IMPROVING ENERGY EFFICIENCY IN OPERATION OF CO_2 RSW SYSTEM FOR FISHING VESSELS

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ABSTRACT

Cooling and freezing are critical processes in the fishing industry. They ensure proper quality of high value products. They also are responsible for a significant fraction of the total energy consumption. Traditionally, cooling on boat is achieved using Refrigerated Sea Water (RSW) refrigeration plants with halocarbon R22 as working fluid. Usage of this fluid is already limited to refill, and it will be totally banned from 2015. The main alternative is ammonia, but has significant drawbacks that can be unacceptable, particularly for smaller vessels. Carbon Dioxide (CO_2) is an environmental friendly, non toxic, non flammable alternative.

A 400 kW CO_2 RSW plant has been investigated in the geometry based in-house simulation tool CSIM. Quasi steady-state cooling of catches has been simulated for two typical conditions: herring fishing in winter and mackerel fishing in the North Sea in late summer. Optimized operation was sought for either minimal cooling time or lowest energy consumption. In winter operation, an improved solution showed approximately 40% less compressor work compared to the baseline on the expense of longer cooling time. The cooling capacity can also be increased on expense of the COP if the high side pressure is raised. This might be necessary if the time available for pre-cooling is shorter than expected.

1. INTRODUCTION

Norway is one of the largest exporters of seafood in the world. Seafood is also the second largest trade goods in Norway after oil. For the fishing industry, cooling-, and freezing processes are essential to ensure the proper quality of their high value products. These refrigeration processes contribute to a significant fraction of the total energy consumption on board the vessels. Refrigerated Sea Water (RSW) systems are widely used to chill fish haul in a simple and effective way. The traditional refrigerants commonly used in RSW causes environmental impacts, have high costs, and may require safety precautions. Carbon Dioxide is an environmental friendly alternative, as it is non toxic and non flammable. In addition, the high density of CO_2 in gas-phase makes it possible to build smaller RSW systems with higher efficiencies.

The RSW-concept uses a refrigeration system to cool down sea water, which is then circulated in large tanks containing sea water and fish. The refrigeration system can be installed on board fishing vessels, and removes the necessity of carrying ice from shore (Wang et al, 2005; Jul, 1986), reducing weight during transport to the fishing location. A simple overview is shown in Figure 1. The fishing season for the Norwegian costal fleet can be divided in two:

- Herring fishing in autumn and winter when the sea water temperature is between 4°C and 12°C
- Mackerel fishing in late summer when sea water temperature is between 10°C and 20°C

The large variation in sea water temperature imposes different operation modes of the RSW plant. This is of particular importance for a CO2 plant, which will either be sub- or transcritical, depending on the temperature of cooling water.

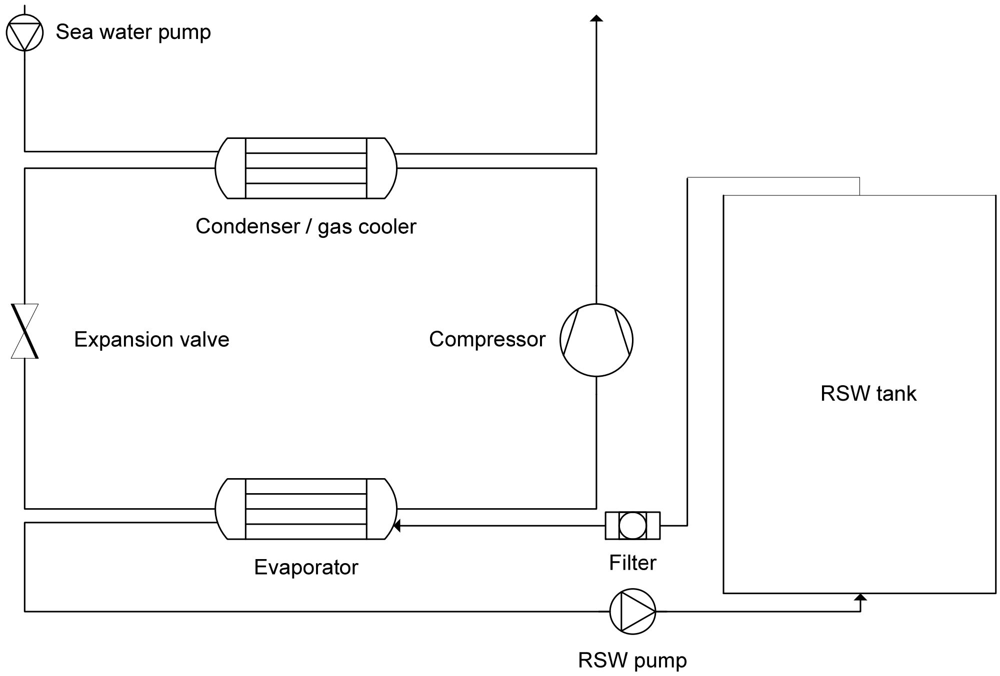

Figure 1: Simplified overview of a RSW system. The fish is suspended by an upward water flow.

In preparation for hauling fish, large onboard tanks are filled with sea water and pre-cooled using the refrigeration system. Caught fish is dumped into the tanks, which increases the temperature of the water. The refrigeration unit is used to circulate and cool the water, which cools the fish haul. The salt content of sea water allows the RSW water temperature to be chilled to -1.5 °C without freezing.

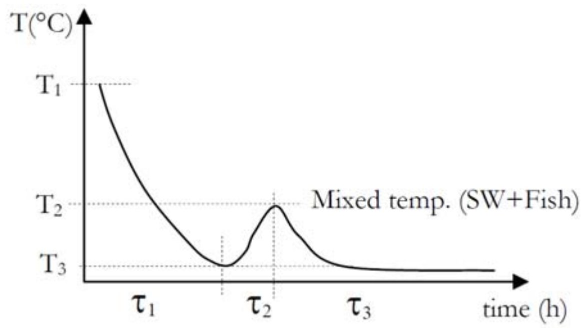

Figure 2: Initial refrigeration (time τ_1), temperature increasing caused by the fish haul (time τ_2) and decline as haul and water is refrigerated (time τ_3) (Thorsteinsson et al, 2003).

The EU Council Directive has given instructions for the maximum advisable time to cool fish haul: the temperature of the catch must reach 3°C within 6 hours and 0°C within 16 hours of hauling. RSW systems are generally not explicitly designed to meet those directives. Usually, the specification will only require a certain minimum cooling capacity at a nominal point of operation; the *design point*.

In this work, the design point requirements is specified to 400 kW cooling capacity at conditions:

- 0 ˚C RSW tank temperature
- -5 ˚C evaporation temperature
- 20 ˚C sea water temperature (cooling water for the condenser)

The catch is generally cooled as fast as possible in order to preserve the quality. There is generally more time available to perform the pre-cooling part of the process, fishermen report 6-12 hours as a typical time to perform this operation.

As illustrated in Figure 2, the pre-cooling of the RSW- tank requires a significant part of the total cooling energy. As there is no added value in fast pre-cooling, different control strategies for minimizing the energy consumption during pre-cooling will be analyzed. Simulations for the ambient conditions present during both summer and winter fishing seasons has been done. Optimized operation was sought for either minimal cooling time, or lowest energy consumption.

2. MODEL AND APPRAOACH

SINTEF has been working with CO_2 RSW systems over several years, a laboratory scaled prototype has been built and analyzed (Rekstad, 2010). More recently, the Norwegian fisherman association funded the design of an industrial demonstrator. The RSW plant was designed in the in-house simulation and optimization tool CSIM. CSIM is a circuit simulator for analyzing the behavior of both conventional refrigerant and transcritical CO_2 cycles. It can be used for steady state simulations, with all operation parameters and the component geometry fixed, or for optimization, finding a high side pressure, a compressor speed, component sizes and pump speeds that provide a desired capacity at maximum efficiency.

CSIM includes detailed heat exchanger models using actual geometry as input and calculating local values for the heat transfer coefficient, pressure gradient and void fractions at the desired level of discretization. For CO_2, the Span and Wagner (1997) equation of state was used to calculate thermodynamic properties. Transport properties were calculated from Vesovic et al. (1990) and Fenghour et al. (1998).

Component models and refrigerant cycle calculations generate a set of simpler constraint equations and an object function that are solved by using a general optimization package called NLPQL by Schittkowski (1985). NLPQL is an implementation of a sequential quadratic programming method for solving non-linear, constrained optimization problems. In CSIM, numerical differentiation for all equality and non-equality functions are used. CSIM is described in more detail by Skaugen (2002).

The refrigeration system is considered to be in equilibrium during cooling, which is a fair approximation to reality, due to rather slow cooling of the large RSW tanks. Steady state simulations were done in five different temperature intervals for the pre-cooling from 20°C sea water temperature. Three intervals were selected for 4 °C sea water. The time needed to cool down the 225 m^3 water contained in the RSW tanks was calculated from the simulation results from different stages of the chilling process, .

All simulations used the same heat exchangers. The evaporator was specified for an evaporation temperature of -5 °C at design point. Design of the gas cooler is a trade off between performance and cost (surface area). In the present study, the gas cooler was somewhat oversized for trans critical operation but did not perform completely satisfactory for sub critical operation due to temperature approach larger than 10K. Other boundary conditions:

- Evaporator water flow rate: 336 m^3/h
- Gas cooler/condenser water flow rate: 80 m^3/h

3. WARM SEA WATER, TRANSCRITICAL OPERATION

The system is designed to give 400 kW cooling capacity at 20 °C sea water temperature while cooling the RSW water from 0 °C to -1°C. The required compressor capacity in this design point was found by setting the high side pressure to 75 bars; which is a suitable pressure level for this heat sink temperature. If not otherwise specified, the design compressor capacity was held constant for all simulations of the pre-cooling process.

As the RSW water is cooled down from sea ambient temperature, the evaporation temperature will decrease, as illustrated in Figure 3**.** This will increase the pressure ratio, since the high pressure is held at constant. The resulting decrease in COP during the pre-cooling is illustrated in Figure 4. Since the design point is given at the lowest COP, the process will in general have a greater cooling capacity during pre-cooling than 400kW. This is also shown in Figure 4.

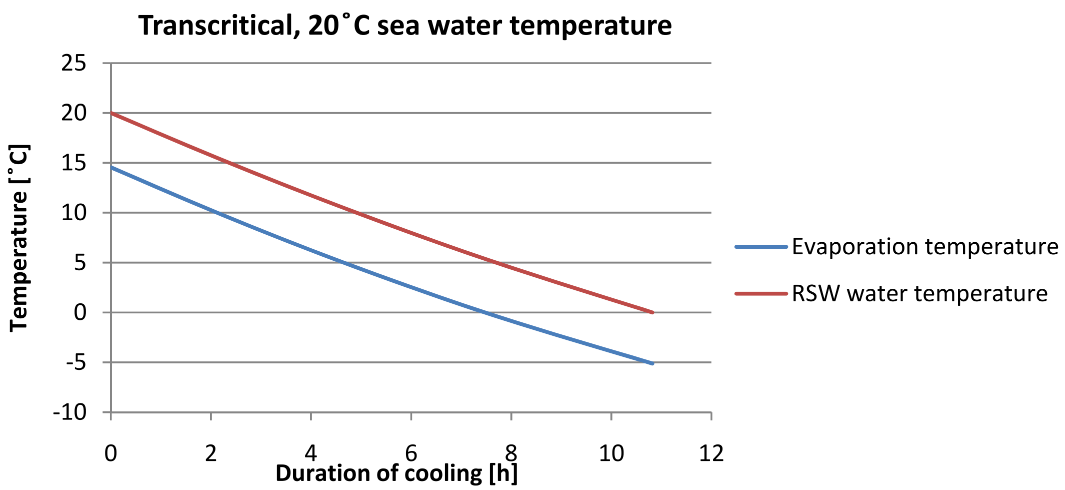

Figure 3: Evaporation and tank temperature at transcritical summer operation

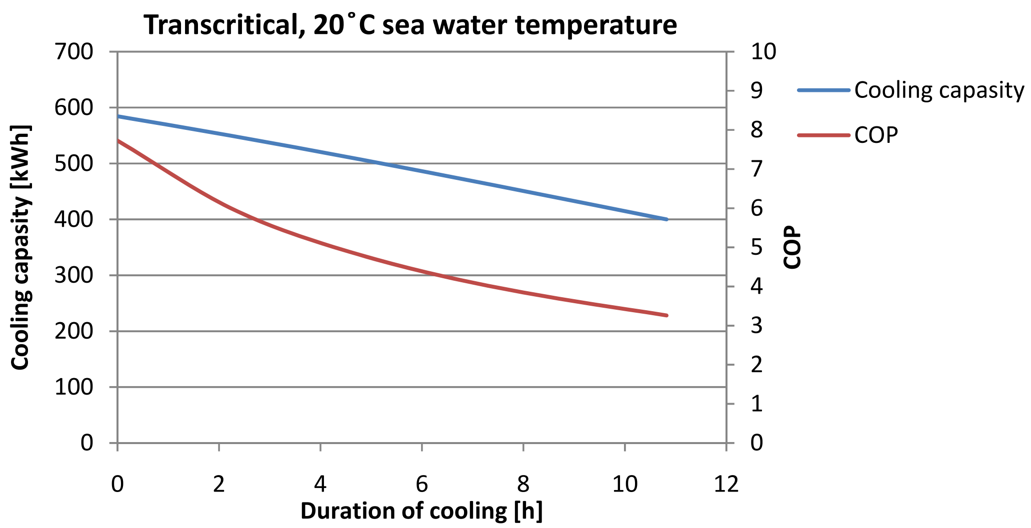

Figure 4: Cooling capacity and COP at transcritical summer operation

The simulation of summer operation pre-cooling shows an average COP of 4.7, and an accumulated compressor work of 1135 kWh. A duration of 10.8 hours would be necessary to cool down the water in the RSW tank from 20 °C to 0 °C. If a shorter pre-cooling time is needed, the cooling capacity can be increased at the cost of reduced COP by increasing the high side pressure.

4. COLD SEA WATER, LARGEST CAPACITY OR LARGEST COP

When the system runs in lower sea water temperatures (winter operation), the RSW can be operated in either transcritical or subcritical mode.

4.1 Transcritical operation

In the simulation of the transcritical operation at 4 °C sea water temperature, the high side pressure and the compressor speed was held at constant. The COP and the cooling capacity will decline during the pre-cooling as shown in Figure 5 and Figure 6. This illustrates the same tendency as previously described, but since the difference in temperature is smaller, the time required is shorter and the change in performance will be less. The reason for the change in slope (dotted line) is the part load of the compressor. If the sea water temperature is low, and the compressor is driven at full capacity, ice formation in the evaporator might occur as the evaporation temperature falls below -5°C. Hence the compressor speed was slowed down to reduce the risk of clogging.

The pre-cooling requires 2.2 hours, and needs 255 kWh of total compressor work, as shown in Table 1 .

4.2 Subcritical operation, optimum high pressure

Optimizations were done to find the condensation pressure which gave the optimum COP for each of three different water tank temperature levels. With these pressures and a constant compressor speed, the water tank cool down process was simulated. The average optimal condensation pressure was 55 bars. The change in COP and cooling capacity during the pre-cooling is shown in Figure 5 and Figure 6. As illustrated, the transcritical operation has a higher cooling capacity and a lower COP than the subcritical. The time needed for pre-cooling was estimated to 3.2 hours, half an hour more than in transcritical operation. The compressor work required was 208 kWh, see Table 1.

The gas cooler works well in transcritical operation and the temperature approach is very low. As a condenser it does not perform as well, which results in higher temperatures of the CO_2 out of the condenser and hence a lower cooling capacity. The average condenser temperature was between 17 °C and 19 °C even though the cooling water is as low as 4 °C.

4.3 Subcritical, optimum high pressure and refrigerant flow

Since the simulated pre-cooling time from 4°C was less than usually available, the system might be operated in a more energy efficient way than previously discussed. Simulations were done in CSIM where both rotational speed of the compressor and condensation pressure were allowed to change to improve the COP for the system. When the compressor speed is reduced, the mass flow decreases, allowing the evaporation temperature to increase while the condensation temperature decreases. The compressor work needed for the pre-cooling is then significantly reduced, due to the lower pressure difference. The lower mass flow naturally also yields a reduction in cooling capacity, and the pre cooling will hence require more time. The process illustrated in Figure 5 and Figure 6 will require a total time of 7.3 hours. This is less than the transcritical operation with cooling from 20 °C, and hence even a further optimization can be done if more time is available. As listed in Table 1 the pre-cooling will need 124 kWh of compressor work, and the overall COP obtained was as high as 8.6.

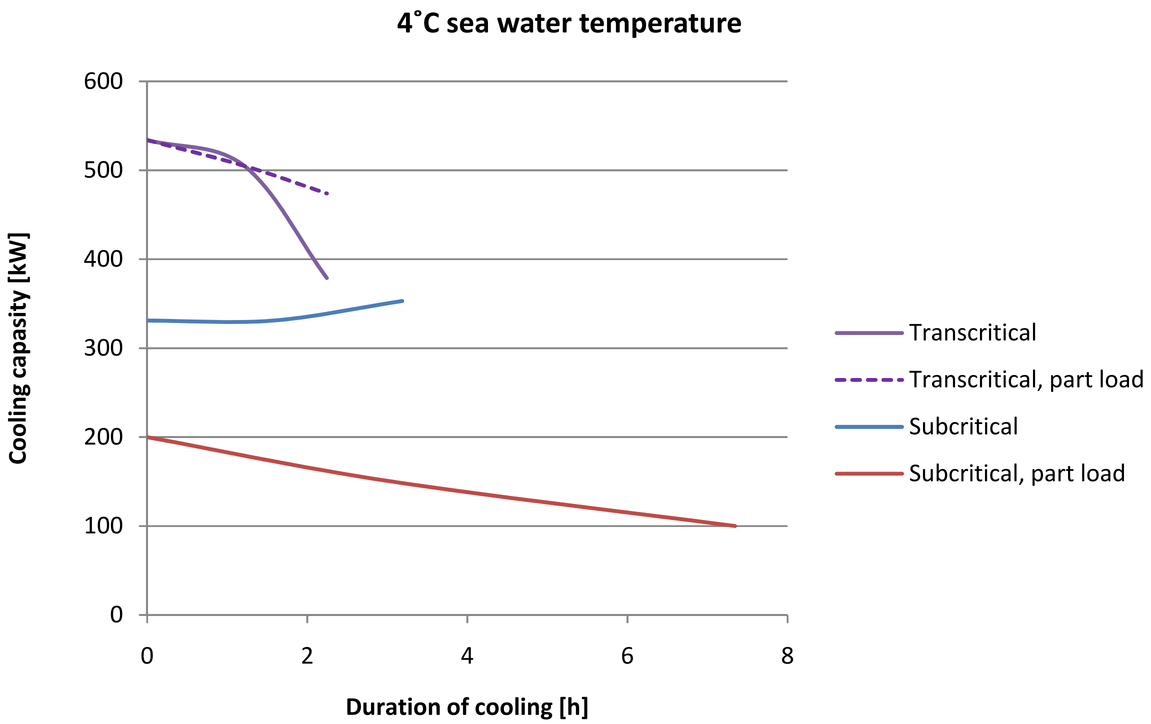

Figure 5: Transcritical and subcritical operation cooling capacity for winter ambient temperatures

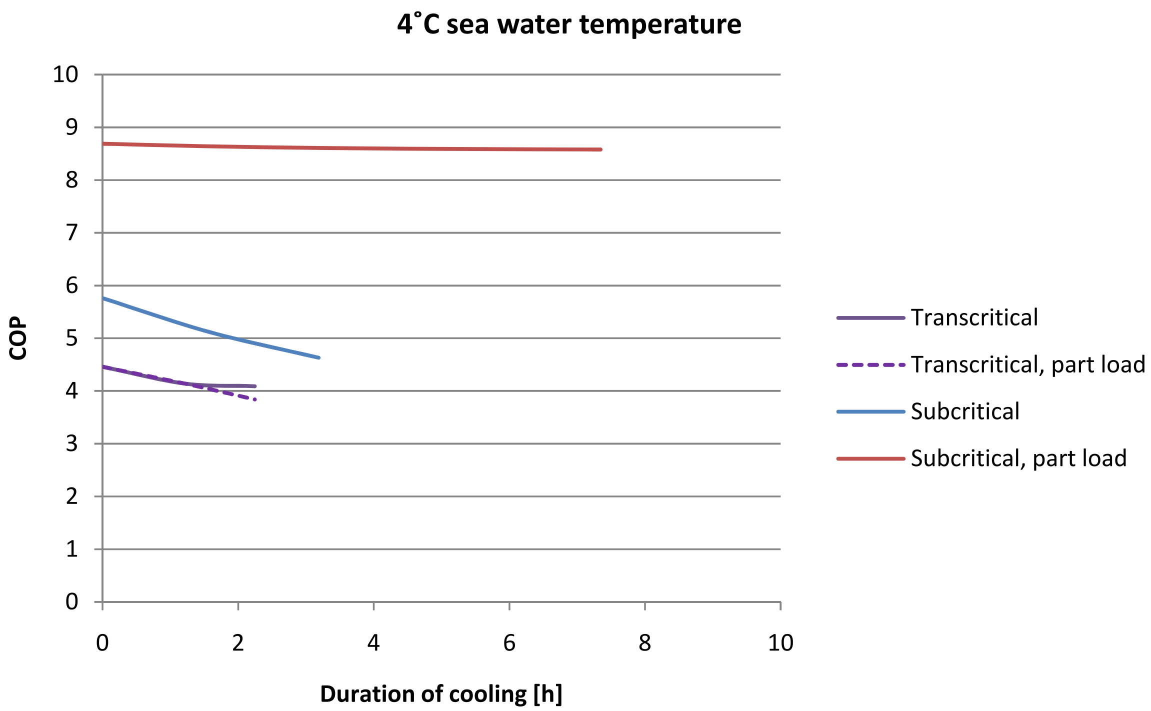

Figure 6: Transcritical and subcritical operation COP for winter ambient temperatures

Table 1

	Compressor work [kWh]	Time [h]	COP
20 ˚C sea water temperature			
Transcritical	1135	10.8	4.7
4 ˚C sea water temperature			
Transcritical	255	2.2	4.2
Subcritical	208	3.2	5.1
Subcritical, part load	124	7.3	8.6

5. CONCLUSION

When the sea water temperature is as high as 20 °C the cool down process of the RSW tank will last for 11 hours before the desired temperature is reached. The cooling capacity can be increased on expense of the COP if the high side pressure is raised. This might be necessary if the time available for pre-cooling is shorter than expected.

When the sea water temperature is low, 4 °C, the RSW can be operated in three different ways, depending on the time available before the catch is caught. The quickest cooling period of 2.2 hours is achieved with transcritical operation. Usually more time is available, and the energy cost can be reduced by operating the system subcritical at the same compressor speed. The cool down time was then estimated to 3.2 hours, and the COP of the process increased from 4.2 to 5.1. In the third way of operating the process, the condensation pressure was altered according to the decrease of the RSW tank temperature and the compressor was driven on part load. This solution gave a reduction in compressor work by as much as 40 % compared to the previous solution discussed. To reach the desired temperature the system required 7.3 hours, which still is less time than the cooling from 20 °C sea water temperature. The average COP for this solution was found to be as high as 8.6.

6. ACKNOWLEDGEMENT

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7. REFERENCES

Jul, M., 1986. Chilling and freezing fishery products: changes in views and usages. *Int. J. Refrig* 9 (1), 174-178.

Fenghour, A., Wakeham, W. A., et al., 1998. The Viscosity Of Carbon Dioxide. *J. Phys, Chem. Ref. Data* 27(1), 31-44.

Rekstad, H., Sætrang, S., Eikevik, T., Ladam, Y., 2010. Evaluation of a variable suction gas heat exchanger in a liquid chiller system using carbon dioxide as refrigerant. In *proceedings of 9th IIR Gustav Lorentzen Conference on Natural Working Fluids*, Sydney, Australia.

Schittkowski, K., 1985. NLPQL: A FORTRAN subroutine solving constrained nonlinear programming problems. *Annals Operations Research* 5, 485–500.

Skaugen, G., Nekså, P., Pettersen, J., 2002. Simulation of transcritical CO_2 vapour compression systems. In *proceedings of 5th IIR-Gustav Lorentzen Conference on Natural Working Fluids*, Guangzho, China

Span, R., Wagner, W. U., 1996. A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. *J. Phys, Chem. Ref. Data* 25(6), 1509-1596.

Thorsteinsson, J.A., Jensson, P., Condra, T., Valdimarsson, P., 2003. Transient simulation of refrigerated and chilled seawater system. In *proceedings of 44th Conference on Simulation and Modelling*, Vesteraas, Sweden.

Vesovic, V., Wakeham, W. A., et al., 1990. The Transport Properties Of Carbon Dioxide. *J. Phys, Chem. Ref. Data* 19 (3), 763-808.

Wang, S.G., Wang, R.Z., 2005. Recent developments of refrigeration technology in fishing vessels. *Renewable Energy*, 30 (4), 589-600.