak corresponds to the addition of an average 357 MJ heat load from the fish.

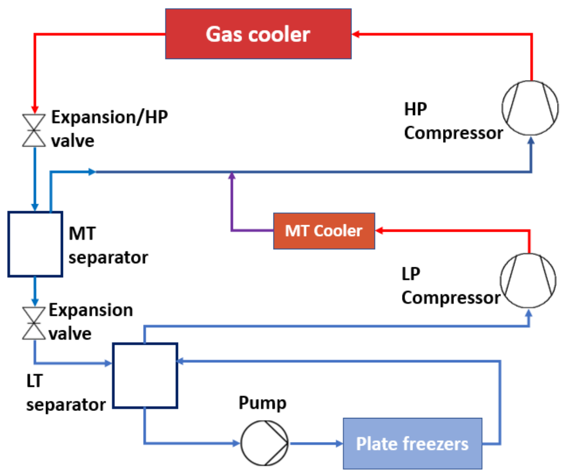

Figure 1a: Simplified two-stage system

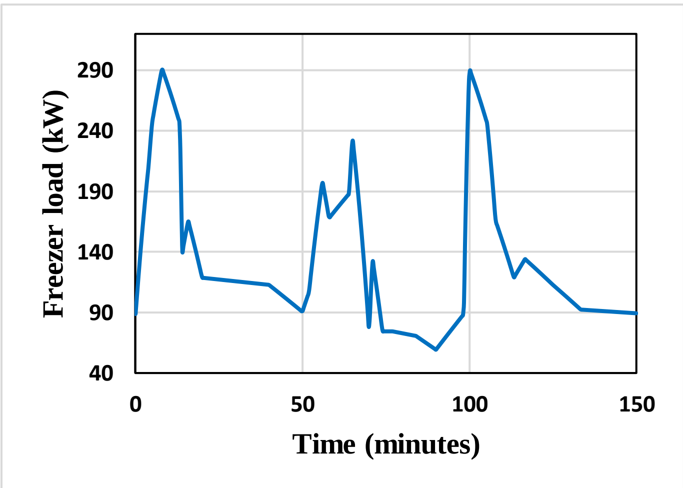

Figure 1b: Freezing load profile

2.3. Rest raw material processing

The thermal demand for onboard fish oil production is analyzed for RRM processing. This system is designed in coherence with the freezing volume of fish. The equivalent amount of RRM produced in 150 minutes freezing cycle is 3000 kg. The two methods of fish oil production are thermal treatment and hydrolysis. In the thermal treatment, the RRM is crushed in a mincer and then heated up to 90 °C. The heating temperature can be less than 90 °C but may have an effect on the oil quality and production rate. It is then further processed in the tri-canter. It is a unique component that separates the stick water (water phase), sludge (solid phase), and oil. It is also called a three-phase separator. After the tri-canter, the oil phase is further treated in a polishing centrifuge to remove the impurities. In the hydrolysis process, after crushing, RRM is mixed with an equal amount of water. It is then heated up to 60 °C before further treatment, as described in the thermal treatment process. The reasonable heating time for the hydrolysis process is 70 minutes (Carvajal et al., 2015). In this paper, heat recovery from the refrigeration system is compared with the thermal treatment process. The heating load of RRM for this process is shown in Fig. 2.

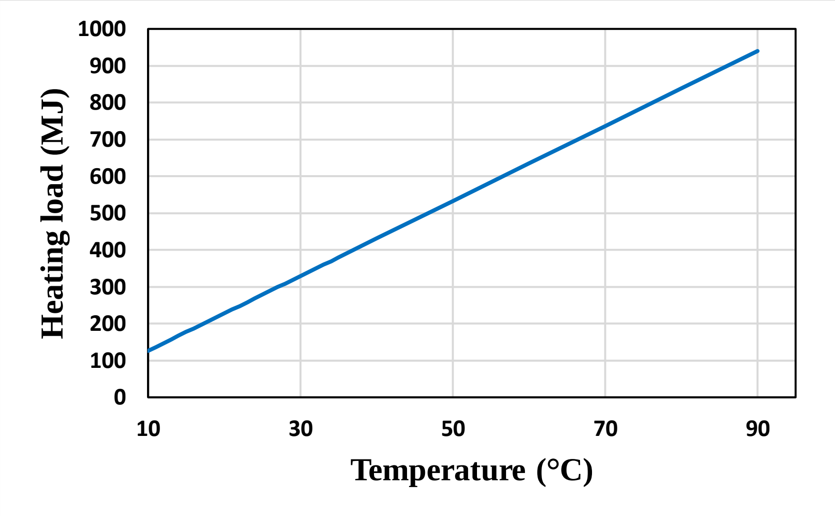

Figure 2: Heating demand for RRM thermal treatment

2.4. Thermal storage

CO_2 as phase change material (PCM) is investigated for integration with the freezing system. The purpose of this thermal storage is 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) is analyzed. The characteristics of aluminium thermal storage are shown in Table 1.

Table 1: Characteristics of thermal storage

Characteristics	Values
Volume of thermal storage (m^3)	1
Number of tubes	34*34
Total heat transfer area tube inner (m^2)	36.3
Total heat transfer area tube outer (m^2)	40
Tube inner diameter (mm)	10
Tube wall thickness (mm)	0.5

The storage conditions of PCM are 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 is integrated with the refrigeration system described in Figure1a. The charging condition of thermal storage is 3 bar (-68.3 °C). The charging is 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. Both designs are shown in Fig. 3a and 3b. The available time for TES charging is an average 40 minutes between two peaks. Liquid level in LT separator or temperature after plate freezer is an indication for charging. According to the freezing load profile in Fig. 1b, the load is higher than the refrigeration capacity for a maximum of 10 minutes. The discharging of thermal storage is investigated with a constant super-heat of 8 K (-42 °C) after the evaporator or freezer. However, the super-heat is not a constant value and varies a lot during peaks. For the current case, the super-heat range is 0 to 8 K in LT separator. The discharging concept is to re-condense the vapors after plate freezers with stored cold energy without any effect on LT separator.

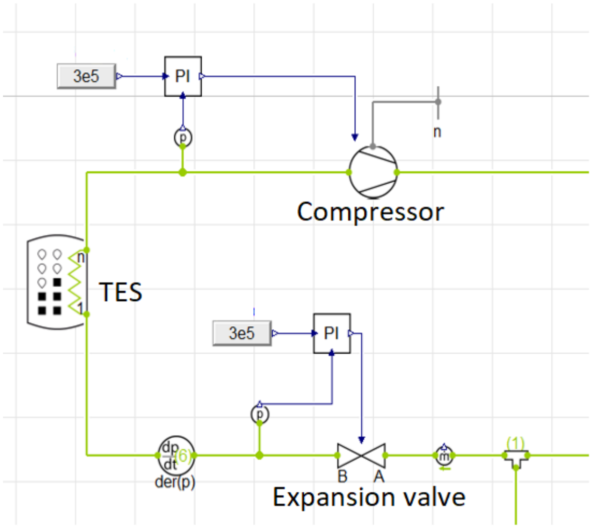

Figure 3a: Thermal storage charging using compressor

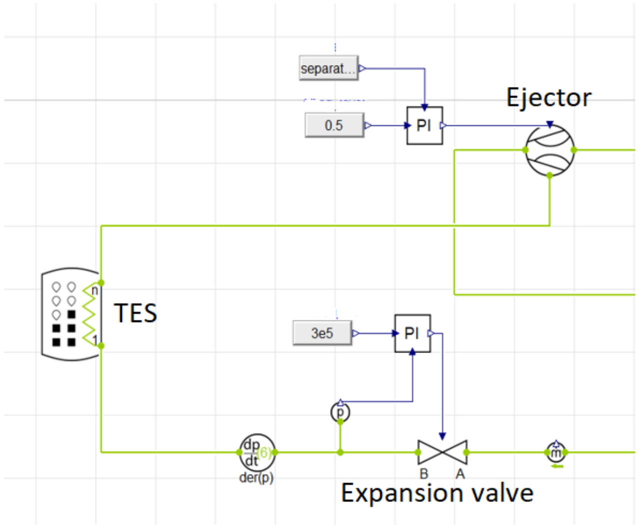

Figure 3b: Thermal storage charging using ejector

3. RESULTS AND DISCUSSION

3.1. Dynamic system performance

The simulation runs with the dynamic freezing load profile (Fig. 1b). The results for the coefficient of performance (COP) of the refrigeration system is shown in Fig. 4. COP analysis is without taking into account the power consumption of pumps because it is very low as compared to compressor work. The pressure levels in the simulation remained constant, irrespective of the load. The compressors isentropic and volumetric efficiency was 0.7. The maximum and minimum COP of freezing is 1.53 and 0.97, respectively. For a dynamic system, the size of LT and MT separator is vital. When the load changes, the compressor takes some time to change the power consumption. In the meantime, the liquid level in a separator damps the fluctuations. A high COP can be expected at a high load due to such consequences. The combined freezing and heating COP shows maximum and minimum values of 4.1 and 3.2, respectively.

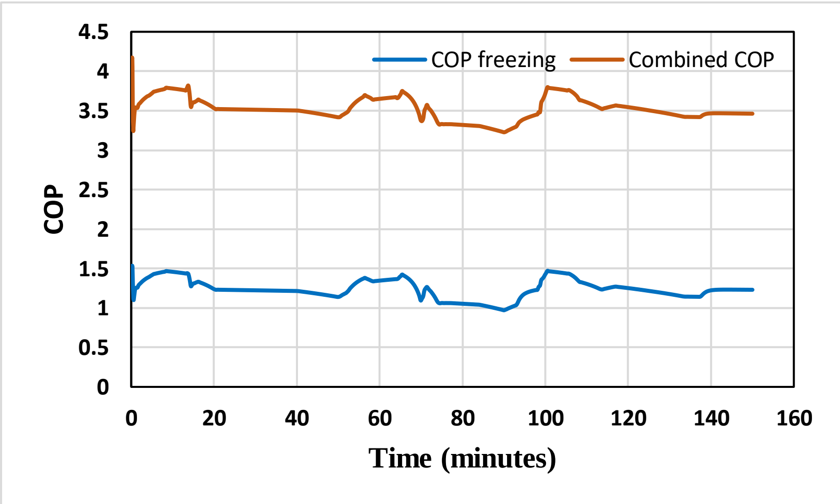

Figure 4: COP freezing and combined COP

3.2. Heat recovery

Heat recovery from the refrigeration system is shown in Fig. 5. The heat recovery values are the sum of both MT and gas cooler. The average heating demand for fish oil production is 261 kWh, and average heat recovery is 298 kWh. If thermal losses of 10 % are included, then the recovered energy is still enough for RRM processing. Integrated freezing and heating is a viable option for sustainable fishing. For RRM processing, MT, and gas cooler heat exchangers can act as a direct heating source or with a secondary glycol/water circuit However, the choice depends on the amount of RRM and hot water thermal storage.

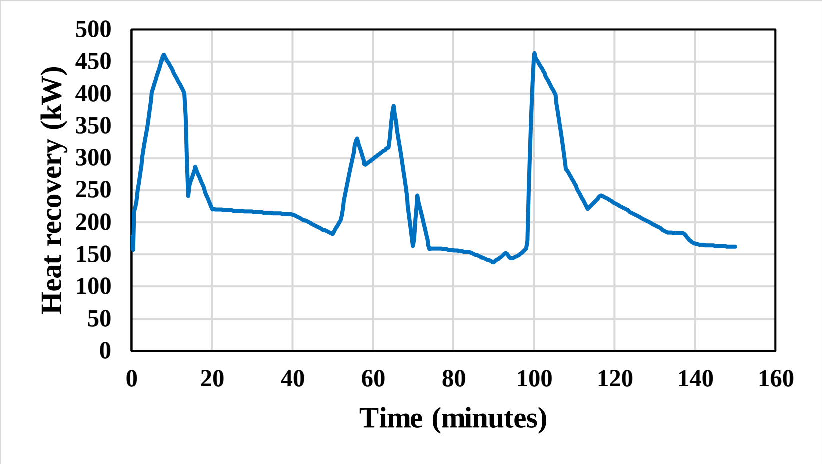

Figure 5: Total heat recovery of the refrigeration system

3.3. Thermal storage charging and discharging analysis

The pressure and temperature (3 bar and -68.3 °C) were maintained constant during the charging of thermal storage with a compressor. After 40 minutes of charging with a flow rate of 0.07 kg/s, the amount of solid CO_2 is 171 kg. For fully charged storage, the required time is 3.8 hours. The thermal storage charging with ejector shows a stable condition at 3.55 bar and -64.8 °C. The mass of dry ice at the end of the simulation is 116 kg, with a charging flow of 0.041 kg/s. The amount of dry ice is less in this case, which is mainly due to low-temperature difference (3.5 K) and lower charging flow.

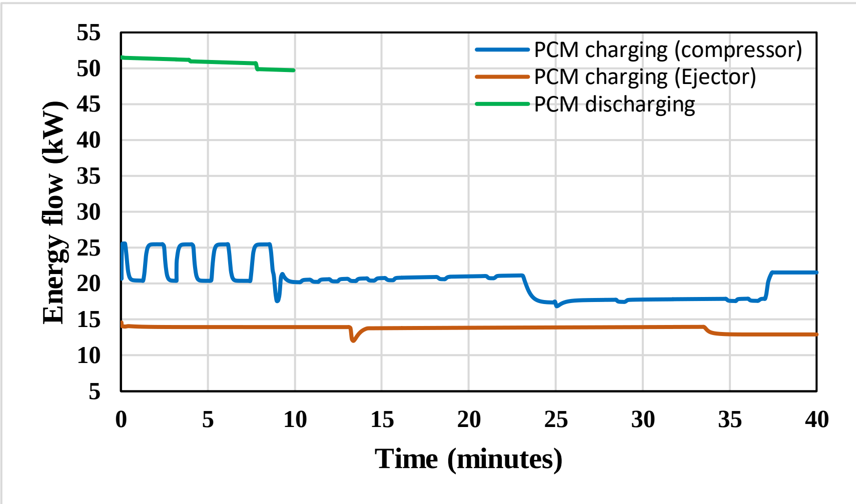

Figure 6: Thermal storage charging and discharging

The time required for fully charged storage with ejector is 5.6 hours under current conditions. In a simulation, the average power consumption of the compressor for charging is 2.9 kW to lift pressure from 3 bar to 6.8 bar. By using an ejector, this additional compressor power can be saved. Two-phase ejector implementation for such low-temperature conditions demands further investigation. However, simulation work shows good results.

The discharging of thermal storage was simulated with a constant super-heat of 8 K for 10 minutes according to the freezing load profile. The maximum discharging value is 51.4 kW. The total melting of dry ice in 10 minutes is 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.

In the view of discharging results and iterative process, a thermal storage size of 0.3 m^3 (75 liters or 112 kg dry ice), including internal heat trasnfer area of 67 m^2 (54*54 tubes), is an ideal option for the reference system. By increasing the size of this small thermal storage, complete melting of dry ice can avoid, which will optimise the heat transfer area and number of tubes.

4. CONCLUSION

In this paper, an integrated freezing and heating refrigeration system was analyzed with low temperature CO_2 thermal storage. The simulations were performed with the dynamic simulation software Dymola with libraries from TIL. Results show an average COP increased by a factor of 2.8 for combined freezing and heating system, compared with only freezing. The average heat recovery from the refrigeration system is 298 kWh, which is in perfect match with the heating demand of 261 kWh for fish oil production by the thermal treatment process. CO_2 thermal storage exhibits promising results. An aluminium thermal storage of size 0.3 m^3 (75 liters), including an internal heat transfer area of 67 m^2 is an ideal option for the reference refrigeration system to cover peak loads. A 50 kWh stored energy reduces the peak time from 10 to 8 minutes. Each day corresponds to almost 28 peaks. The saved time in 24 hours is 56 minutes, which means an additional production capacity of equivalent 56 minutes in one day.

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REFERENCES

Carvajal, A., Slizyte, R., Storrø, I., Aursand, M., 2015. Production of high quality fish oil by thermal treatment and enzymatic protein hydrolysis from Norwegian spring spawning herring by-products. Journal of Aquatic and Food product Technology, 24, 807-823.

Dassault Systems, DYMOLA Systems Engineering, 2020. URL, https://www.3ds.com/products-services/catia/products/dymola/.

Hafner, A., Gabrielii, C. A., Widell, K. N., 2019. Refrigeration units in marine vessels. Alternatives to HCFCs and high GWP HFCs, Nordic council of ministers, Team nord.

Hafner, A., Nordtvedt, T. S., 2011. Energy saving potential in freezing applications by applying cold thermal energy storage with solid carbon dioxide. Procedia Food Science, 1, 448-454.

Niu, X. D., Yamaguchi, H., Iwamoto, Y., Nekså, P., 2011. Experimental study on a CO2 solid-gas-flow based ultra-low temperature cascade refrigeration system. International Journal of Low-Carbon Technologies, 6, 93-99.

TLK-Thermo GmbH, TIL suite Thermal Systems, 2020. URL, https://www.tlk-thermo.com/index.php/en/software/til-suite.

Valentas, K. J., Rotstein, E., Singh, R. P., 1997. Handbook of Food Engineering Practice. Taylor and Francis group. Boca Raton, New York, 106 p.

Ølsen, R.L., Toppe, J., Karunasagar, I., 2014. Challenges and realistic opportunities in the use of by-products from processing of fish and shellfish. Trends in Food science and Technology, 36, 144-151