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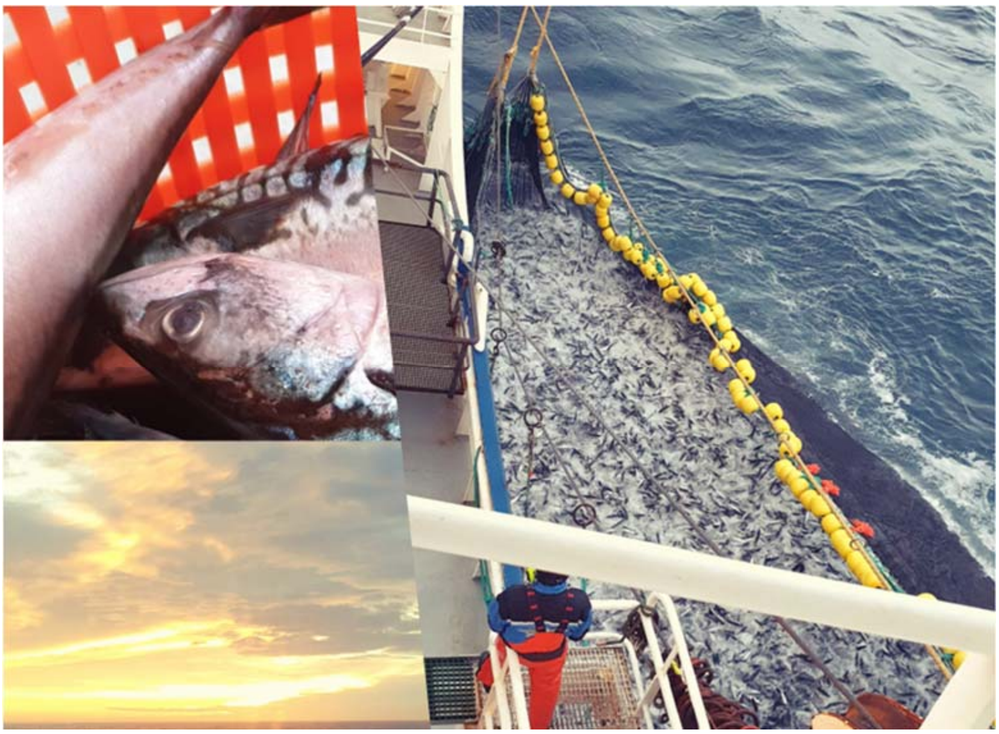
Report

Energy measurements onboard pelagic purse seiner

Report from research cruise autumn 2020

Author(s)
Eirik Starheim Svendsen
Marte Schei



SINTEF Ocean AS

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SINTEF Ocean AS
Address:
Postboks 4762 Torgarden
NO-7465 Trondheim
NORWAY
Switchboard: +47 46415000

Enterprise /VAT No:
NO 937 357 370 MVA

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AUTHOR(S)
Eirik Starheim Svendsen
Marte Schei

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ABSTRACT
This report describes a research cruise carried out on a pelagic purse seiner during the autumn 2020 on the North Sea. The cruise was carried out to perform an assessment of the energy efficiency of the onboard RSW system. In order to execute this assessment, the vessel was instrumented with sensors logging data of the onboard energy systems. This report further describes the data retrieved from the cruise and includes an analysis of the data with respect to energy efficiency.

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PREPARED BY	CHECKED BY	APPROVED BY
Eirik Starheim Svendsen	Tom Ståle Nordtvedt	Kristina Norne Widell
Eirik S Svendsen	Tom S. Nordtvedt	Kristina N. Widell
Eirik S Svendsen (Feb 16, 2021 09:03 GMT+1)		

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1 Background

This research cruise was conducted as a part of the CoolFish-project. CoolFish will develop technologies and concepts for more integrated, energy-efficient and climate friendly cooling, freezing and heating systems onboard fishing vessels. It will also increase the knowledge transfer between research and industry, both nationally and internationally. The project is funded by The Research Council of Norway through their ENERGIX programme. It is led by SINTEF Ocean with research partners SINTEF Energy Research and NTNU and with industry partners MMC First Process, Ulmatec Pyro, Selvåg Senior/Sørheim Holding, Øyangen, Gasnor, Danfoss, PTG and Isotherm Inc.

1.1 Objectives

The main objective of the research cruise was to gather data of onboard energy systems, i.e. power consumption of the refrigeration systems (compressor, pumps), temperature levels in the RSW system at different locations and fuel consumption during different stages of the fishing trips.

The purpose was to gain knowledge of when demand for thermal energy occurs and how efficiently the onboard systems solve this task, and to establish a baseline for which improvements (technology and/or operation) of the systems can be measured.

The results will be used for e.g. modelling and simulation of marine refrigeration systems and as valuable input for design of energy efficiency technology.

1.2 Thanks!

The cruise would not be successful if not for the great support, hospitality and facilitation from the crew of Selvåg Senior. Their accommodating attitude enabled us to do our work in a safe manner. Thank you!

2 Fishing vessel and operation

The M/S Selvåg Senior is a combined fishing vessel equipped for purse seining and pelagic trawling, and have fishing quotas for e.g. mackerel, herring, European spat, greater argentine, blue whiting and caplin.

Tonnage	Engine	Dimensions
Brutto: 1960 tonne	Type: Wärtsilä 12V32	Length: 67,40 m
Netto: 588 tonne	Output: 5520 kW/7400 HP	Width: 13,00 m
Deadweight: 2350 tonne	Speed: 15 knot	Draught: 8,30 m

Figure 1: *Selvåg Senior at harbor in Fiskerstrand*

2.1 Refrigeration and RSW system

There are two more-or-less identical refrigeration systems installed onboard the vessel, both covering refrigeration demands for the RSW system. The RSW system consists of 9 tanks (sections of 3), which are connected to the evaporators through a system of pipes and valves. Together with 2 primary seawater pumps, this allows for distribution of refrigerated seawater in several ways. You could either use one of the refrigeration systems to serve chilling for all of the tanks, or you could use both systems to simultaneously serve refrigeration to only one of the tanks, and many combinations in between these modes. In addition, the flow direction can be reversed, which is normally done for cleaning/flushing purposes. Despite the numerous ways of operation, it is observed that the typical operation is to use one of the refrigeration systems handling the midsection, while the second system handles the bow- and stern section.

The refrigeration system employs NH_3 as the working fluid and has a cooling capacity of 2x1020 kW. The charge is approximately 100 kg for each system. The system consists of a frequency-controlled screw compressor (Howden XRV 204/1.45), a seawater condenser, throttling device (high-pressure float valve) and a tube-and-shell evaporator with refrigerant on the shell side. The evaporator is equipped with a small refrigerant pump which draws liquid refrigerant from the bottom and returns in on top, spraying refrigerant over the tubes and thus increases heat transfer. This pump is controlled by a frequency converter.

Figure 2: *Pictures from machine room. Left: evaporator. Top right: Compressor package. Bottom right: Part of valve station for RSW system*

The figure below shows a simple diagram over the tanks onboard Selvåg Senior, their volume and share of total volume. The labelling denotes (in abbreviated Norwegian) which side and section they belong to, e.g. SB2 is starboard side of section 2 (or midsection). As can be seen, the stern section is the largest holding about 45% of the total volume onboard. An earlier project focused on effective chilling in RSW tanks by investigating tank design, due to reported difficulties to maintain even chilling in these large tanks. For that reason, SB3 is modified with an additional suction point on the stern wall side of the tank. For all other tanks, suction is done through a partly submerged pipe from the top, while feeding of seawater is done through perforated pipes at the bottom of the tanks.

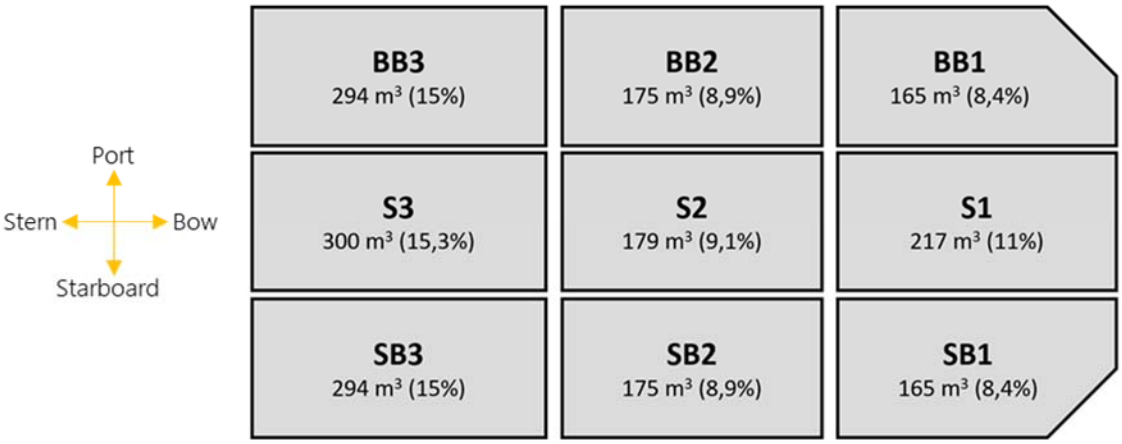

Figure 3: *Diagram showing the number of tanks onboard Selvåg Senior*

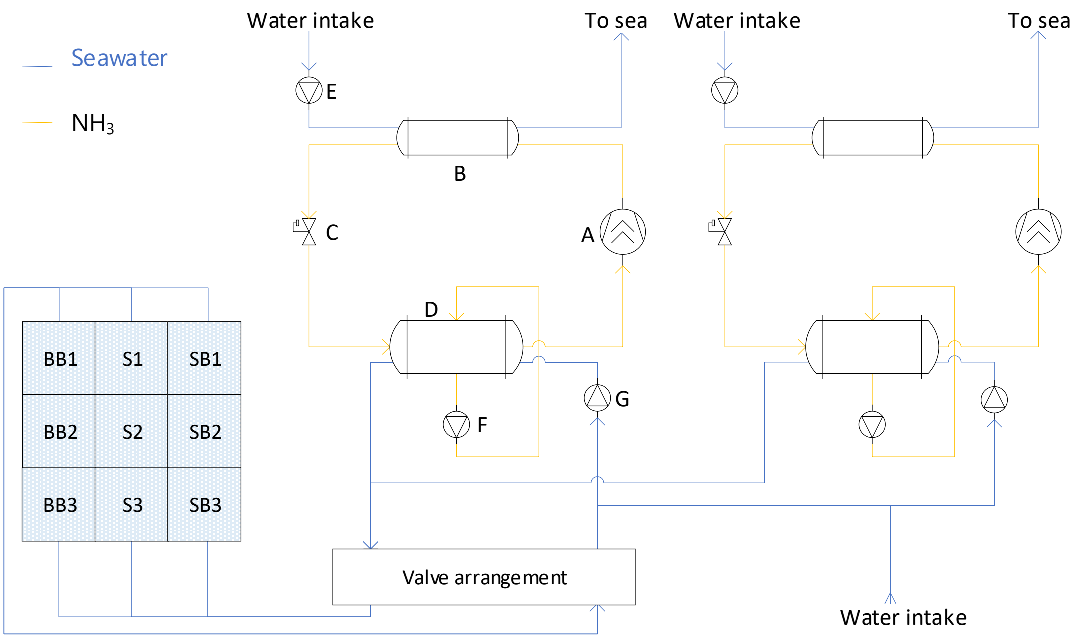

Figure 4: *Simplified P&ID of the RSW system. A: screw compressor, B: condenser, C: throttle valve, D: evaporator, E: seawater pump for condenser (open circuit), F: Liquid refrigerant recirculation pump, G: RSW pump*

2.1.1 Heat loads

The heat loads for the RSW system can be divided to mainly two parts; prechilling seawater from initial (T_1) to target temperature (T_3) and chilling a mixture of fish and seawater from an average temperature (fish/prechilled seawater, T_2) to target temperature (T_3). The length of the different periods ($\tau_{1,2,3}$) depends on amount of seawater, quantity of fish and capacity of refrigeration system. The refrigeration system must also handle heat loads due to heat transmission through the RSW tank walls and heat added by the circulating pumps.

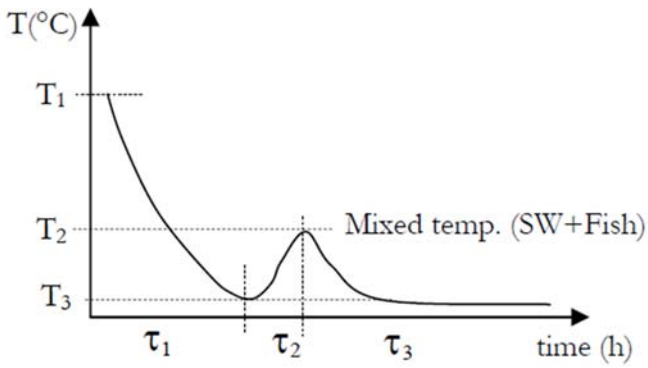

Figure 5: *Characteristic chilling curves for a RSW system showing prechilling and chilling of fish. Adapted from (Thorsteinsson et al., 2003)*

2.2 Fishing process

This is a brief description of how the fishing operation using a purse seine is done.

After arriving to the fishing grounds the process of locating a school of fish starts. In technical terms, this is solved by using the onboard instruments such as echo meters and radars, but the skill and experience of the crew using them is just as important. Decisions based on what are shown in the instruments are just as vital as the instruments themselves, and for mackerel, lacking a swim bladder, it can be challenging to determine the size of the school observed on the instruments. When a proper school is located and the decision to fish has been made by the skipper, the purse seine is released into the water while the vessel moves in such a fashion that it encircles the school of mackerel. The bottom of the net is then pulled and closed, so that the mackerel is "herded" alongside the starboard side. A pump head is then lowered into the net, drawing the fish from the net and into the different RSW tanks onboard via a straining box separating fish and water. For this particular purse seine, the total length is around 8-900 meters, and was used at depths to around 190 meters.

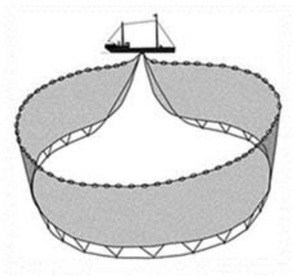

Figure 6: *Purse seine (from Wikipedia)*

Regarding the refrigeration and RSW system, normal operation when leaving harbour is to fill up several of the tanks with seawater (or fresh water from onshore) which is then chilled when steaming towards the fishing grounds (pre-chilling). Number of and which tanks are charged is dependent on type of fishing and the target catch size. For this mackerel cruise, the midsection, BB1, SB1 and S3 was charged with seawater (1159 m^3) and the aim was to catch about 500 tonnes of mackerel. This corresponds to a mackerel filling ratio of about 40%. Pre-chilling is complete when the water holds a temperature in the vicinity of -1,5 °C, at which point the refrigeration systems are switched off and are not switched on again before fishing unless temperature levels rise above 0 °C. For further reference, refrigeration system 1 was handling chilling of the midsection and system 2 covered refrigeration for the bow and stern section.

The end stage of the fishing operation is to pump the catch onboard the tanks. The process usually starts by filling up the midsection, followed by the bow section and finally the stern section, one tank at a time. When pumping the mackerel onboard it is necessary to avoid a too large free fall distance between the pump discharge and water surface, which is solved by simultaneously and continuously moving seawater from the actual tank (and into another empty tank). The mackerel has no swim bladder and therefor sinks to the bottom of the tanks. Extra caution is exercised when operating the seawater pumps to avoid "jet streams" from the water inlets which can damage the fish. The resulting guts and fish entrails could form a barrier on the water inlets and thus impair the overall circulation. For this reason, the seawater pumps were operating at a maximum of 80% (according to chief).

If we consider the chilling process (of mackerel) the first stage of chilling the load is accomplished solely by the pre-chilled seawater. Design of the RSW system does not allow for simultaneous chilling and moving of seawater from one tank to another, so the refrigeration system is not running until end of the pumping process. In effect, this means that the seawater temperature in the loaded tanks will rise to some value between initial water temperature and temperature of the load, dependent on size of the load and time it takes to complete the pumping process. Once the refrigeration system is switched on, it stays on until harbour is reached and the unloading process starts, only interrupted in the event of another fishing attempt.

As mentioned, target catch size is around 500 tonnes. There is however never a guarantee for catching fish, or rather, how much fish that will be caught. Besides quality of the vessel and fishing gear, and skill of the crew, luck is one of the factors that remains in the equation. For mackerel in particular, time is of the essence when the first catch is onboard as quality degradation starts immediately as the fish is out of the sea. If the catch is rather small and there is available time to attempt another catch, that could be done to get closer to the target size. However, getting too much fish is neither desired as there will be fewer buyers bidding on large loads, and thus reduce the price. All this means that the total catch size might have a rather large variation which needs to be accounted for when trying to optimise the refrigeration process in terms of new technology or operation.

2.3 Atlantic mackerel

The Atlantic mackerel is a pelagic which commonly found in large schools to a depth of about 200 m. An adult mackerel weighs about 300-500 g with a length of 30-35 cm, albeit there are recorded catches of individuals as large as 60 cm and weight 3,4 kg. The fat content has a seasonal variation, ranging from about 3-5% in the spring to about 25-30% in the autumn. Average annual catch size for the Norwegian fleet has been around 200 000 tonnes for the last five years, and a landed value in the range 2-2,5 billion NOK (SSB, 2020).

3 Methods

Main objective of the cruise was to gather data and measurements from the onboard energy systems. The following list shows the main tasks:

- Instrument a RSW tank with temperature loggers
- Gather fuel consumption during different stages of the trips
- Gather energy data from the refrigeration/RSW
- Gather catch data
- Conduct talks with crew iot gain knowledge of modus operandi and discuss efficiency measures

In addition, a timeline was to be established, dividing the trip into relevant stages for which the different measurements could be binned. Based on earlier experience the operation of e.g. the refrigeration system is very different whether the vessel is carrying load, pre-chilling seawater or if the vessel is on ground searching for fish. The same experience has been noted on fuel consumption data from other projects: the consumption varies a lot dependent on whether the vessel is steaming towards fishing grounds, on ground searching or fishing or steaming towards harbour with valuable load onboard. For this reason, the following stages were decided on beforehand should be noted with date and timestamps to better analyse the gathered data:

- Steaming towards fishing ground
- Searching for fish
- Fishing operation
- Steaming to harbour

3.1 Instrumentation of RSW tank

One of the RSW tanks were instrumented with temperature loggers to reveal any potential temperature gradients in either the vertical or horizontal direction. Two ropes with loggers were prepared beforehand and attached to available anchor points inside the tank BB2, as can be seen in Figure 7.

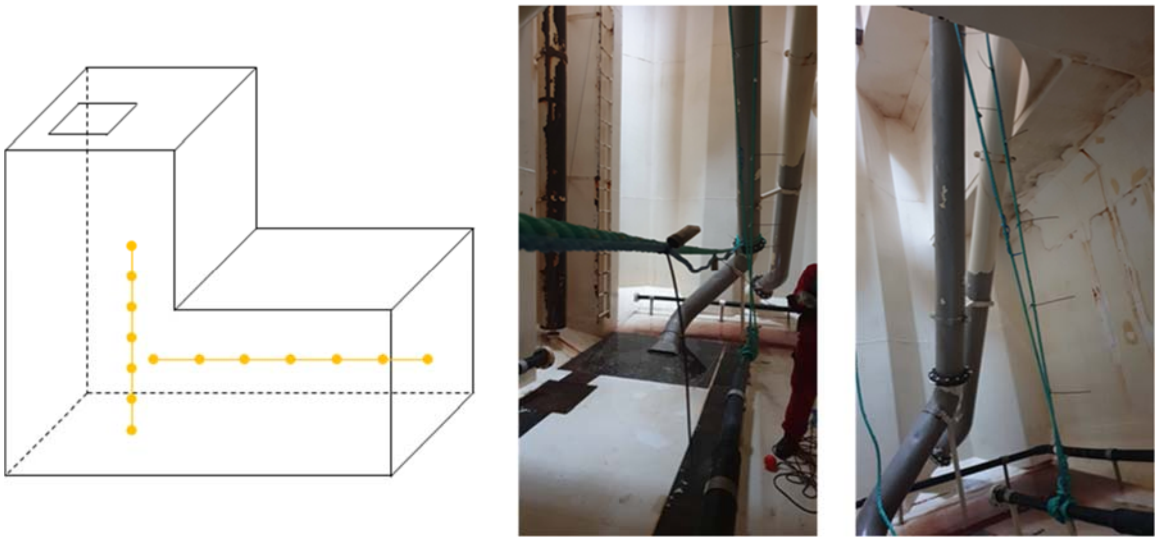

Figure 7: *Left: 3D representation of BB2 along with placement and number of loggers. Middle/right: Pictures of the arrangement*

Seven loggers of the type HOBO Pendant Temperature Data logger (UA-002-64) (accuracy: ± 0.53 K) were attached to each rope, with 100 cm distance between loggers on the horizontal rope and 66 cm distance on the vertical rope. Sampling rate was set to 30 seconds. As part of the preparation, the loggers' deviation from 0 °C were controlled using a mixture of ice/water. Any deviation was accounted for in final measurement data.

3.2 Machinery and fuel consumption

A conventional machinery provides propulsion and electric power supply. The main diesel engine drives the propeller via an axle and gearbox. Electric power supply (during trips) is provided by an axle generator (2300 kW @ 60 Hz) driven by the main engine. In addition, there is two diesel generators (1x1168 kW @ 60 Hz, and unknown) which are used when the vessel is at harbour.

Fuel consumption was registered manually from an onboard system at regular intervals. The system reported accumulated fuel consumption of the main engine (from first time of operation). Calculating fuel consumption for the different stages was performed as part of the subsequent analysis.

$$FC = M_{t-1} - M_t \ (litre)$$

Where *FC* is fuel consumption in litres, *M* is measured value at time *t*. Dividing by known distance (nautical miles) or period length (hours) between time of measurements was also performed to report specific consumption values. It should be noted that fuel consumption of auxiliary generators was not registered.

Measuring fuel flow is known to be challenging and the accuracy is highly dependent on type of measuring device. The diesel engines are typically overfed with fuel, 3-4 times more than needed, to be able to handle sudden change in speed. Excess fuel is returned to the tank. According to the chief engineer, volumetric flow meters are attached to both the feed and return pipe, and the difference between these two measured values equals the consumed fuel.

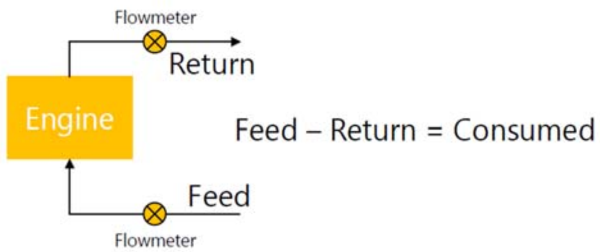

Figure 8: *Measuring fuel consumption*

We were not able to gather specifics on the accuracy of this system. During talks with the crew, some slight disagreement regarding accuracy was noticed. This system was also discussed in a workshop held within the CoolFish project shortly after, were a general remark regarding this kind of measuring setup was described to less accurate than other available methods, due to the volumetric property change of fuel that needs to be accounted for between the feed and return which can be challenging to calculate.

3.3 Energy measurements of the RSW system

During spring 2020 the vessel was instrumented with several loggers on the RSW system by Øyangen. The following sensors was installed:

- Temperature sensors on RSW inlets (both evaporators)
- Temperature sensors on RSW outlet (both evaporators)
- Power readings on frequency converters for the following components
  - 2 x refrigeration compressor
  - 2 x condenser pump (seawater pumps)
  - 2 x refrigerant recirculation

  - 2 x RSW pumps
- 2x Volumetric flow meters for the main RSW circuits (flow through evaporators)

Calculation of heat flows of the RSW system is according to the following formula:

$$\dot{Q}_{RSW} = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \cdot \frac{1\ h}{3600\ s}\ [kW]$$

Where the specific heat and density of seawater is assumed constants at 3,994 kJ/kgK and 1027,3 kg/m3. Energy calculations are then performed as integration of heat flows in MS Excel.

Coefficient of power (COP) is defined as the heat removed divided by power input to the system, where the latter usually means power to the compressor. Two COPs are used in this report. COP_{COMP} is calculated only accounting for power input to the compressor and is useful when comparing data with other studies, as this is commonly reported. COP_{TOT} is calculated accounting for power input to the compressor, but also for all the pumps in the system (RSW, condenser and recirculatory) which are necessary for the refrigeration system to work.

$$COP_{COMP} = \frac{\dot{Q}_{RSW}}{\dot{P}_{COMP}}$$

$$COP_{TOT} = \frac{\dot{Q}_{RSW}}{\dot{P}_{COMP} + \sum \dot{P}_{PUMPS}}$$

High COP values can in this case be interpreted as efficient use of fuel, as it is the sole provider of power generation onboard the vessel.

3.4 Catch data

During and after fishing operation, the following parameters were logged:

- Date and time for the different steps of the fishing operation (releasing of purse seine start/end, net pursed, pumping start/end)
- Total size of catch
- To which tanks the catch is pumped
- Average size of caught mackerel (done by crew)
- Weather during operation

In addition, sea water and air temperature were measured. An assumption was made that the core temperature of the mackerel holds the same temperature as the sea water. Measurements were done using Testo 110 measuring instrument with a 12 cm long probe (accuracy: ±0,2 K).

3.5 Datafiltering

A large amount of data was gathered from both the energy systems and temperature loggers in the BB2 tank. Considering only the energy system readings, 14 parameters were logged with a sample frequency of 10 seconds, which over 8 days equals 967 680 data points. From the HOBO loggers a total of 391 680 were gathered. Data was analysed using MS Excel.

For the temperature loggers of the energy system, there was a concern related to the accuracy and resolution. Data reveals a resolution of 0,1 K, which for this case is a quite large range for energy calculations, given the large flows and small temperature differences over the evaporator. Furthermore, this also created noise in the dataset, which transferred to all calculations involving these temperature readings. In order to smooth the data, a choice was made to filter this noise to properly study the relevant energy performance trends of the system. This was done by applying a moving average filter to the temperature difference ($dT_n = (T_{in} - T_{out})_{RSW,n}$, n=1,2 for system 1 or 2) with a window of 360 seconds (6 minutes). This new calculated value was then used for energy calculations presented in this report. Figure 9 shows an example of how this plays out with comparison between unfiltered and filtered dT, and subsequent calculations of Q_{RSW}.

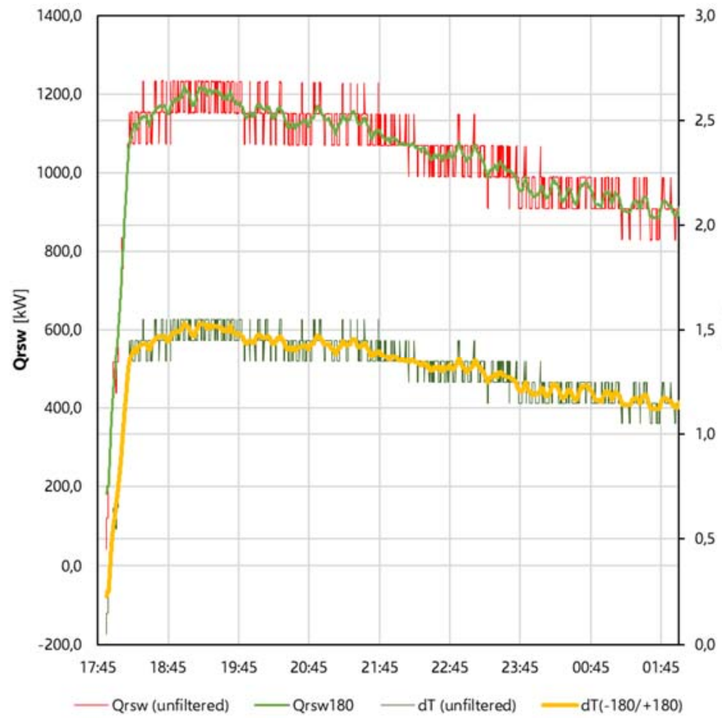

Figure 9: *Filtering of data*

4 Results

4.1 Overview

The research cruise was conducted in the period between the 29th of September to 6th of October, and included two mackerel fishing trips to grounds south-south east of the Shetland Islands. Both trips lasted just above 2 days and covered distances between 478-489 nautical miles. Figure 10 shows both trip routes.

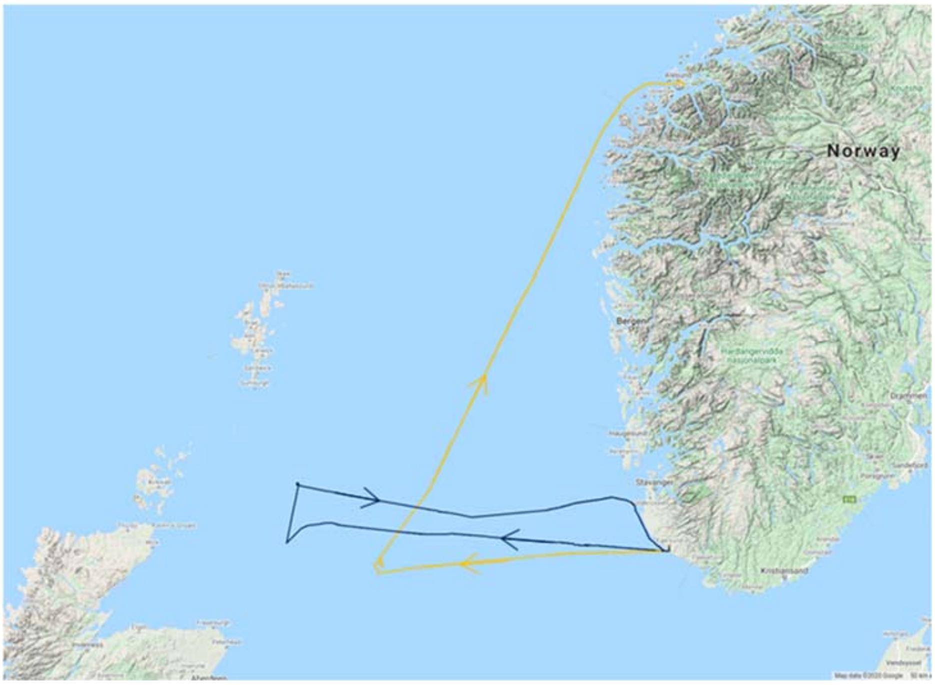

Figure 10: *Blue line is first trip, yellow line is second trip*

During trip 1 only one fishing operation took place before returning to harbour, while the second trip yielded 2 fishing operations. The following table shows data describing the operations. For the first trip 175 m3 of mackerel was caught, while 580 m3 was caught during the second trip. An assumed density of 1072 kg/m3 has been attributed to mackerel for converting the reported catch volume to tonnes.

Table 1: *Catch data*

Trip/catch	Start/end	Weather	Avg. weight (kg)	Catch (tonnes)	Tanks filled
Trip 1, catch 1	30/9 19:50-22:24	15 knots, 11,8/12 °C (sea/air)	0,451	188	BB2, S2, SB2
Trip 2, catch 1	4/10 10:36-13:15	12,5 knots, 13,4/13,3 °C (sea/air)	0,43	214	BB2, S2, SB2
Trip 2, catch 1	4/10 17:29-20:33	9 knots, 12,3/12,8 °C (sea/air)	0,45	407	BB1, S1, SB1, S3

4.1.1 Operational mode timeline

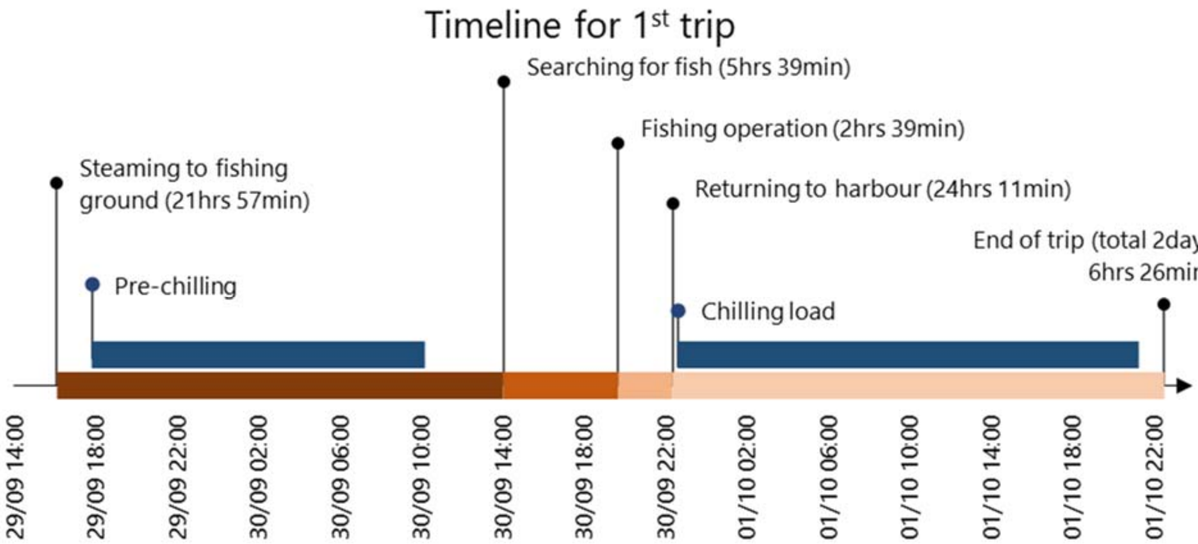

Figure 11: *First trip overview*

Figure 11 shows an overview over the first trip, to and from Egersund. This was the second attempt of the season to locate the fields in which schools of mackerel could be found. As can be seen, and as expected, the most time-consuming stages of the trip is the actual movement to and from the fishing grounds, given its distance from the Norwegian coast. The timeline also reveals the overall operation of the refrigeration systems: shortly after leaving the coast, seawater is pumped into some of the tanks and pre-chilling commences and is completed in about 16 hours. It is not switched on before fish has been caught and pumped into the tanks, where it stays on until arrival at harbour again. Time spent on field for this trip was around 8 hours, returning to harbour before a second catch attempt could be made due to night time. Total trip length was 478 nautical miles.

Weather for the first stage was ranging from calm to strong breeze, with wind direction mostly tailwind and crosswind. On field and during the return stage, winds were ranging from strong breeze to gale with wind coming in head direction. Air temperatures for the whole trip ranged from 8 to 12 °C.

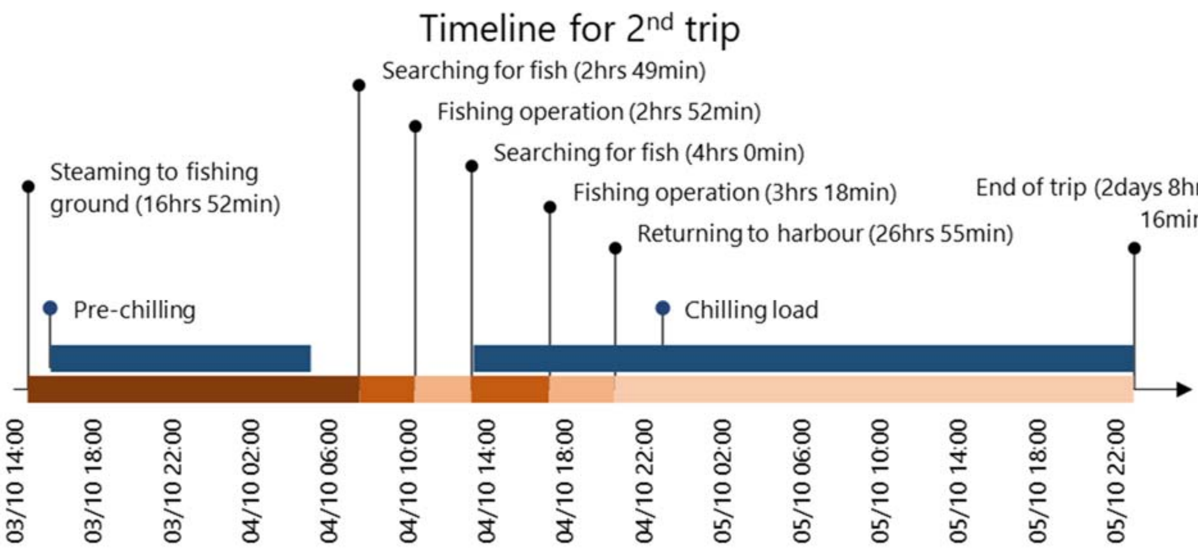

***Figure 12:** Second trip overview*

The second trip started with departure from Egersund and to fishing grounds somewhat more south-southeast of the previous. Arriving earlier at field allowed for two successful fishing attempts before returning to harbour. Return was set to Fiskarstrand, which in time and distance was longer than for the first trip. Total trip length was 488 nautical miles.

Wind strength for the first stage ranged from strong breeze to near gale, coming in at the tail. When arriving on field, the wind started to slack, and for the return it was slacking even more.

4.2 Energy measurements

As earlier described, the refrigeration has two main heat loads to handle, namely prechilling of seawater as part of fishing preparations and chilling of fish/seawater mixture once fish has been loaded onboard the tanks. During the cruise there was gathered data for 6 periods of interest; 3 prechilling periods and 3 chilling periods, which will be further reviewed and discussed in this chapter. The following table lists key information regarding each period.

***Table 2:** Description of refrigeration periods of interest*

Period	Section	Estimated heat load	Duration
Trip 2 - Chilling - System 2	Bowsection, S3	5 609 kWh[1]	34h 13min
Trip 2 - Chilling - System 1	Midsection	2 868 kWh[1]	41h 13min
Trip 1 - Chilling - System 1	Midsection	2 829 kWh[1]	22h 39min
Trip 2 - Prechilling - System 2	Bowsection, S3	10 770 kWh[2]	13h 15min
Trip 2 - Prechilling - System 1	Midsection	9 044 kWh[2]	12h 28min
Trip 1 - Prechilling - System 1	Midsection	9 044 kWh[2]	13h 26min

[1]Calculated accounting only for initial reduction of temperature [2]Assuming temperature reduction of 15 K

The figure below shows the share of power consumption, by components, during some selected periods. It can be seen that the compressors are the main consumers of electrical energy independent of stage. During the pre-chilling periods, the compressors have a share of ~75% of total energy consumed (of period total), while for load chilling (chilling of mackerel in tanks) it is about 60%.

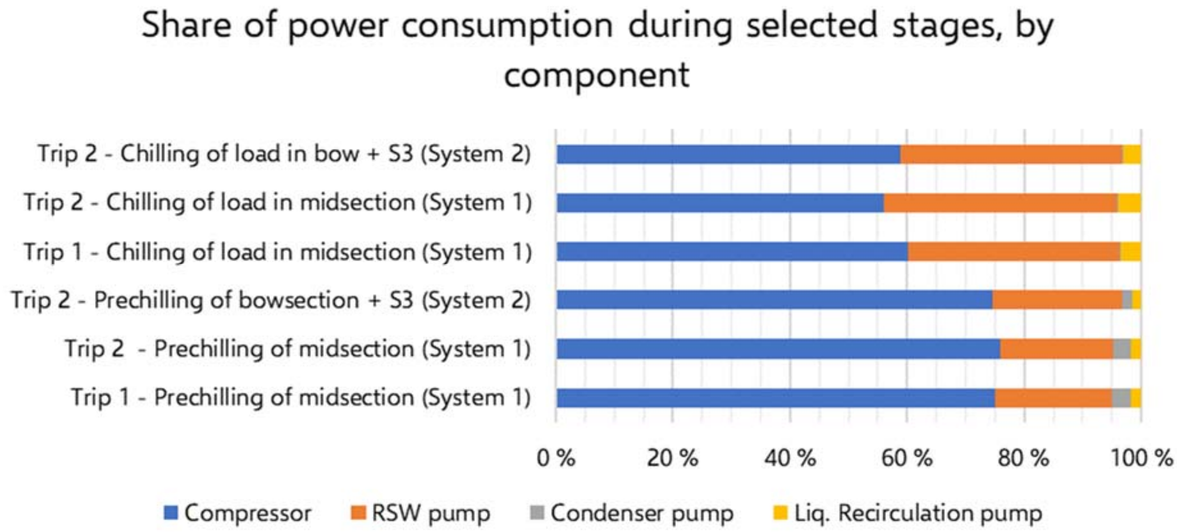

Figure 13: *Share of power consumption during selected stages by component*

The condenser pumps exhibit a strange behaviour yet to be explained at the writing of this report. During the first stage of pre-chilling periods, the pumps run at high speeds which levels off soon thereafter and shuts off while the refrigeration system is still running. At present the feasible explanations is either faulty readings from the sensors attached to these pumps, or the condensation heat is handled by some other feature of the system not shown in drawings or documentation available to the author. The graphs below show two examples of the described behaviour.

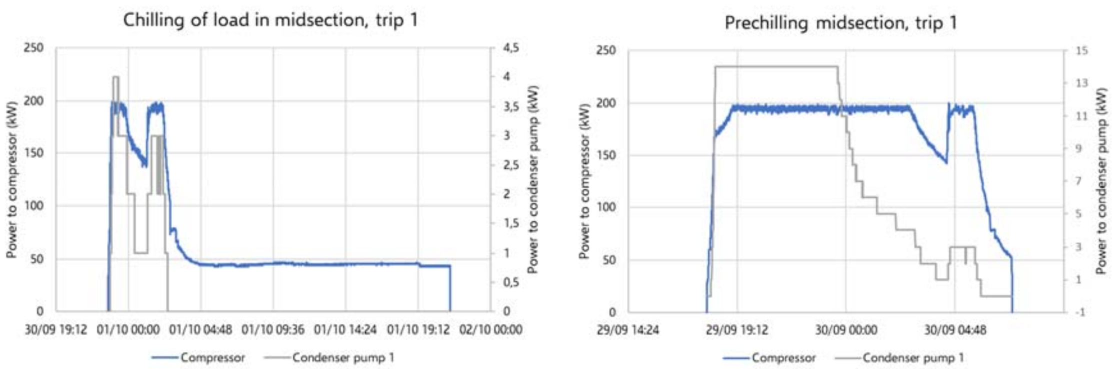

Figure 14: *Power duty of compressor and condenser pump during different periods (system 1)*

4.2.1 Pre-chilling

The graphs below show the COP for the three prechilling periods calculated with the two methods earlier described. The COP_{TOT} will obviously yield lower values as they include power input to pumps as well as the compressors. However, due to the almost constant, and low share of consumption by the pumps, the trends are the same for both methods.

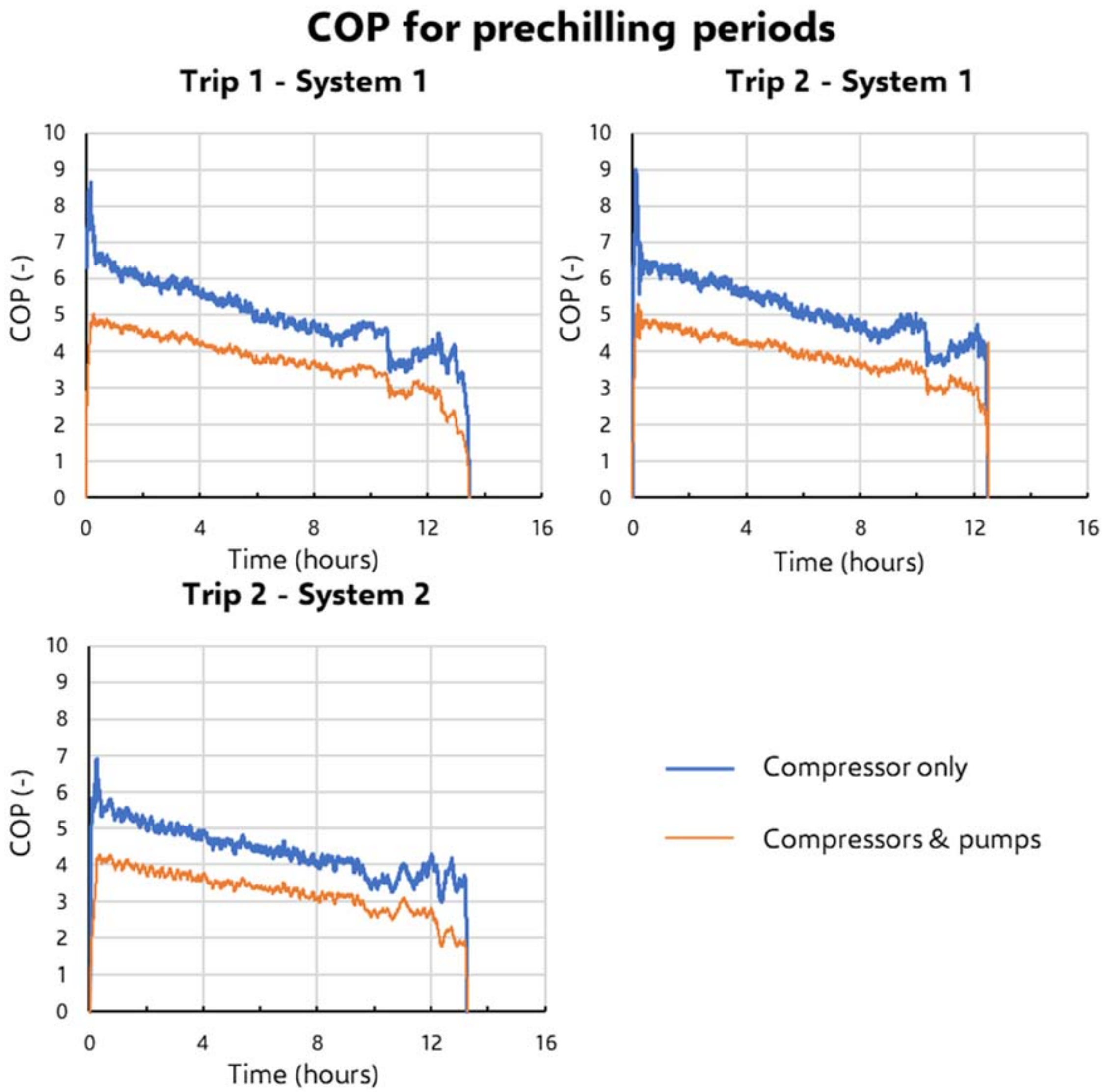

Figure 15: *COP for prechilling periods. Fat blue lines are calculated accounting only for power input to the compressors, while thin orange lines include power input to pumps in the system*

Notice the initially high COP which steadily declines throughout the period. This can be understood by the declining chilling duty of the seawater as the temperature reduces. Power inputs are more or less constant throughout the period, as well as RSW flow through the evaporator, but the amount of heat which is transferred from the seawater stream to the refrigerant is decreasing as the temperature difference between in- and outlet decreases.

System 1 had two prechilling periods which are comparable (same amount of seawater to be chilled and equal operational parameters), the only difference being that for the second trip target temperature was a bit higher (-1,0 °C vs -1,2 °C) resulting in a shorter period. The curves reveal a similar performance for both trips. System 2 exhibits a similar trend as to system 1, but with lower overall values. This is in part due to a lower initial seawater temperature for system 2 (prechilling previously chilled seawater).

Table 3: *Average values for prechilling parameters. P_{SUM} is power input to compressors and pumps, Q_{RSW} is chilling duty, dT is temperature difference over evaporator.*

Period	Averages P_{sum} [kW]	Q_{RSW} [kW]	Flow [m3/hr]	dT [K]	COP_{comp} [-]	COP_{tot} [-]	Start/End temp. [°C]
Trip 1 - Prechilling - System 1	232	881	694	1,11	5,0	3,7	15,1 / -1,2
Trip 2 - Prechilling - System 1	237	931	692	1,18	5,2	3,9	14,7 / -1,0
Trip 2 - Prechilling - System 2	239	790	696	0,99	4,4	3,2	11,7 / -1,1

The table above lists selected average values for the period along with initial and ending temperature of the seawater, as measured by the inlet/outlet loggers. It should be noted that, on average, the loggers for system 1 shows a temperature 0,3 K above that of the temperature loggers within the BB2 tank. This might be due to heat added by the RSW pumps.

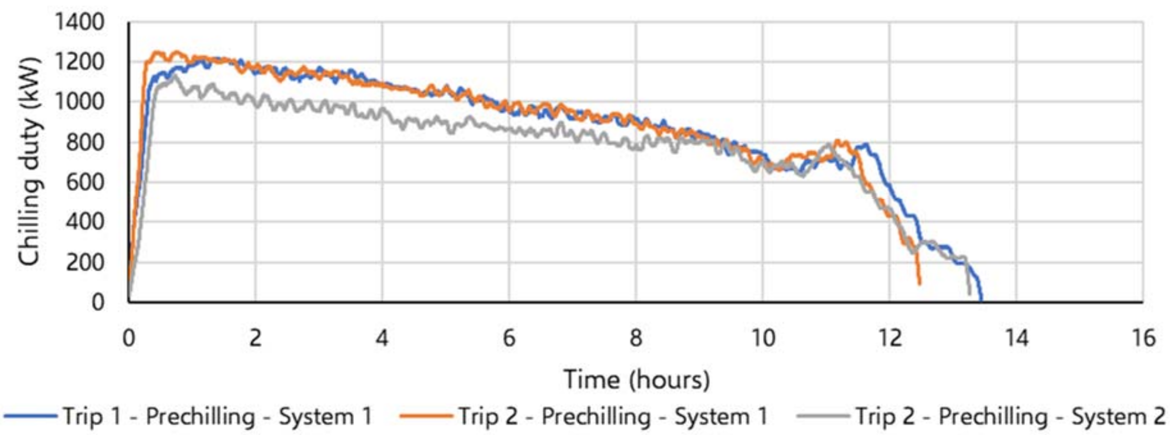

Figure 16: *Chilling duty curves for prechilling periods*

While average values for chilling duties are listed in Table 3, the above graph shows that this is steadily decreasing throughout the period due to smaller and smaller temperature difference over the evaporator (RSW side). Maximum chilling duty is measured at right above 1200 kW.

By measuring the amount of heat removed from the seawater stream in the evaporator and comparing it to estimated heat load calculations, one can get an idea of the size of heat loads due to transmission loss through tank walls and heat added by pumps.

Table 4: *Estimation of additional heat loads*

Period	Heat loads (kWh) Estimated	Measured	Difference
Trip 1 – Prechilling - System 1	9 828	11 864	2 037
Trip 2 – Prechilling - System 1	9 466	11 633	2 167
Trip 2 – Prechilling - System 2	9 191	10 478	1 287

The estimated heat loads are calculated using the measured initial/ending temperatures for the different sections, while measured values are retrieved from the energy loggers. For system 1 we see that an additional amount of ~2000 kWh of heat transferred from the seawater. Assuming this is due to transmission loss and heat added by pumps, these two loads account for about 17-19% of the total. For system 2 the same share is 12%.

4.2.2 Chilling

While the initial load chilling is done by the prechilled seawater, the chilling period in this subchapter refers to chilling done by the refrigeration systems. This period starts when the last fish has been loaded onboard the vessel, and thus starts from a temperature in between the initial fish temperature and the prechilled seawater temperature. Average temperature of the sea surface during the three catches was measured to 12,5 °C, and assuming this is equal to the fish temperature, mixture temperature should be in the range of 3,2-4,8 °C (for the specific catch amounts), which harmonize with the measurements (3,4-4,8 °C). Albeit continuous, the chilling period can be thought of as two separate periods where the first is to reduce temperature of the fish to target temperature, and then to maintain the temperature until the trip is over.

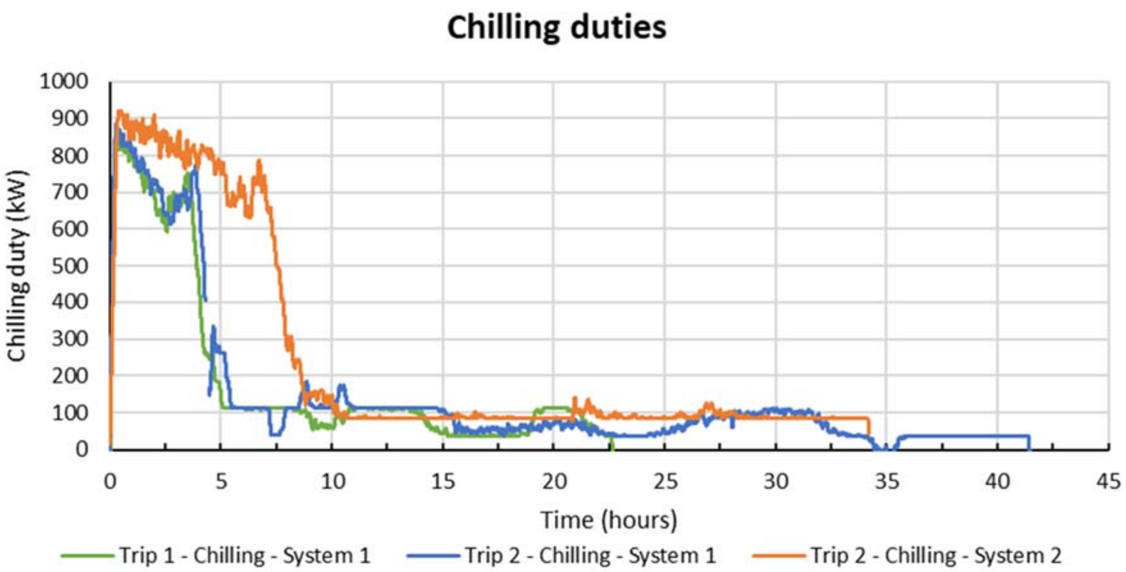

Figure 17: *Chilling duty curves for chilling periods. The gap in the blue curve is because the system was turned off for a short period (unknown reason)*

The chilling duty curves shows, as expected, high values initially and rapidly declining as temperature of the tanks is decreasing. When the temperature reaches target temperature, a clear transition to maintenance chilling can be seen in the graph. Length of this period depends on size of catch, mixture temperature and chilling capacity, and for these instances they occur around the 5- and 9-hour mark. System 1 was subjected to similar loads for both trips, same catch size (175-200 m^3) and mixture temperature, which is revealed by the similar development in chilling duty for these instances. System 2 was subjected to much larger catch size (380 m^3) which prolongs the time before target temperature is reached. The following table shows average values of selected parameters for the different periods, distinguishing between initial chilling and maintenance chilling.

***Table 5:** Average values of selected parameters for periods of chilling, distinguishing between initial and maintenance chilling*

				Averages				
Period	**Length**	P_{SUM}	Q_{RSW}	**Flow**	**dT**	COP_{COMP}	COP_{TOT}	**Start/end temp**
Trip 1 - Chilling - System 1	*[hr]*	*[kW]*	*[kW]*	*[m³/hr]*	*[K]*	*[-]*	*[-]*	*[°C]*
Initial	5,1	195,3	595,8	656,6	0,79	3,9	2,9	3,4/-1,2
Maintenance	17,5	89,9	81,8	647,2	0,11	1,8	0,9	-
Total	22,7	113,7	197,6	649,1	0,26	2,3	1,4	3,4/-1,2
Trip 2 - Chilling - System 1								
Initial	5,6	198,0	613,2	657,9	0,82	4,0	3,0	3,5/-1,2
Maintenance	35,8	88,7	70,6	651,6	0,10	1,6	0,8	-
Total	41,4	103	141,4	652,4	0,19	1,9	1,1	3,5/-1,2
Trip 2 - Chilling - System 2								
Initial	9,3	221,5	669,8	727,5	0,81	3,9	2,9	4,8/-1,1
Maintenance	24,9	97,3	89,4	726,0	0,11	2,1	0,9	-
Total	34,2	131,1	247,5	726,4	0,30	2,6	1,5	4,8/-1,1

As can be seen there are large differences between the initial and maintenance chilling periods. For one thing, the refrigeration systems perform better at higher loads (initial chilling) which reflects on the COP's. Furthermore, the chilling duty decreases drastically in the maintenance period, with average demands around 70-90 kW. It seems that the compressors have a weaker performance at part-load operation, as the measured power input to the systems is larger than the chilling rates. While length of the maintenance period will vary dependent on other factors, it is fair to claim that it is normally the longest operational period of the refrigeration system for vessels going far to sea.

***Table 6:** Heat loads during chilling*

			Measured heat load	
	Catch size	**Estimated heat load**	**Initial**	**Maintenance**
Period	[m³]	[kWh]	[kWh]	[kWh]
Trip 1 - Chilling - System 1	175	2 656	3 043	1 436
Trip 2 - Chilling - System 1	200	2 696	3 305	2 533
Trip 2 - Chilling - System 2	380	5 253	6 249	2 226

The table above shows the estimated heat loads to chill the caught amount of mackerel and seawater for each period, using measured start/end temperatures and the measured amount of heat transferred from the seawater in the evaporator. Comparing the initial heat load and estimated heat load shows that the share of heat loads which can be attributed to transmission losses and heat added by pumps is about 12-18%. This is similar to the prechilling periods, albeit system 2 this time has the highest share. During maintenance, the loads are due to transmission and pump losses only.

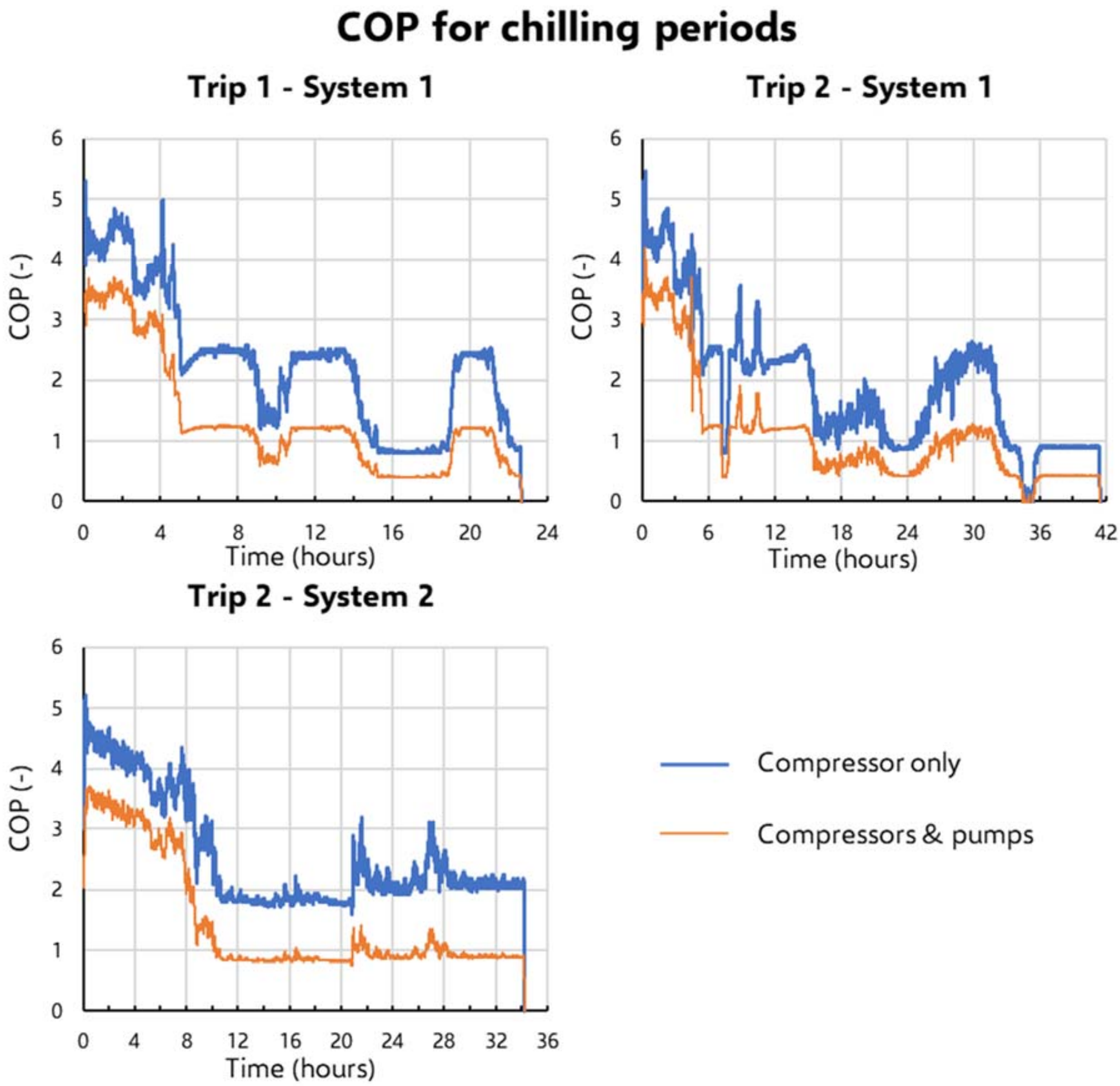

__Figure 18:__ COP for chilling periods. Fat blue lines are calculated accounting only for power input to the compressors, while thin orange lines include power input to pumps in the system

The COP has a similar trend as for the prechilling periods with high initial values, steadily decreasing as the load decreases, before stabilizing at low values during maintenance chilling. There is some noise in the depicted curves, which in part can be attributed to the sensitive calculation of chilling duties: given the large seawater flow rates and small temperature differences over the evaporators, a small deviation in the temperature measurement will create a large deviation in calculated chilling rate.

4.2.3 Other

Total power consumption by the refrigeration systems were measured to 9 306 and 15 007 kWh for trip 1 and 2 respectively. Specific power consumption, accounting for amount of caught fish, is 49,6 and 24,1 kWh_{el}/tonne fish.

The refrigeration systems run for a large share of the total trip hours (66-80%), with most hours dedicated to maintenance chilling (48-67%). When sorting the COP values in bins from >5, 4-5, 3-4, 2-3, 1-2 and <1, and adding all operational hours together, the following chart is generated.

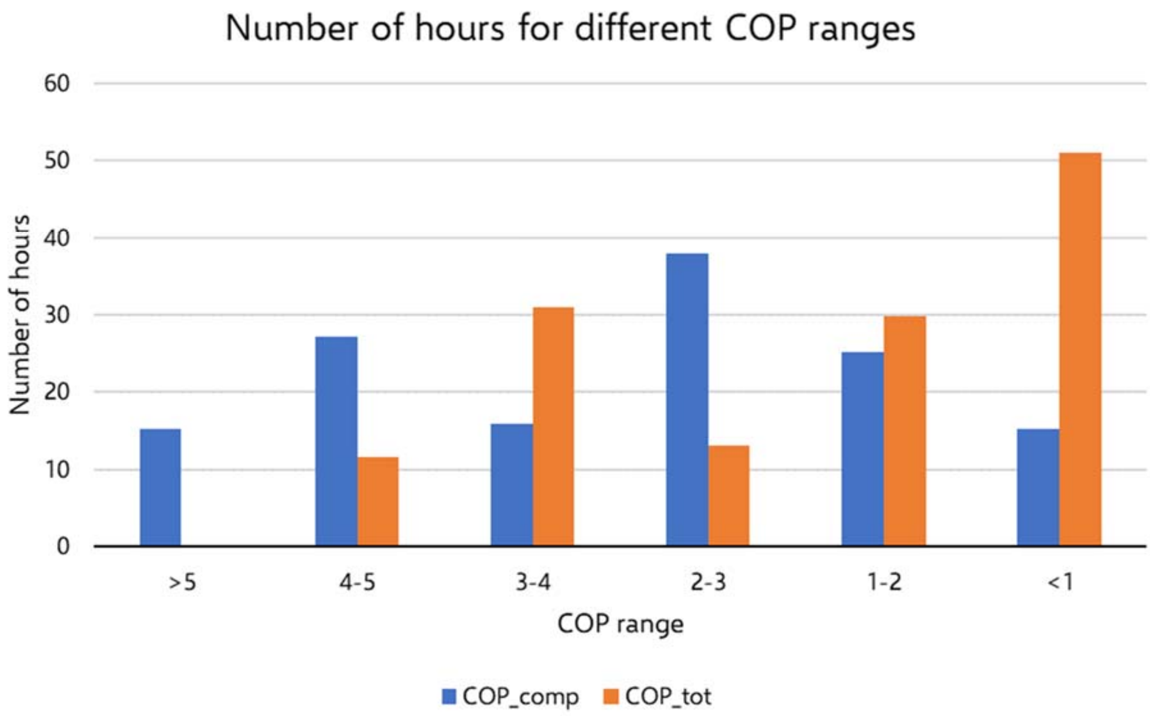

***Figure 19:** Number of hours for different COP ranges, based on data from both systems and trips*

Accounting only for power input to the compressor, the normal way to calculate COP, it can be observed that the systems run mostly in the range with a COP between 2 to 3. If accounting for power inputs to pumps as well, most hours are spent in the low range less than 1.

4.3 Temperature measurements in BB2

4.3.1 Pre-chilling

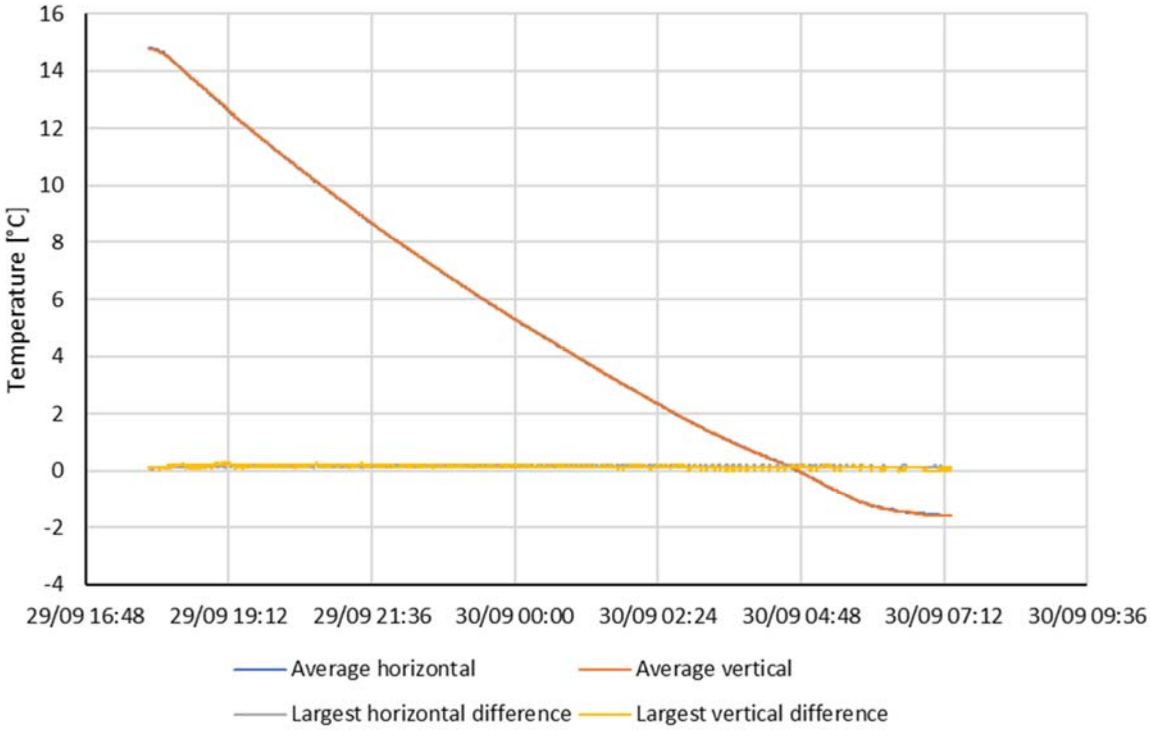

Figure 20: *Temperature distribution during pre-chilling of seawater in BB2 (trip 1). Note that for both averages and largest differences the curves overlap*

The figure above shows average horizontal and vertical temperature distribution in BB2 during pre-chilling of seawater, as well as two curves showing the maximum difference between the horizontal loggers and vertical loggers during the same period. As can be seen, no significant temperature gradient can be observed during the pre-chilling process, which suggests that the temperature distribution within the tank is uniform. The maximum difference between loggers on the horizontal axis was measured to 0,227 K (single observation), while for the vertical the maximum value was measured to 0,296 K, which both are within the accuracy range of the loggers. The same trend was observed for pre-chilling during the second trip. As for the process itself, the tank initially contained 175 m^3 seawater holding 14,8 °C, and was chilled to -1,6 °C in a time of 13 hours and 26 minutes. This means a chilling rate of about -1,22 °C/hr. For the second trip, pre-chilling chilling rate was calculated to -1,27 °C/hr.

4.3.2 Chilling of catch

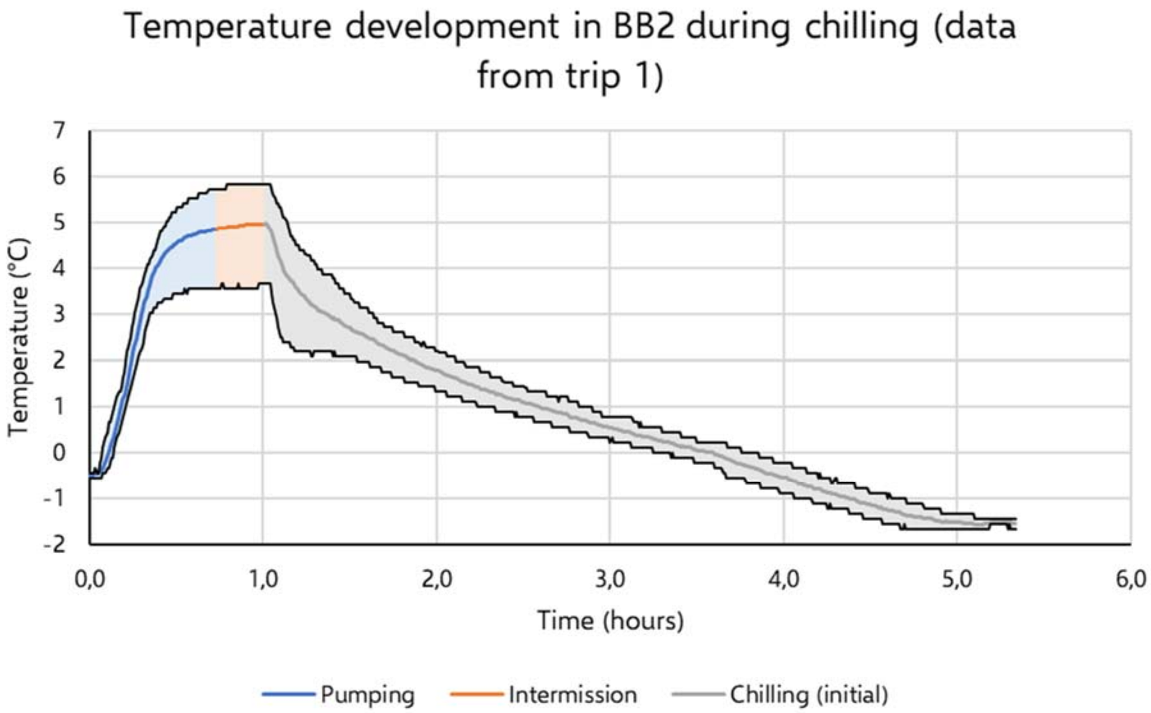

***Figure 21**: Temperature development in BB2 during loading and initial chilling of fish, data from trip 1*

The figure above shows the temperature development within the BB2 tank as it is loaded with fish (80 m3 mackerel), a 20-minute intermission period and initial chilling process. The solid colored lines shows the average tank temperature, while the black-bordered shaded areas shows the maximum and minimum logged temperature at that instant. The refrigeration system is turned off during loading and stays off until all fished is onboard. Since BB2 was the first tank being filled with fish, there is an intermission period before chilling commences due to other tanks being filled. Initially during fish loading we see that the temperature rises quickly from -0,5 °C while it reaches a level between that of the cold water and warm fish at almost 5 °C. In this loading period the warmest temperatures are registered at the bottom of the tank, which falls in line with expectations since the mackerel, lacking a swim bladder, falls to the bottom as it is pumped onboard. Figure 22 shows the final temperature measurements of all loggers at the moment loading has ended. Note that maximum temperature difference in the tank in this instant is just above 2 K.

During intermission period the temperature is still levelling between cold water and fish, and has a slow but steady increase. As the refrigeration system is engaged, there is a rapid decrease in temperature. In spatial terms, the coldest part of the tank is now registered at the bottom and warmest at the top, as cold water is bottom-fed to the tank. As the temperature is decreasing, a more uniform temperature in the tank is also establishing as revealed by the band of max-min temperatures. During maintenance chilling (not shown in graph, starts at end of curve) the difference is negligible.

It takes approximately 3,5 hours from when fish is loaded till tank temperature has reached 0 °C, and 5 hours before the target temperature of -1,5 °C is reached and maintained from thereon. Chilling rate from when refrigeration is turned on until maintenance chilling is calculated to -1,5 °C/hr.

Figure 22: *Snapshot of temperature loggers in BB2 right after loading is completed and before refrigeration is engaged. Left: horizontal axis. Right: Vertical axis*

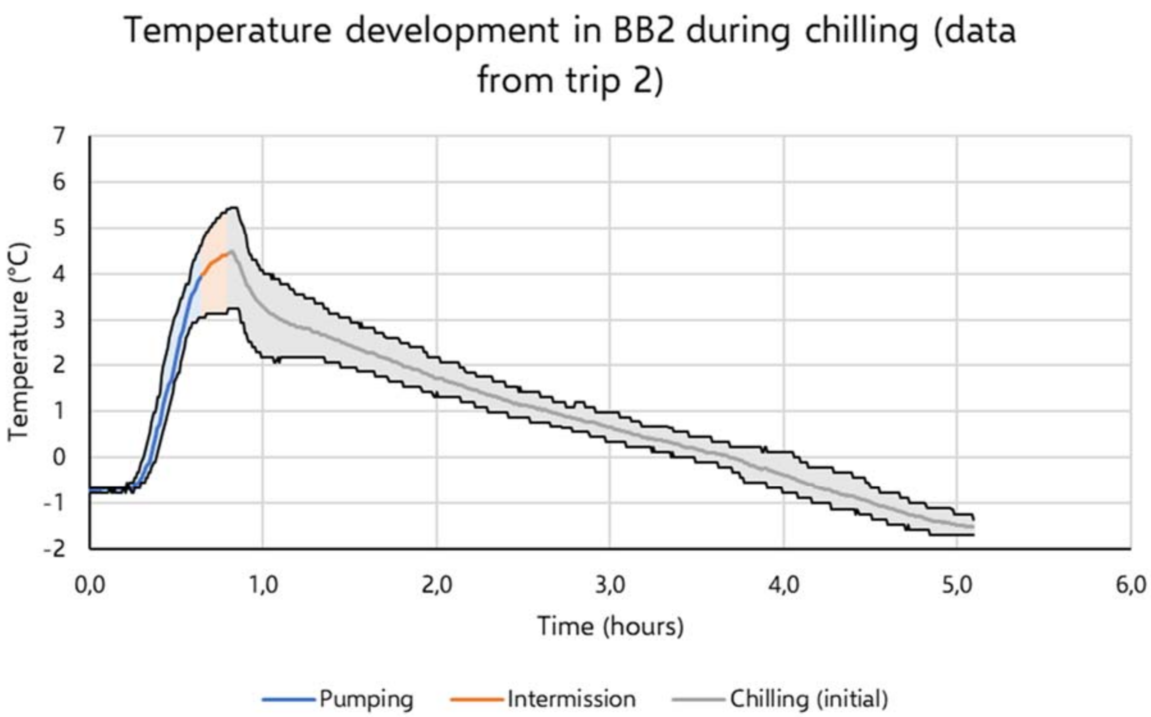

Figure 23: *Temperature development in BB2 during loading and initial chilling of fish, data from trip 2*

The same trend can be seen during the second filling of fish which occurred on trip 2. Maximum temperature difference is right above 2 K, with hot spots showing the same trend as for trip 1. Note that for this case, the refrigeration system had a short break right before the 4-hour mark. This is shown in the max-min band as it slightly increases around this mark, before narrowing in after refrigeration resumes. Chilling rate for this case is calculated to -1,4 °C/hr, and has the same tonnage as for trip 1.

4.3.3 Overall

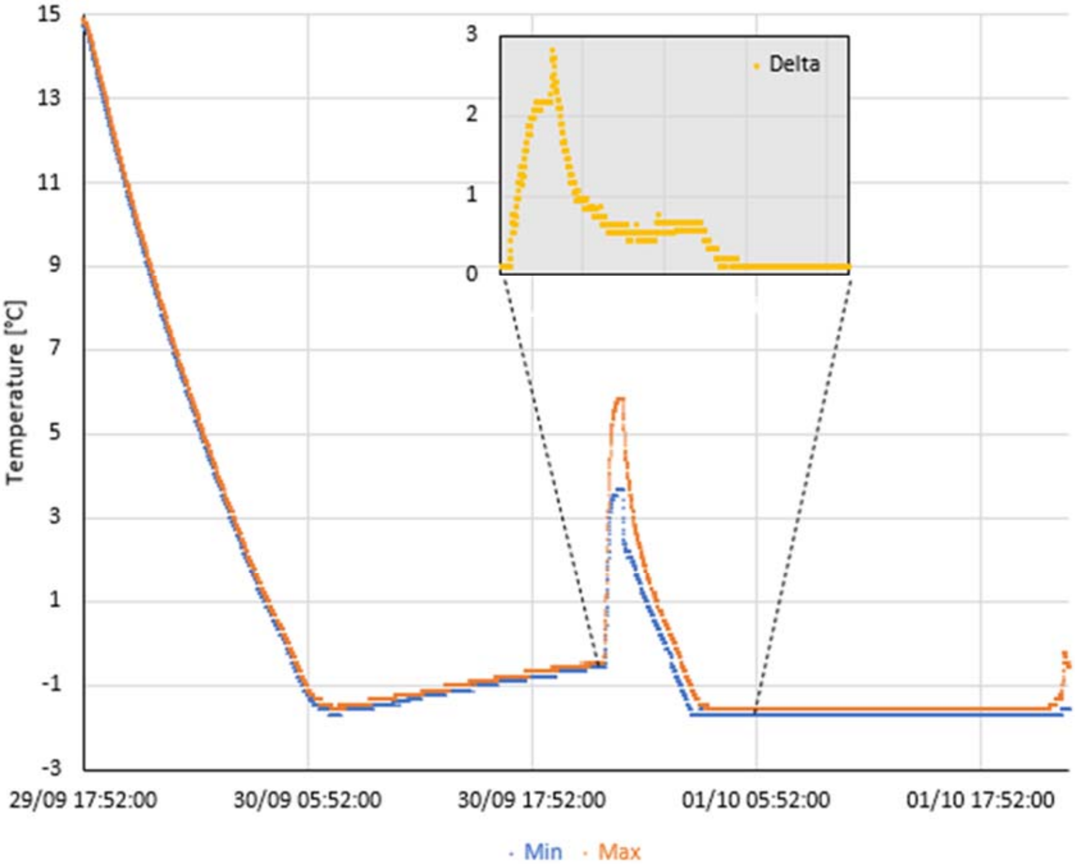

Figure 24: *Maximum and minimum measured temperatures in BB2 during the entire period of the first trip*

The above figure shows the maximum and minimum measured temperatures in BB2 during the first trip, from start to end. As can be seen, no large differences between measurements occurs outside the fishing operation and initial refrigeration stage. The detailed plot shows the delta between maximum and minimum measurements for the latter period. Maximum difference is right below 3K, with an average difference of about 1K. When temperature within the tank has reached -1,6 °C, the load has been sufficiently refrigerated and is kept at this temperature until unloading at harbour. For the second trip, not figured, the trend is the same.

4.4 Fuel consumption

Miscommunications with the crew made for some errors in logging of fuel measurements for the first trip, which has led to calculations being made to estimate fuel consumption for some parts. These are noted in the table below

Trip 1

Stage	Distance (nmile)	Time (hrs)	Consumption (l) Total	L/nmile	L/hour
Steaming towards fishing grounds[1]	218,9	21,9	10 661	48,7	485,7
On field: searching[2]	33,0	5,6	2 458	74,5	435,1
On field: fishing[3]	1,4	2,8	770	548,6	271,9
Steaming towards harbour	224,9	24,0	11 657	51,8	485,7
Total	**478,2**	**54**	**25 547**		
Average				**180,9**	**419,6**

Trip 2

Stage	Distance (nmile)	Time (hrs)	Consumption (l) Total	L/nmile	L/hour
Steaming towards fishing grounds	164,1	16,9	6 554	39,9	388,6
On field: searching[4]	8,9	6,8	1 916	215,6	281,1
On field: fishing[5]	8,0	6,2	2 173	272,3	352,4
Steaming towards harbour	307,9	26,5	11 544	37,5	435,3
Total	**488,8**	**56,4**	**22 187**		
Average				**141,3**	**364,3**

[1] Start value of counter was not noted, so stage consumption is calculated based on the assumption that L/hours is equal to that of the known value for stage 4 (to harbour). This is also why the L/hour is equal for both these stages.
[2] No registration of fuel consumption was made during transition from searching to fishing. An additional amount has been added to the readings based on available l/hour measurements
[3] Calculated from known measurement when transitioning from fishing to return stage, subtracted consumption for searching stage
[4] Both searching-stages lumped together
[5] Both fishing-stages lumped together

The measurements from the second trip holds a higher accuracy compared to the first trip, as they are all based on readings from the onboard systems. However, as earlier stated, as the accuracy of the measurement device itself is unknown, all values must be considered approximations.

Assuming a MGO density of 0,84 kg/litre and global warming potential of 2,69 kg $CO2_{eq}$/kg MGO (Hognes and Jensen, 2017), a fuel use coefficient (kg fuel/kg fish) can be calculated for each trip. For trip 1 and trip 2, the fuel use coefficients are 0,117 and 0,030 kg fuel/kg fish respectively. In comparison, Jafarzadeh (2016) reported an average fuel use coefficient of 0,085 kg fuel/kg fish for Norwegian purse seiners based on data from 2003 to 2012. Global warming potential (not including refrigerant leakage) is 59 100 and 50 134 kg $CO2_{eq}$ for each trip respectively, or a specific GWP/kg fish of 0,315 and 0,081 kg $CO2_{eq}$/kg fish. Regarding the specific calculations, it is easily observed that the catch amount plays heavily into the reported values.

5 Summary

Results from energy measurements taken during a week-long research cruise onboard Selvåg Senior during mackerel fishing has been presented in this report, together with voyage, catch and fuel data.

Regarding measurements, it has been shown that high accuracy is important when measuring temperatures at the evaporator seawater in- and outlet. Large flowrates and small temperature differences infers that a small deviation in the temperature difference has a large influence on chilling calculations. In this report this has been solved by filtering data with moving averages as to remove noise and still maintain the overall trends of the data.

Analysis of the refrigeration systems show, in line with expectations, that the compressors are the primary power consumers (60-75% dependent on process), followed by the RSW pumps (20-40% dependent on process) while the condenser and liquid recirculation pumps shares the last. During periods of refrigeration, the pumps all have a more-or-less constant power consumption, while the compressors are being regulated with respect to cooling capacity. An unexplained anomaly with the condenser pump readings was also described. Cooling capacity of the refrigeration system was measured to a maximum of right above 1200 kW, which occurs initially of the prechilling process. However, as the refrigerated seawater decreases in temperature, so does the evaporation level and thus cooling capacity.

Prechilling of seawater is the heaviest heat load the refrigeration systems must handle. For this cruise, 3 separate instances of prechilling occurred with amounts of 529-630 m3 and initial temperatures at 11,7-15,1 °C. Prechilling periods lasted 13,5-13,5 hours, ending at a target temperature of about -1,2 to -1,5 °C. For this case, the tanks are ready 7,5-14,3 hours in advance of loading. An estimation of how much energy must be removed from given amounts of water and measured initial/end temperature levels was calculated and compared with measured energy removed. Assuming this difference is due to transmission losses and heat added by pumps, these loads account for 12-20% of the total heat load. Average cooling capacities and COPs (comp./tot) were measured to 790-931 kW and 4,4-5,2 / 3,2-3,9. Analysis of temperature loggers in the BB2 tank shows a uniform temperature within. It was also shown that the temperature readings from within the tank, and temperature readings from evaporator seawater inlet had a deviation of about 0,3 K. This might be due to heat added by the pumps.

Chilling of load, i.e. a mixture of fish and seawater, can be divided into two parts: 1) initial chilling, where temperature levels are brought from an initial mixture temperature to a target temperature of about -1,5 °C, and 2) maintenance chilling, where the refrigeration systems maintain target temperature in the load. For this cruise, 3 instances of load chilling occurred, with fish volumes of 175-380 m^3.

Periods of initial chilling starts with high chilling rates which steadily decreases as target temperature is reached. Average chilling rates and COPs (comp./tot) for the three cases ranges from 596-670 kW and 3,9-4 / 2,9-3. Target temperatures were reached within 5,1-5,6 hours for amounts between 175-200 m3, while for the case of 380 m3 fish load, targe temperature was reached within 9,3 hours. Calculated chilling rate based on the temperature loggers within BB2 showed values of -1,4 to -1,5 °C/hr (80 m^3 of fish). In line with expectations, a temperature gradient in the vertical direction was revealed by the data, with maximum temperature difference at almost 3 K during chilling.

Maintenance chilling is subsequently following the initial chilling period, and lasts until the vessel has reached harbour and is ready for unloading. Length of these periods lasted from 17,5-35,8 hours, which translates to shares of 48-67% of each systems overall operational period. At the same time, these are the periods with lowest heat loads (average 70,6-89,4 kW) and COPs (comp.: 1,6-2,1 and tot.: 0,8-0,9). In other words: while the cooling output is reduced by 86-88%, the power consumption to the systems are only reduced by 54-56%.

Period length of maintenance chilling largely effect the overall efficiency of the refrigeration systems. When only accounting for power input to the compressors in the COP calculation, most hours of the total operational hours are in the range of 2-3. Accounting for pump work as well, this changes to COP of 1 or less. Specific power consumption of the refrigeration systems for trip 1 and 2 were 49,6 and 24,1 kWh_{el}/tonne fish respectively.

Regarding fuel consumption, the first remark is that for further work a more thorough method of retrieving data should be selected. Miscommunication and, in hindsight, too low logging frequency, leads to uncertainty in the reported values and calculations based on these. Furthermore, many factors not captured in this research cruise play into the fuel consumption, such as weather conditions, throttle of engine etc., which would contribute to analyse the data. For this cruise, there were two trips where the longest (in time and length) also was the trip with lowest overall fuel consumption. The trips also resulted in large variation of catches (175 vs 580 m3). Fuel use coefficient for the trips were calculated to 0,117 and 0,030 kg fuel/kg fish respectively, and specific GWP (not including refrigerant leakages) were calculated to 0,315 and 0,081 kg $CO2_{eq}$/kg fish. It is easily observed how the catch amount plays into the reported values.

6 References

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