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Thermal Energy Storage with PCM for Refrigerated Sea Water System of Fishing Vessels

Muhammad Zahid SAEED[a], Kristina N. WIDELL[b], Armin HAFNER[a], Eirik Starheim SVENDSEN[b], Tom Ståle NORDTVEDT[b]

[a] Norwegian University of Science and Technology
Trondheim, 7491, Norway, muhammad.z.saeed@ntnu.no
[b] SINTEF Ocean
Trondheim, 7465, Norway, Kristina.Widell@sintef.no

ABSTRACT

This paper investigates thermal storage integration with the refrigerated seawater (RSW) system of a fishing vessel. Four different scenarios were investigated, including ice in tanks, two design modifications in chilling tanks, and plug-in thermal storage. The use of ice in chilling tanks as cold thermal storage was assessed since it can assist RSW system and reduce total chilling time. This was done by the addition of 5 m^3 ice, which resulted in a reduced cooling time of 30 minutes. Suggestions for design modifications in chilling tanks were also introduced to assess the potential of built-in thermal storage. A concept for plug-in thermal storage was also designed, employing a phase change material of 4 °C. Results showed that 1 m^3 thermal energy storage could provide an average of 30 kWh for chilling fish during peak load.

Keywords: Refrigeration, Phase change material, Chilling tanks, Fishing vessels, Refrigerated sea water, Energy efficiency.

1. INTRODUCTION

In Norway, the pelagic species herring, mackerel, and blue whiting contribute the highest wild catch. Among the wild fish caught in 2019 in Norway, 52% were pelagic fish (statistics Norway, 2019). The total yearly world fisheries catch of pelagic fish account for approximately 20%-25% (Stephenson et al., 2019). Pelagic fish live far from shore and is commonly caught by purse seiner. Harvested fish is then stored in tanks until delivery for onshore processing. Tanks equipped with mechanical refrigeration are called RSW (refrigerated sea water) systems. If ice is added to the tanks with water, they are described as CSW (chilled seawater). The various methods of preparing the tanks before the fish input are termed fill strategies (Thorsteinsson et al.,2003). The purpose is to have minimum temperature in tanks before fish is introduced. The historical method of storing fish in ice boxes leads to complex handling due to increased catch volumes. However, this method is still applicable for smaller boats and effective with sufficient ice.

In RSW systems, the seawater in tanks is pre-chilled to -1 °C or slightly lower before fish is introduced. The water ratio depends on fish species and if it is for human consumption or fish oil and meal production. For human consumption, the water percentage is typically 40% (Nordtvedt et al., 2019). The water is often pumped between tanks to balance the load on the vessel and avoid instability. When the fish is loaded in the pre-chilled water, the temperature increase from -1 °C to higher temperature (equilibrium temperature between fish and water). After the fish input, the RSW pumps circulate water between the chilling tanks and the evaporator. The RSW systems start with some time margin to avoid fish clogging (Nordtvedt et al., 2019). The process continues until the final temperature in tanks is -1 °C (Kleman, J. 1977). In CSW, the ice is produced onboard or brought from the land and no water circulation between chilling tanks and evaporators. The CSW system results in faster chilling up to the required temperature. When all the ice melts, the temperature in the tanks will increase unless supplementary ice is not added (Thorsteinsson et al.,2003).

Thermal storage is an advanced feature that can store energy at lower refrigeration loads and discharge when the demand is high or to boost the capacity for faster chilling. The current onboard barriers are insufficient capacity in smaller vessels and uneven temperature distribution in larger chilling tanks. The robustness and automation of the solutions are necessary to avoid extra labor and time. Nordtvedt et al., (2019) analyzed the uneven temperature distribution in chilling tanks. They reported improvement in temperature distribution by altering the flow patterns in chilling tanks. Thorsteinsson et al., (2003) studied the RSW and CWS systems. They explained the different methods, but technical specifications and capacity of the refrigeration system were not disclosed. Pineiro et al., (2004) described that ice could be used for chilling in the form of flake, slurry, and ice blocks. Slurry ice is a two-phase mixture of ice and water. The slurry ice dominates flake and ice blocks due to its high heat exchanging capacity, fluidity, and reduced fish surface damage.

Limitations with uneven chilling and limited cooling capacity onboard has led to the study described in this paper. The study aimed to investigate a combined RSW and CSW system to reduce the chilling time, design modifications in chilling tanks, and thermal storage integration for high refrigeration capacity during the start of the fish chilling process.

2. SYSTEM DESIGN AND DESCRIPTION

A reference case for this study was Selvåg senior (Nordtvedt et al., 2019). This fishing vessel has a refrigeration capacity of 2040 kW and a total chilling tank volume of 2000 m^3. For the analysis of system modifications, two chilling tanks (300 m^3 and 294 m^3) and a single catch size of 356 m^3 were assumed. The catch size is equal to 60% of both tanks, and the water volume capacity is 238 m^3, which corresponds to 40% of the tank's capacity. For the base case calculation model, the initial temperature of the fish and pre-chilled water in the tank were assumed to be 13 ºC and -1 ºC, respectively. Using mackerel's thermal properties and the energy balance, the equilibrium temperature (fish and water) in the chilling tank was 9.3 ºC. The chilling of fish and water from 9.3 ºC to -1 ºC with a refrigeration capacity of 2040 kW under ideal conditions will take 186 minutes. Four optimized cases were investigated numerically to improve the performance of the RSW system. In the first case, the RSW unit was assisted with various amounts of ice, and the temperature was analysed by calculations. Design modifications for chilling tanks were introduced in case 2 and case 3 to store thermal energy with PCM for peak loads. For these two cases, simulations of PCM were carried out on Ansys R1 2020. In the last case, a plug-in thermal storage was examined under charging and discharging scenarios on the Dymola platform with libraries from TLK thermo.

2.1. Optimized case 1

In this optimization case, various amount of ice was considered together with fish in the tank. The addition of ice in the chilling tank as energy storage can reduce the cooling time. This ice should be in the form of slurry to avoid any damage to the fish. The simplified system with one compressor and ice handling mechanism is shown in Fig. 1. An automated ice crusher will ensure efficient handling. Ice can be produced onboard or brought from land, but it is dependent on the type and size of vessel. The bigger fishing boats are often equipped with high refrigeration capacity, and ice can be made onboard with minor system modifications. The smaller boats with less refrigeration capacity do fishing close to shore and can benefit from taking ice from the land.

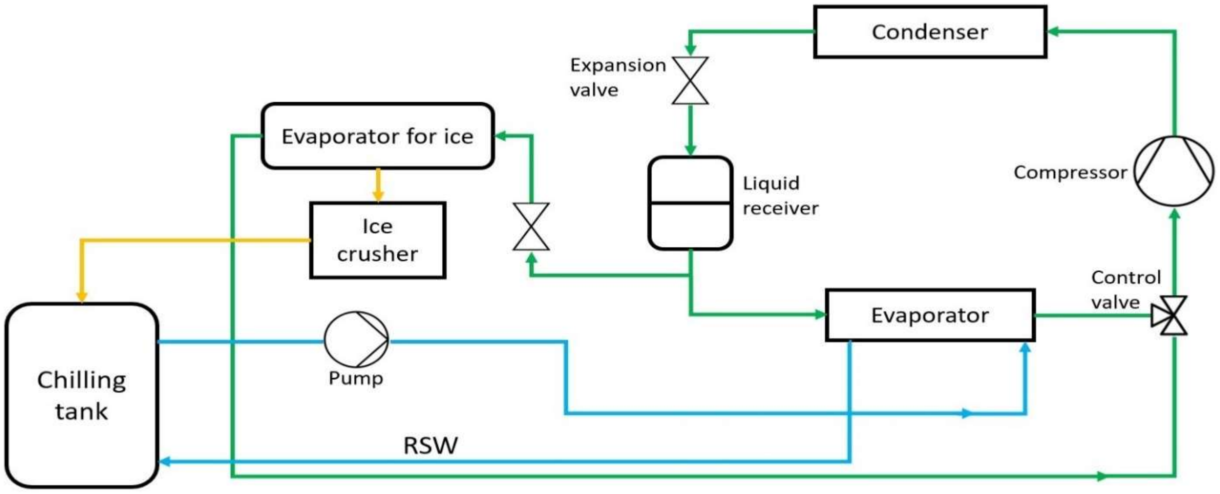


Figure 1: Refrigeration system with ice mechanism and chilling tank

Fig.2 shows the chilling tanks and the method to store and distribute ice between tanks. There are nine tanks, BB1, BB2, BB3, S1, S2, S3, SB1, SB2, SB3, and the idea is to have one tank (S1) temporarily reserved for ice storage. This tank can be filled with fish after utilization of the other eight tanks. It is vital to maintain the ice in the form of slurry to make it easy to distribute in tanks before dumping fish. The ice slurry can be distributed with existing RSW pipes and without additional costs.

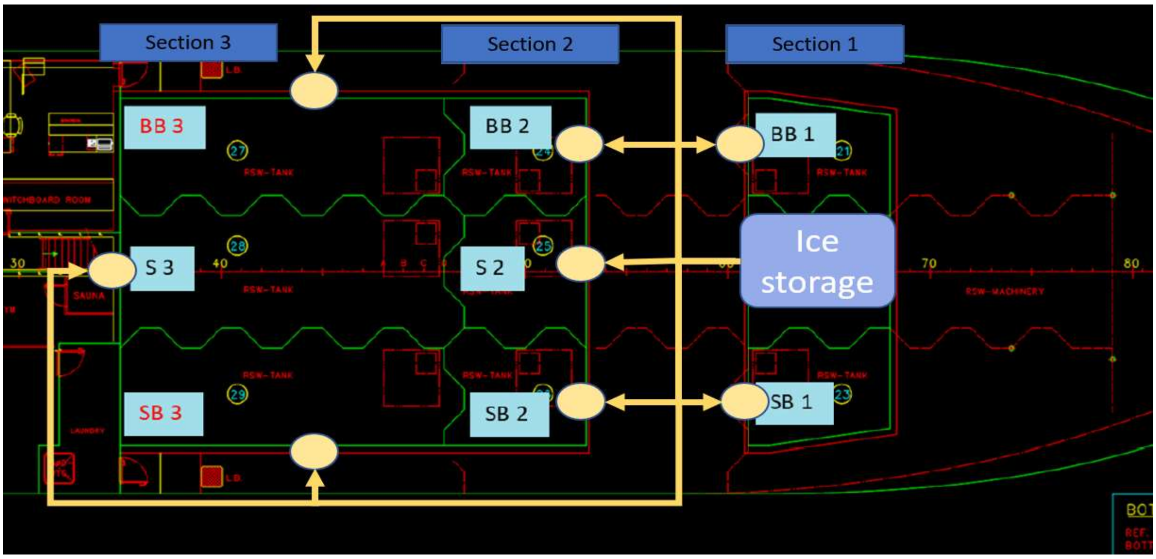
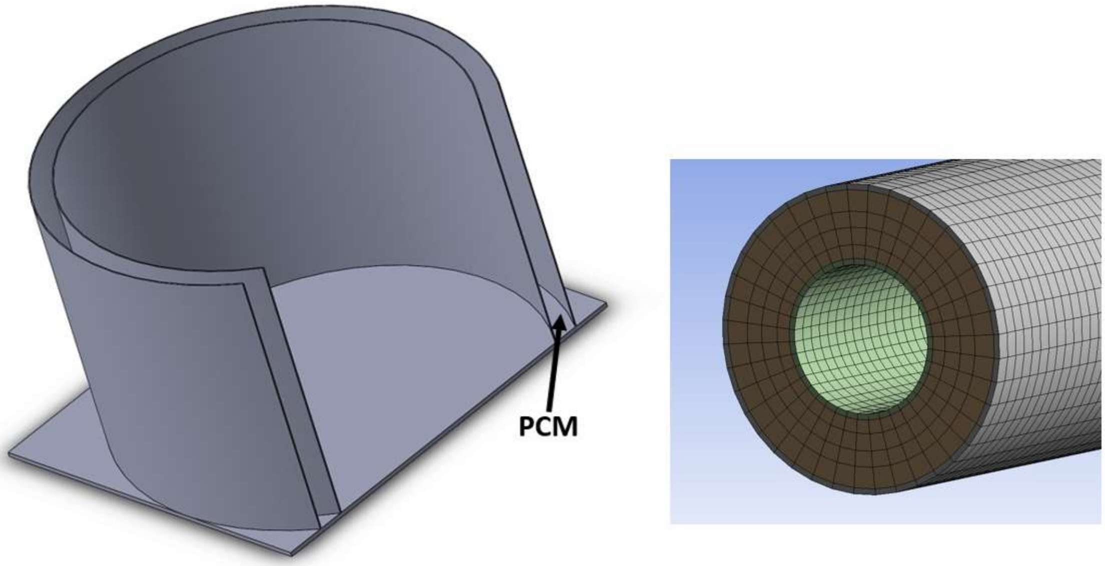


Figure 2: Proposed system for storing and distribution of ice (adapted from Nordtvedt et al., 2019)

2.2. Optimized case 2 and 3

The ice storage on the tank’s outer side and within tubes is challenging because it will need less than 0 °C to store thermal energy in the form of ice. The best scenario for this design is to have PCM, which should melt and freeze at temperature higher than 0 °C. At peak loads, the PCM will boost the refrigeration capacity. Afterward, PCM in liquid form can remove from the outer shell and reinject for charging when the chilling tank temperature is close to 0 ºC. In these cases, PCM with 4 ºC phase change temperature was investigated in the tank's outer shell and within the tank's tubes. The choice of 4 ºC is mainly to have enough temperature difference for charging and discharging from seawater in tanks. PCM properties were: density 766 kg/m^3, latent heat 235 kJ/kg, specific heat capacity 2.18 kJ/kgK, thermal conductivity 0.21 W/mK, phase change temperature 4 ºC, and maximum operating temperature of 150 °C (PlusICE range, 2018).



(a) (b)

Figure 3: (a) Chilling tank with PCM in the outer boundary, (b) Ansys fluent analysis for PCM

The design illustration of the tank with PCM on the outer side is shown in Fig. 3. Chilling tanks on the reference case were rectangular, but in this design a circular shape was used for initial small-scale investigation. However, this will change to rectangular shape in full scale analysis. In case 3, PCM tubes were introduced within the tank, as shown in Fig. 4. The volume of PCM tubes can compensate for the required water ratio in the tank. Due to the dense cooling effect from tubes, the water percentage in the tank can decrease linearly with the volume of tubes, with no effect on the fish's storage volume.

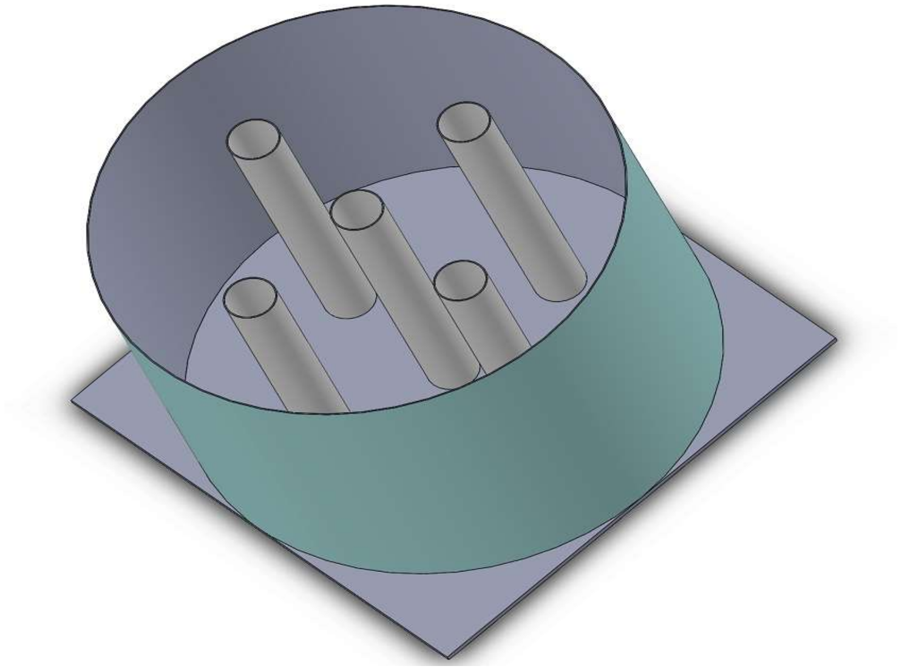


Figure 4: Chilling tank with PCM tubes

The PCM analysis for case 2 and case 3 was performed with a single 3D design on Ansys fluent R1 2020. The computational geometry of the designed 3D models in case 2 and case 3 was reduced to a simplified Ansys design, as shown in Fig. 3. The outer side was filled with PCM, and the inner side for RSW flow. The radius of the outer pipe was 2.5 cm and the inner pipe 1.35 cm. Adiabatic conditions were considered for the outer pipe wall, and constant PCM properties were used. The PCM charging was performed with a seawater temperature of -0.5 ℃ to 2 ℃ and a flow rate of 2 kg/s. The flow rate of RSW pump is typically higher than 6 kg/s for such chilling systems, and the reduced flow for this Ansys case is due to a small-scale investigation. The initial temperature of PCM was kept constant at 4.3 ℃ in all cases for charging. The PCM discharging was analyzed with water temperature from 10 ℃ to 7 ℃ and with the same flow rate of 2 kg/s. The initial temperature of PCM was 3.9 ℃ for all discharging cases.

The mesh sensitivity analysis was not investigated in this work. The transient simulations in Ansys fluent were performed with the pressure-based solver and absolute velocity formulation. The solution methods were SIMPLE scheme and discretization with Green Gauss cell-based gradient, second-order pressure, first-order upwind momentum, and first-order upwind energy. Fixed time advancement type was selected with a time step size of 1 second. Default parameters were used for solution controls.

2.3. Optimized case 4

In this case, a thermal energy storage tank (1 m^3) with a PCM was integrated on the return line of the RSW system. In this way, it is possible to charge and discharge the storage with the same line. It will release energy during peak load, and recharging can be performed at a lower temperature. The controlling of the system is more simple compared to the other cases. The schematic layout of the system is shown in Fig. 5. This simulation was carried out on a dynamic simulation software Dymola with components and libraries from TLK thermo GmbH. The charging case was performed by varying the RSW temperature from 1 ℃ to -1 ℃ and with a flow rate of 6.8 kg/s. During discharging, the RSW temperature varied from 9.3 ℃ to 6 ℃. The simulation time for both cases was one hour.

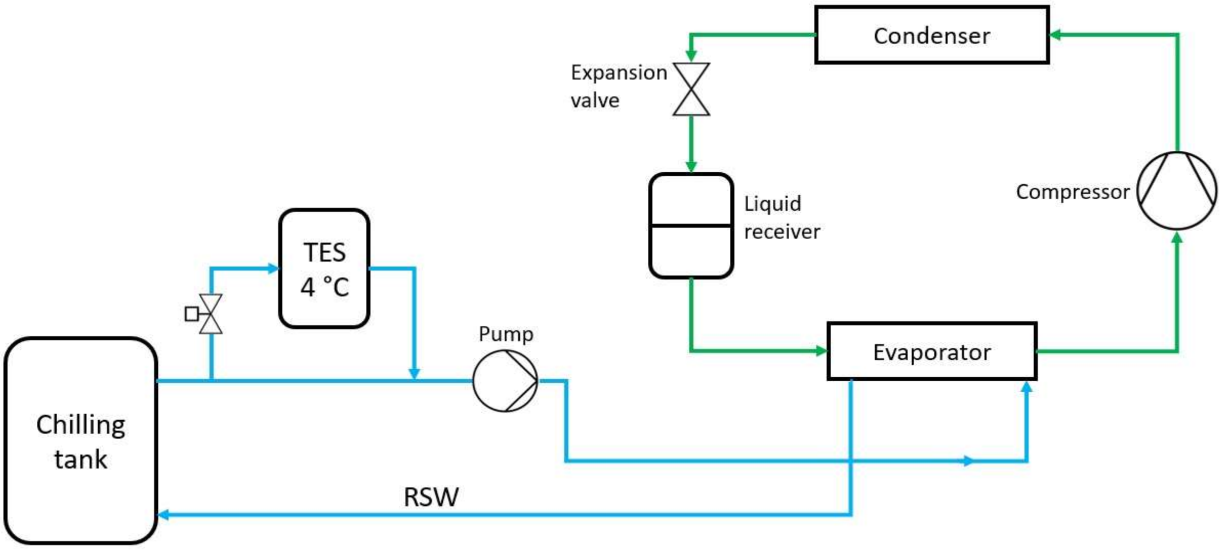


Figure 5: RSW system with plug-in thermal storage

3. RESULTS AND DISCUSSIONS

3.1. Optimized case 1

The addition of ice in the chilling tanks has an effect of reduced temperature. The time margin is often necessary after the dumping of the fish to avoid clogging, which is a reasonable justification to have ice onboard. Fig. 6 shows the temperature in the chilling tank with different amounts of ice. With 5 m^3 ice, the temperature in the tanks was 7.5 °C. It means the RSW system will start with an initial temperature of 7.5 °C in the chilling tank instead of 9.3 °C.

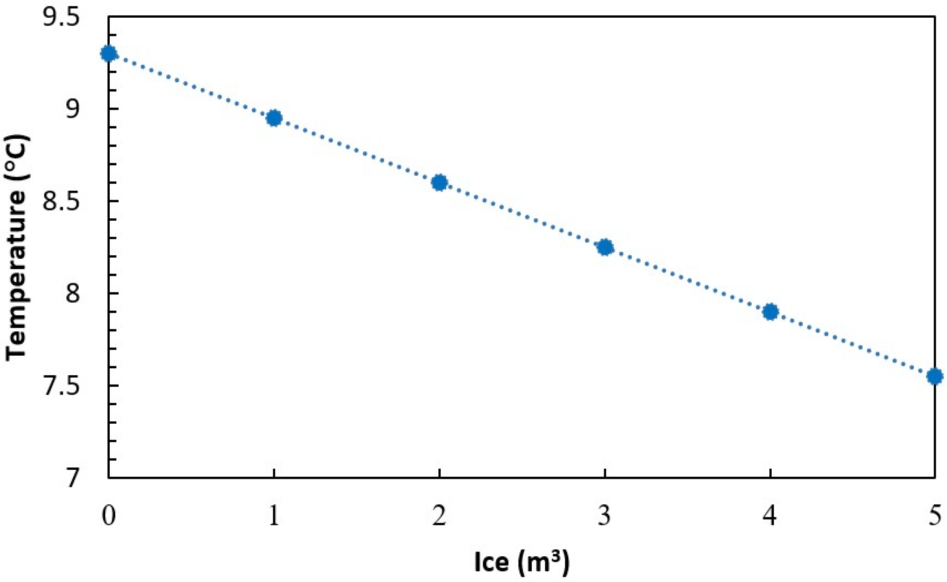


Figure 6: Chilling tank temperature with an addition of ice

The reduced time of chilling with the corresponding amount of ice is shown in Fig.7. The 5 m^3 of ice decreased the chilling time by 30 minutes. It is likely that the RSW system can start before melting of all ice. The whole effect on the chilling time will remain same either the RSW unit start after or before melting all of the ice. The time reduction can also contribute to a better quality of fish.

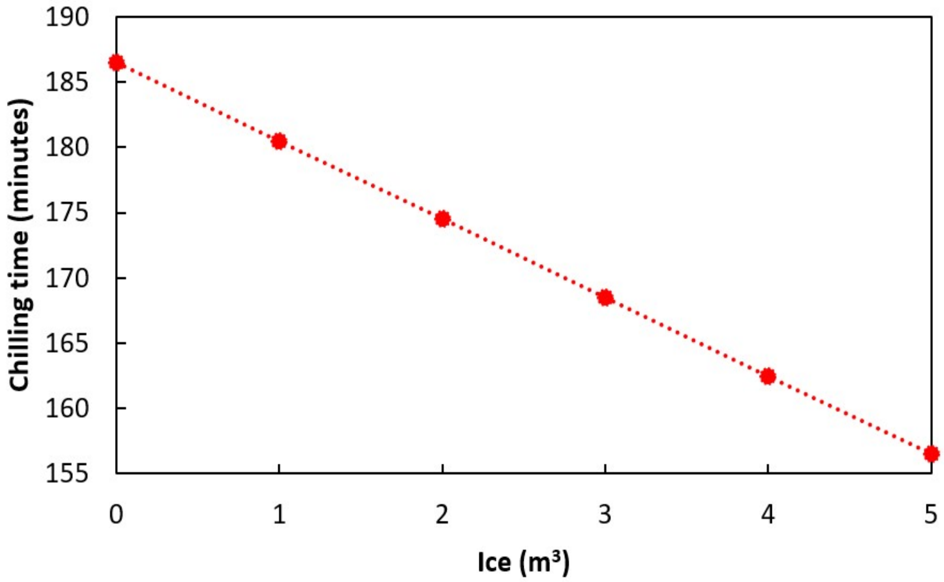


Figure 7: Chilling time reduction by the addition of ice

3.2. Optimized cases 2 and 3

The average liquid fraction of the charging and discharging processes from Ansys simulation is shown in Fig. 8. The charging of PCM with -0.5 °C seawater temperature is comparably faster than in other cases and is mainly due to the high-temperature difference between PCM and water. After 60 minutes of charging PCM, the average liquid fraction was 0.6 with -0.5 °C and 0.76 with 2 °C. The discharging process of PCM is faster with 10 °C water temperature, and after 60 minutes, the liquid fraction was 0.57 with 10 °C and 0.36 with 7 °C. It can be observed from Fig. 8 and Fig. 9 that for the first 10 minutes, the heat transfer is very high and is gradually decreasing. The reasons are the high thermal conductivity and high-temperature difference close to the PCM and water interface boundaries. Beyond the interface, additional thermal resistance reduced the heat transfer. Thicker tubes or shells with PCM will not be a very effective solution for high discharging output. Multiple tubes as shown in Fig. 4 can contribute to high discharging capacity at peak loads.

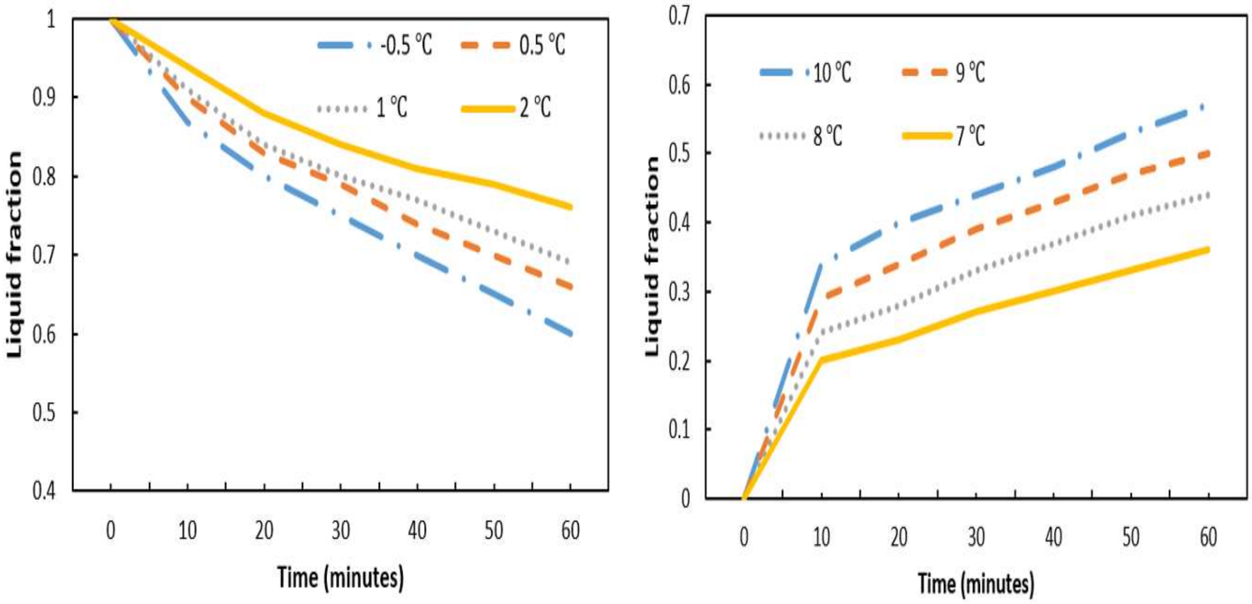


Figure 8: Charging and discharging liquid fraction of 4 °C PCM (Ansys)

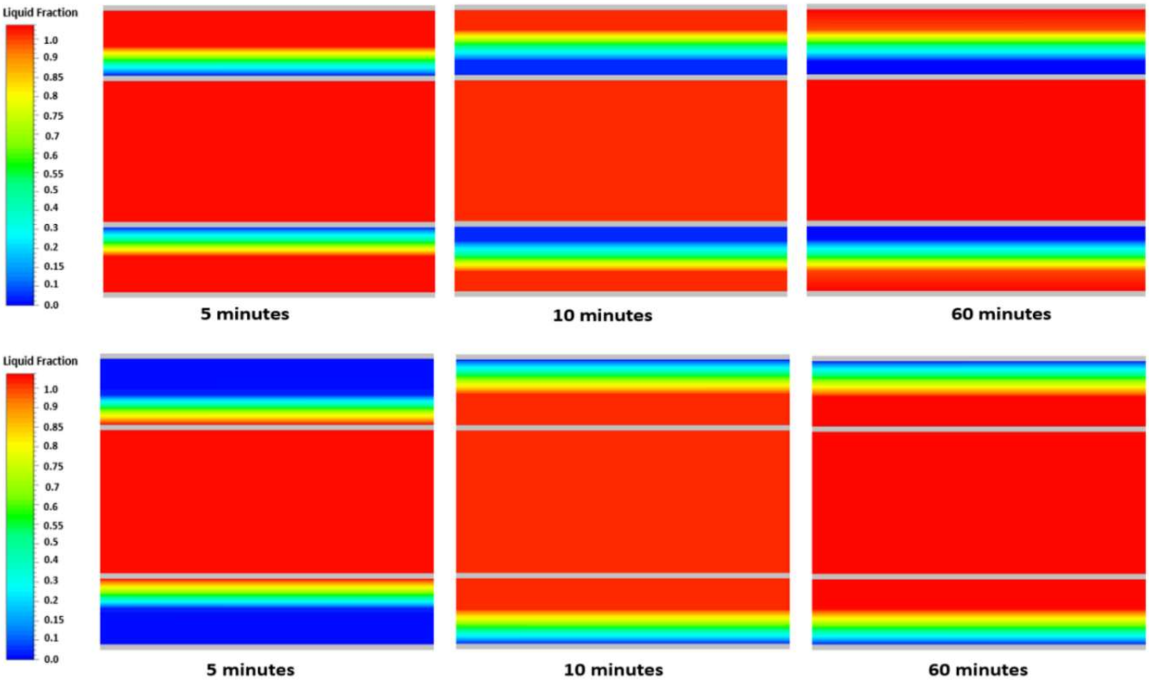


Figure 9: Charging (-0.5 °C) and discharging (10 °C) contours at different time instants

3.3. Optimized case 4

The charging of thermal storage in Fig. 10 shows that the charging capacity is increasing. The trend is due to the higher temperature difference between PCM and RSW line with time. The average charging capacity under designed conditions was 31.6 kWh. In Fig. 10, the discharging capacity of thermal storage is reducing, which is due to decreasing temperature difference between PCM and RSW line with time. The average discharging capacity in one hour was 30 kWh. From the results of Fig. 10 it can be concluded that the charging is slightly faster than the discharging, and a phase change material with a 3 °C can also be a potential option for fishing vessels.

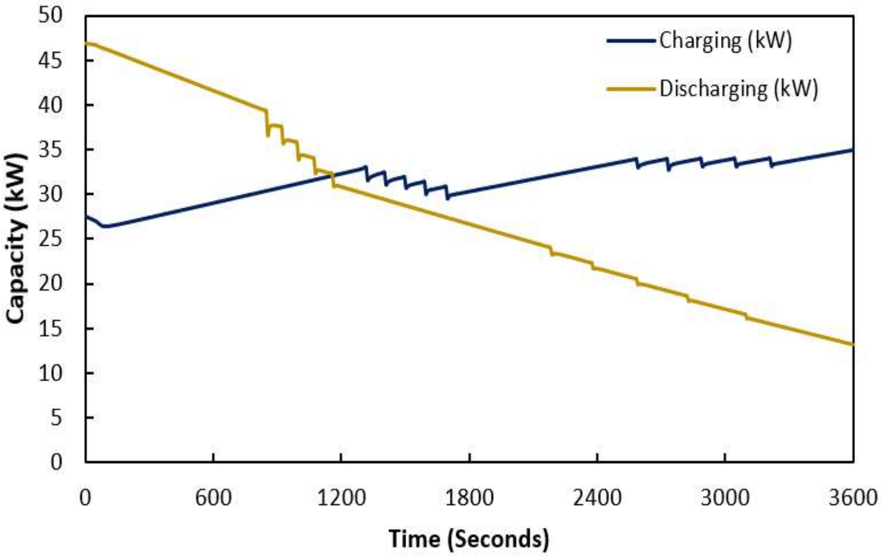


Figure 10: Charging and discharging of 4 °C PCM

3.4. Discussion

The optimization in the first case could reduce the chilling time and hence high-quality fish, but the automation of ice production and distribution is essential for successful implementation. Case 2 and case 3 can be implemented, but the detailed evaluation is crucial for the optimum thickness of tubes or outer shell. In addition, the round tanks will have less PCM storage space as compared to rectangular. Case 4 possesses a greater flexibility for adjustment with various temperatures and systems.

All the four cases have possibility for further development. The work of case 2 and case 3 will need extensive research and it is a long-term development. Case 1 and case 4 have larger effect on temperature reduction and more potential for implementation. Case 1 can make a highest impact if installed accurately. Case 4 is an immediate solution. It can further investigate with water/ice as a PCM because it is useful for fast charging and discharging due to its high thermal conductivity and latent heat compared to a 4 °C PCM. However, more system adjustments are required for water/ice than PCM, for example, it would need additional components due to charging of storage with refrigerant and discharging with a water loop. This system can also be implemented on the refrigerant side, but it is case sensitive. The cost analysis and benefits between water/ice and PCM should be evaluated in further work.

4. CONCLUSIONS

An investigation for a thermal energy storage was performed with numerical simulation softwares Ansys fluent and Dymola for the RSW system onboard a fishing vessel. The objective was to reduce the chilling time for bigger catch and better use of refrigeration system at low loads. Four different cases were analyzed in this work. The first case was with the addition of ice in the chilling tanks, and the result showed that 5 m^3 ice could reduce the chilling time of the reference system by 30 minutes. In the second and third cases, chilling tank design modifications were suggested for thermal energy storage. The outcomes concluded that thicker PCM tubes or outer shell would not be efficient for high discharging capacity. However, full-scale analysis is required for comprehensive evaluation. The fourth scenario was assessed by plug-in thermal storage of 1 m^3 size, including internal pipes. Under the reference case defined conditions, an average of 31.6 kWh and 30 kWh were achieved for charging and discharging, respectively. It is recommended to investigate further the case 1 and case 4 due to their potential competitiveness in cost and time.

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