TRANSIENT SIMULATION OF REFRIGERATED AND CHILLED SEAWATER SYSTEM

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ABSTRACT

Fishing technology onboard fishing vessels fishing pelagic species has received increased attention, especially the influence of storage method on fish quality and the vessel's energy consumption. More flexible storage methods are needed to give higher quality to the landed pelagic species thereby lowering energy consumption and investment costs. Today, when sizing storage systems, high capacity in the pre-chilling period is used as a designing criteria resulting in large installed refrigeration capacity and limited flexibility. To analyse the demands of better fish quality and lower energy consumption of these systems, a new storage method is simulated to compare it with standard storage methods like refrigerated seawater (RSW) and chilled seawater (CSW). The purpose of the simulation is to analyse the chilling of the catches and operational cost of the systems to see if combined system (RSW/CSW) gives better results. A mathematical model is developed and applied to simulate a periodic and quasi-steady fishing voyage including a pre-chilling period followed by chilling of one catch. The models are developed in a new software tool, called MarenEDT™, which can handle optimisation of non-linear and non-convex models and simulation of steady-state and transient models. A case study is presented in this paper.

Keywords: Simulation, Energy, MarenEDT, Fishing vessel, Purse Seiner, RSW, CSW

INTRODUCTION

Pelagic species, such as mackerel, herring, capelin and blue whiting are harvested by purse seiners[1] for conservation and meal production and are kept chilled in the onboard storage tanks. These tanks are designed for circulation of refrigerated seawater (RSW), or for ice where the ice or seawater is used as a chilling medium called chilled seawater (CSW). Different species, various fishing areas and voyage length require different methods of cooling and storage.

The seawater part of the storage system in a purse seiner consists of a number of storage tanks, pumps and pipes connected together. In most of the ships, the tanks are mounted as follows: 1 to 6 tanks longitudinally and 2 to 3 across the ship. The tanks are internally clad with stainless steel or painted with an epoxy resin. The seawater plants can have varying configurations due to the requirements they have

[1] Purse Seiner is fishing vessel using purse or trawl for catching of pelagic species. Large tanks are used to store the fish.

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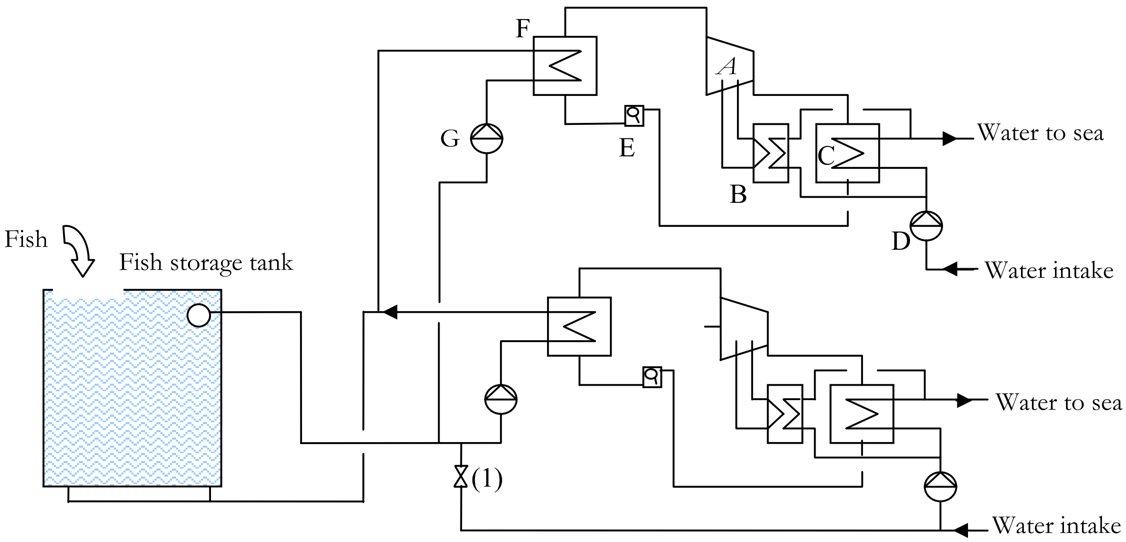

Figure 1: Two identical RSW-systems circulating water to one or more fish storage tanks. A- screw compressor, B- oil cooler C- condenser D- sea water pump for condenser, E- throttle valve, F- evaporator, G- RSW pump for evaporator.

to satisfy. Plant layout and size can be affected by performance and demands such as need to shift seawater from tank to tank and the chilling requirements.

The storage technology (storage inclusive cooling) is of paramount importance when maintaining high fish quality onboard a purse seiner.

RSW SYSTEM

In a standard RSW system, the system is fed via the water intakes in the hull (see figure 1). After the system has been filled, the valve (1) is closed and the RSW pump (G) circulates the seawater in the system through a filter to the evaporator and back to the tank through manifolds in both the bottom and top of the tank.

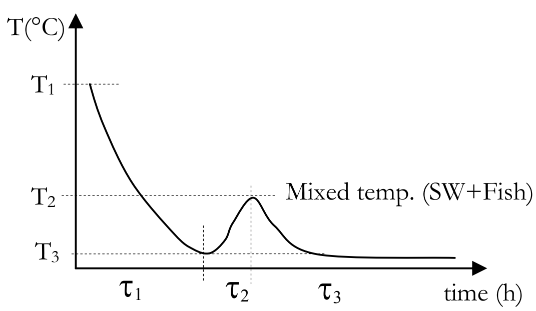

Figure 2: Expected chilling down curve for RSW system.

An expected chilling process is shown in figure 2. In the first time period (τ_1), the water (general thumb rule is 1/3 of the total tank volume) in the storage tank is pre-chilled from temperature T_1 to T_3. In the second time period (τ_2), fish is dumped into the pre-chilled storage water. This raises the temperature up to an average between the fish and the chilled seawater (temperature of the mixture, T_2). In the third time period (τ_3), the temperature is lowered to the target temperature and maintained there until the fish are landed. The length of the third time period depends on the capacity of the refrigeration system and quantity fished.

CSW SYSTEM

When operating with a CSW system, the tanks do not have a seawater circulation system (see figure 3). Conversely, when using a CSW system, sufficient freshwater ice is taken along on a fishing voyage or the ice is produced onboard by ice machines similar to those shown in figure 3.

When mixing ice with water, two methods are the most common:

- At the same time the fish is added to the storage tank, the ice is mixed with the fish; and
- The ice is produced directly into the fish storage tanks. Before fish is added to the tank, ice and water is mixed together in the tank, filling approximately 30% of the tank's volume.

In figure 4, a system is shown where the ice is directly produced into the fish storage tanks.

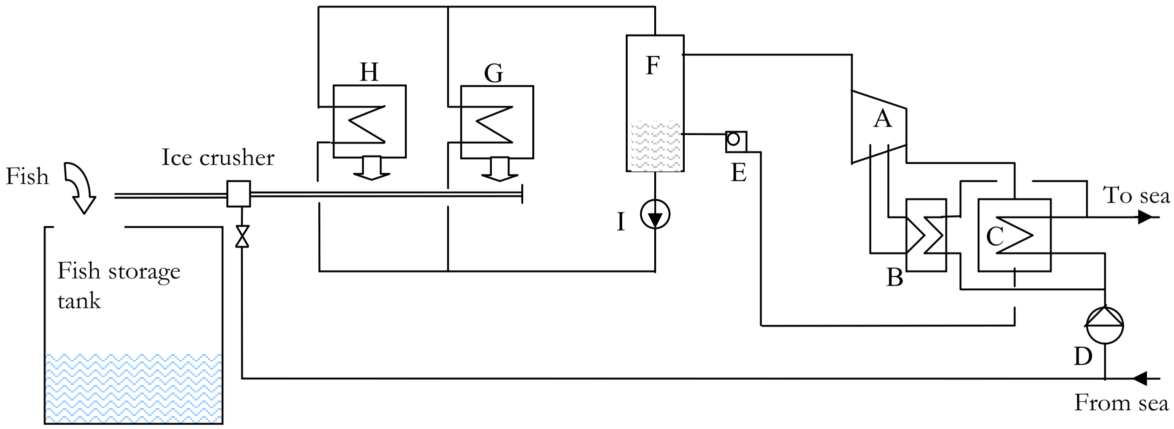

Figure 3: One CSW system with two ice machines. A- screw compressor, B- oil cooler, C- condenser, D- sea water pump for condenser, E- throttle valve, F- pump separator, G and H- ice machines, I- refrigerant pump.

This gives rapid chilling of the fish in time period three (τ_3), from start temperature (the fish temperature) to a target temperature. Before the fish is added, the ice keeps the fish tank at the storage temperature T_3. After all the added ice has melted, the temperature begins to rise again. Therefore this method does not guarantee that the target temperature will be maintained unless ice is added to the tank in accordance with the melting (Magnussen, 1985).

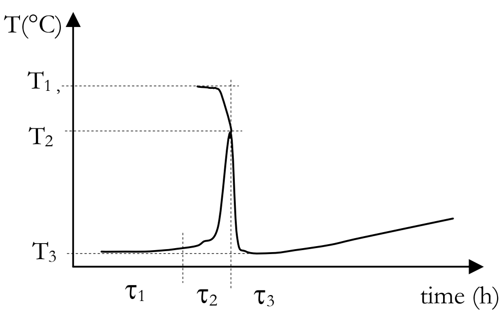

Figure 4: Expected chilling curve for CSW system.

In figure 3, an onboard CSW system is shown including two ice machine units which are connected via a single stage refrigeration system. The ice from the ice machines is dumped to an ice crusher where the ice is mixed with water and then moved to the fish storage tank.

In some CSW systems, the tank bottom is supplemented with tubes. These tubes are used for compressing air in the tank to ensure the proper mixing of fish, water and ice i.e. the so-called champagne[2] method. However, there is a tendency for the ice to keep floating in the upper part of the tank, so it is still not always well mixed.

Comparing the two chilling methods mentioned above, the advantages of an RSW system is the pre-chilling of the storage water in the fish storage tanks before fishing and the possibility of maintaining steady temperatures over longer periods after a catch has been chilled to target temperature. The CSW system advantages are mainly for the rapid chilling of the fish and the possibilities of storing the refrigeration capacity. Storing of capacity means smaller systems and lower energy consumption.

Filling of tank

The preparation of the tank prior to filling with catch is important to keep the freshness of the fish (as discussed in a report of chilling process in RSW systems by Magnussen, 1985), which indicates the importance of chilling the catch immediately after it is pumped onboard). Other research (Thor Larsen, 1990) discusses the salt-uptake problem based on how the correct mixture of fresh water and seawater can hinder salt uptake in fish. The salt uptake in fish is not discussed in this paper but the readers can obtain information of the problem in work by (Thorsteinsson, 2000).

Different methods of preparing or filling the tank before the fish is dumped into it are specified as fill strategies. These are based on having as low a temperature as possible in the tank before fish is dumped into it and mixing the correct amount of freshwater to the seawater or ice to give a maximum of 1.1% salinity of the storage water as recommended by Thor Larsen, 1990.

[2] The compressed air from the vacuum pump pressure side is used for champagne system

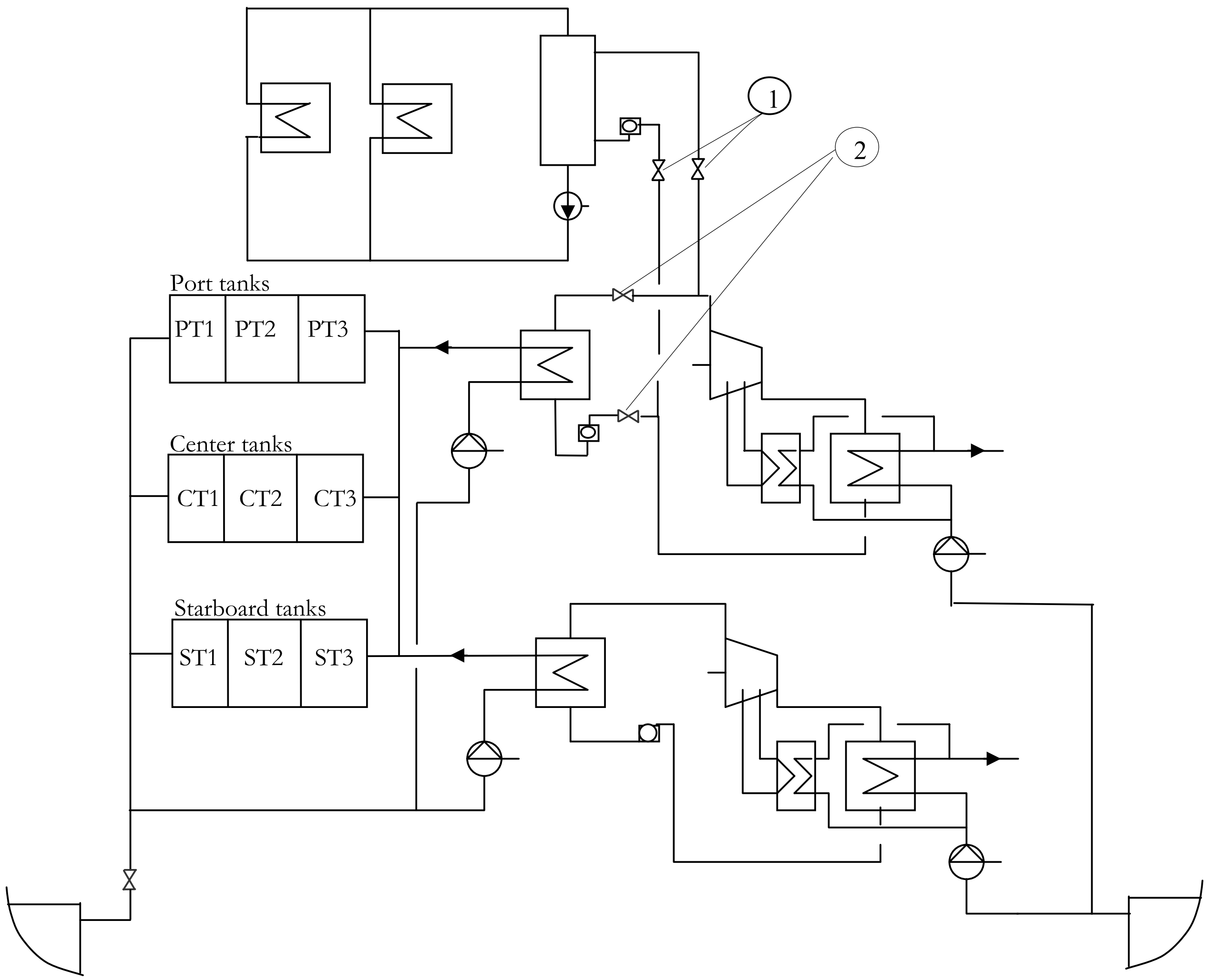

Figure 5: Principe diagram of the combined system (RSW/CSW).

COMBINED SYSTEM

A method of connecting these two system solutions (RSW and CSW) into one combined system capable of utilizing the advantages of each system in the same vessel is simulated. This is expected to improve fish quality and lower energy consumption of the system.

This concept (RSW/CSW), is a complete conservation system comprising of two systems connected to a common seawater-system.

These systems can operate together in order to utilise the advantages of each sub-system, specifically:

- The pre-chilling from the RSW system.
- Steady target temperature from RSW system.
- The rapid chilling to target temperature from the CSW system.
- Storage of the refrigeration capacity from the RSW system.

Operating the system

When pre-chilling water using the RSW part of the system, the storage tanks (PT1, CT2, ST1) are filled with water/seawater which is circulated through the RSW-evaporator (see also component F on figure 1) until the temperature of the water has reached the target temperature. Both RSW systems runs until the pre-chilling of the water is finished, then production of ice starts. The ice machines deliver first the ice to tank CT1 which is the tank that is first filled up with fish.

Put another way, when pre-chilling the storage water, the heat load on the storage system is at maximum, and the load from the heat transfer into the tanks from the surroundings is relatively small. When fishing starts, the load from catches dumped into the tank and the heat transfer will seldom reach more than fifty percent of the maximum load. This enables one or both of the units to be stopped after the pre-chilling period to be connected to the ice machines, for ice production.

When operating the system, one has to be aware of advantages and disadvantages of each sub-system in order to select the best possible operating strategy. If the correct strategy is selected, excess uptake of salt will be avoided which will improvefish quality and ultimately, lower energy consumption. The system consists of multiple units or components interacting with each other. The flexibility of the system to run different operating strategies is based on the possibility of various combinations of the systems depending on the type of fishing.

MODELLING

In this section, the fundamentals for modelling are outlined. For further information, see (Thorsteinsson, 2000). The parameters important for fish quality and energy consumption are systemised so they can be added to the model along with the length of fishing voyage, sailing time, chilling period, seawater temperatures and the maximum/minimum catches. Additionally, environmental factors influencing the choice of materials in the components are outlined.

Fill strategies

Three main fill strategies are simulated:

- Chilling with refrigerated seawater (RSW) where the tank is prepared by pre-chilled water before adding the fish. This method lowers the fish temperature from the temperature T_1 to a mixture temperature or start temperature for fish chilling period called T_2. From this temperature, the chilling is started and ended at a target temperature called T_3. When running the system under these conditions, the storage water can be seawater, freshwater or a mixture of both (see figure 1 and 2).
- Chilling only with ice-mixture (CSW) where the fish storage tank is partly filled with ice/water before fish is added. The temperature of the fish is lowered from T_1 to T_2 (mixing temperature). Only freshwater ice made on a plate ice machine is used in the model (see figure 3 and 4).
- The third filling strategy is the most complicated but the most flexible i.e. using both RSW and CSW. When using this method, the storage tank is partly filled with pre chilled seawater. The ice is added to the pre-chilled water until the tank is approximately 30% filled with water and ice. Firstly, only the ice is used for chilling the fish. When all the ice is melted the RSW chilling is started and operated until the temperature of the mixture in the tank has reached the target temperature (see figure 5).

If the catch is not enough to fill one tank, then chilling is done by ice-mixture or pre-chilled fresh water. The water system cannot be started up before the tank is filled. No seawater is added to prevent salt uptake.

Fish model

For calculation of the chilling time and heat load of fish in the tank, a fish model is developed to calculate the temperature and heat transmission in different sections in the fish. The following assumptions and simplifications have been made:

- The fish has a complex geometry. It is, for all practical purposes, impossible to model the fish's geometry with implicit methods.
- The freezing process causes the physical properties (density, heat conductivity etc.) to change dis continually or, at the very best, rapidly.
- The surface conditions of the fish are very difficult to predict due to the complex nature of the fish's surface and fluid thereon.
- The physical properties and sizes of the fish may vary considerably in a catch. Methods of calculating the physical fish properties are based on work by Hardarsson(1996).

The heat flow is defined as a one-dimensional heat conduction and the fish defined as an infinite cylinder or a sphere. The cylinder is divided into a number of concentric cylinder shells with identical thickness.

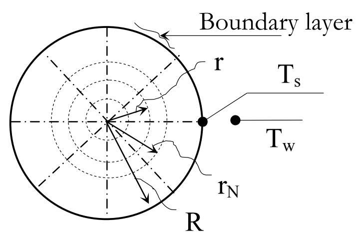

Figure 3: Expected chilling curve for CSW system.

Where r, r_N are radius of the sphere and R is the outer radius, Ts is the surface temperature, Tw is the temperature of the storage water.

The heat transmission between each shell and the outer shell and the water can be calculated using formulas for heat transfer in tubes (Mills, 1995. Page 69).

Refrigeration system model

The compressors used in the concept are screw compressors (SAB series produced by York). The compressor oil used for lubricating and cooling the compressor is chilled by a water-cooled heat exchanger. The mathematical model is developed employing the following simplifications and assumptions:

- Homogeneous distribution of refrigerant and oil in the control volume.
- Homogeneous pressure distribution in the whole control volume.
- Steady flow conditions.
- Heat convection to the surroundings is not calculated but given as a constant in %.
- The heat load from the compressor is removed by the condenser and the oil cooler.

The compressor volumetric efficiency is the amount of gas delivered, divided by the total swept volume gas mass under free air pressure and temperature conditions. The compressor isentropic efficiency depends mainly on the internal volume ratio for both high and low pressure ratios (Haugland, 1993) and (Thorsteinsson, 2000).

Evaporator and condenser model

The evaporator and the condenser are two tube pass, single stream heat exchangers. The mathematical model is developed employs the following simplifications and assumptions:

- Steady flow conditions.
- Uniform velocity distribution in pipes.
- Temperature variation only in axial direction.
- Constant properties.
- Overall heat transfer coefficient U constant over heat transfer surface.
- Negligible energy loss to environment.

The fouling resistance inside the pipes (waterside) is defined but on the refrigerant side the fouling resistance is included in an empirical equation defining outside heat transfer coefficient (Mills, 1995).

Ice machine model

The ice machine used is a vertical plate ice machine. In operation the, water from the tanks at the base of the machine is pumped to the top of vertical freezer plates. From there it flows down both sides of the plates, forming films of water that freeze into solid plates of ice. The release of ice is triggered by warm gas circulated under high pressure through the plates. One section is defrosted while the other freezes. Because of the changing of water to ice on the plate, a problem occurs that is called a moving-boundary problem. For ice, the Jakob number is small and therefore the conduction across the ice layer can be calculated as being in a quasi steady-state (Mills, 1995 p.186).

It is assumed that the ice freezing is:

- One-dimensional solidification.
- Quasi-steady conduction across the ice layer.
- Sensible heat loss of the water cooling from 2°C to 0°C is small compared with the enthalpy of fusion. The fusion enthalpy (water to ice) is 335 kJ/kg.

The production capacity can be calculated from the ice production time. The connective heat transfer areas include both sides of the vertical plates. For further information, see (Thorsteinsson, 2000).

MODELLING TOOL "MAREN EDT"

MarenETD, including all the software components, is written in the computer language Delphi 6.0 Professional. The main modules in the software are the modelling editor, parsing and blocking, the simulator and the optimiser. Included in the system is the model database and RefProp (NIST product).

The user interface includes the modelling window, a solution window for steady-state models and a window for solution of selected variables. The solution window for transient models is a child window which is only opened if the models include differential equations. The modelling window's intended development makes modelling work faster, safer and easier to overview.

After editing the model and during execution, the software handles the equation counting, the parameters and the variables and it recognises the variables in all the equations written in the editor. After the equations have been solved by the solver, the results are shown on the child window to the right.

To increase the solver's speed and to make the solver more robust, a blocking algorithm is implemented in the software. The depth first search method is used to arrange the model equations into blocks that the solver is able solve.

Transient solver

Available in Maren EDT is the Euler method which is the most elementary form of methods using the derivation of the Taylor's Theorem. A more advanced method is the Runge-Kutta method. Maren EDT uses Runga-Kutta method of order 4. Both Euler's and Runge-Kutta methods have the disadvantage that the user has to set the desired step size of the integration. For some cases, small step size is needed for a relative short period of time while larger steps could be used for the remainder of the time therefore Runge-Kutta-Fehlberg method is inplemented.

CASE STUDY

In this case study, two ASL II-60 units (York production) are used and vertical plate ice machines that produce 30 ton/24 hours each. The sea water temperature 17°C, pre-chilled volume of water is 300 tons, filling three storage tanks. The weight of fish added to the pre chilled water is 350 tons. Time to first catch is 8 hours and the waiting time is 1 hour (both units stopped). Ice added to the catch is 6 tons at 0°C. Also the pre chilling starts at time 0 hour from the temperature of 17°C (see figure 5). The pre-chilling period ends when the catch is dumped into the tank after 8 hours thus increasing the temperature of the storage water. This is followed by chilling the water and the catch to 1°C.

On figure 5, two different simulation results are shown where curve 1 is showing the chilling if only the RSW system is used while curve 2 is showing the chilling if both the RSW and CSW systems are operated.

In the beginning of the fishing trip, both RSW systems are running for 4 hours. At that time one of the systems is stopped to be connected to the ice machines for production of ice. After 8 hours the 350 tons of fish is added to the tank and the temperature of the water is increased to 12°C.

After pre-chilling, the two curves are shown on figure 5. The first one (1) shows the chilling of the fish if no ice is used for chilling. The time to chill the catch will be 21 hours which exceeds the allowable EU chilling requirements (see the dots on figure 5) (EU Council Directive 92/48/EEC of 16 june 1992). In this directive two limitations are specified:

- Firstly, the cooling rate must ensure that the temperature of the catch has to reach 3°C before 6 hours (after filled on tank).
- Secondly, 0°C the cooling rate must ensure that the temperature of the catch has to reach 0°C before 16 hours (after filled on tank).

On the other hand, using ice for chilling the catch is more rapid and is in accordance with the EU requirements.

This indicates that if only using RSW system to cool down the catches, a bigger RSW system is needed in order to meetthe requirements.

CONCLUSION

The objective of this work has been to analyse the viability of the RSW/CSW concept. To be able to carry out this analysis it was chosen to develop and implement a suitable model in such a way that the RSW/CSW Concept, both the RSW system and the CSW system could be

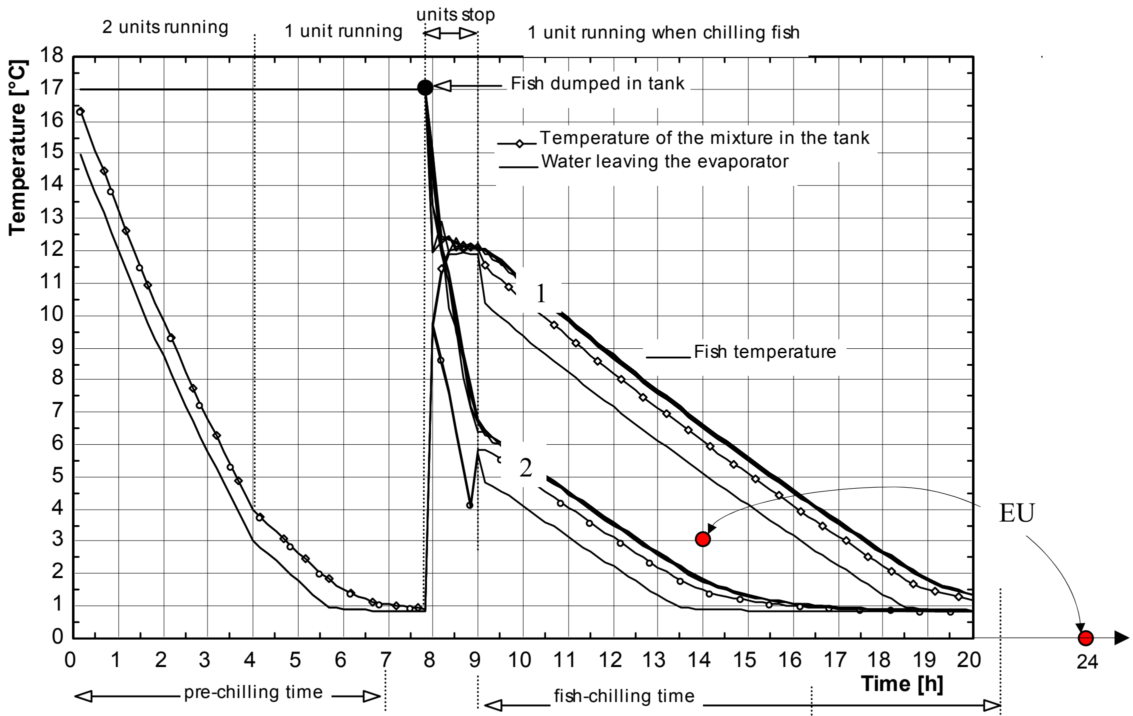

Figure 5: Chilling 300 tons of water in the pre-chilling time and thereafter 350 tons of fish from 17°C.

simulated. To perform the analyses, the following work was carried out:

- In order to simulate the different storage methods, a new mathematical model was developed, capable of simulating the traditional RSW and CSW system as well as the RSW/CSW Concept.
- This model was validated with reliable software to ensure reliability. In the time limits for the project no experiments were made.
- In order to compare different sizes of RSW systems, two sizes of traditional RSW systems were simulated.
- In order to compare the RSW/CSW Concept with traditional storage methods, a simulation of this new storage method was made and compared to simulations of the RSW and CSW systems.

This work has been motivated by the need for improved landed pelagic species quality, lower energy consumption and environmental limitations from authorities. From the simulation results it seems to be an interesting possibility to install combined RSW/CSW systems in order to both minimise the annual operating costs and increase the fish quality.

REFERENCES

Larsen T. (1990) Meldinger fra SSF. Ferskvannskjoling av kolmule. no. 2 p.7-12

Ola M. Magnussen. (1985)*"Technology developments in chilling, freezing and storage of fish",* Norwegian University of Science and Technology, SINTEF Energy Research,

Tor Larsen. (1990),*"Ferskvandskøling af kolmule",* Meldinger fra SSF nr. 2,

Anthony F. Mills. (1995) *"Heat and mass transfer",* Richard D. Irwin. Inc., 1995, ISBN 0-256-11443-9.

Vidar Hardarson, 1996 "*Matvarens termofysiske egenskaber og deres betydning ved dimensionering av frysetunneler*", Doktor Ingeniöravhandling Institute for Klima og Kuldeteknik Trondheim.

J. A. Thorsteinsson, 2000 **"***Creating a model for conservation system onboard purse seiners fishing pelagic species*" MSc. Thesis Institute of Energy Technology, Aalborg University.

Kell Haugland, 1993 *"Undersökelse av skruekompressorens arbejdsprocess",* Ingeniöravhandling Institute for kuldeteknik Trondhjeim, ISBN 82-7119-504-2.