REFRIGERATION SYSTEM FOR SRI LANKAN FISHING BOATS

W.K. Wimalsiri, D.A.W. Weerakoon, N.M.C. Weerasinghe, M.J.P. Fernando
Department of Mechanical Engineering
University of Moratuwa.

REFRIGERATION SYSTEM FOR SRI LANKAN FISHING BOATS

W.K. Wimalsiri, D.A.W. Weerakoon, N.M.C. Weerasinghe, M.J.P. Fernando
Department of Mechanical Engineering
University of Moratuwa.

ABSTRACT

The fisheries sector in Sri Lanka has been expanding during past decade with growing local demand and export of fish. In order to cope with the demand, the size of fishing boat used for multi-day, deep-sea fishing has now increased up to 60 ft. There are more than 1700 such boats working around Sri Lanka and building of such boats progress continuously. Most of these designs are based on the extension of small multi-day boats but no attention is paid to the technical feasibility of increasing boat capacity by scaling up the dimension to make the boat bigger. Although there are important factors and views to be discussed with regard to altering a design, such factors are beyond the scope of this research.

In view of the operation of these boats at least 2-3 weeks are needed to complete one voyage of fishing. However, the concept of fish preservation still remains conventional by using the ice cold fish hold that was used for small multi day boats. This method of fish preservation would have been economical for small boats that carry about 2-5 tonne of fish but as the boat size increases, preservation by ice may have following disadvantages.

a. Full capacity of fish hold cannot be used for storing fish
b. High fuel consumption at departure condition to carry considerable amount of ice.
c. Impossible to maintain an acceptable temperature inside the fish-hold.
d. Duration of fishing and amount of the catch is limited depending on available ice.
e. Operating cost of the vessel increases and the quality of fish becomes poor due to the all above factors.

Although there are refrigeration systems available in the foreign market, the cost and compatibility of such systems to local requirement are questionable. A system that satisfies required refrigeration capacity for a 40 ft boat costs about 1.5 million rupees.

Intention of this research is to investigate the economical feasibility of designing and construction of suitable refrigeration system to overcome the above problem.

INTRODUCTION

National development of fisheries is an important aspect of social and economic consideration of the country as Srilanka is an island that has a large sea area approximately 23 times of its land area. Also about 2% of the total employed population are engaged in fisheries related industry and there are aid programmes to distribute boats and other equipment to develop fisheries industry.

The following can be presented as objectives of development of fisheries sector in Sri Lanka.

1. To increase the nutritional status of the people of the country through the increase of per capita consumption of fish.
2. To promote optimum exploitation of Sri Lanka fisheries
3. To increase the income and standards of living of all those engaged in fisheries related industry.
4. To increase foreign exchange earnings through export of fish.

The above objectives can be achieved by improving the following key areas.

1. Competitive and technically sound boat manufacture and supply market in the country.
2. Methods and technology of fishing including fish finding methods.
3. Methods of fish preservation to maintain quality of caught fish.
4. Processing of fish for export markets.

However there are difficulties pertaining to the development of the industry as most of the people involve in the industry are less educated and relatively poor because of the uncertain and risky nature of the job. Most of the fishermen purchase their boats on government subsidy schemes and face lot of technical and navigational problem during operations.

Higher economical advantages can be achieved by harvesting the deep-sea fish resources covering Exclusive Economic Zone (EEZ) where a wide range of fish distribution is available. The most important fact that limits deep-sea fishing is the method of preservation of caught fish at sea.

Concepts of Fish Preservation at Sea

Fish lose quality because of either bacterial or enzymatic activity or both. Low temperature storage of fish reduces these changes significantly, delaying the spoilage and deterioration. Different methods can be used to preserve fish at sea. Some of these are limited to large vessels as they require large space and more technical facilities. On the other hand objectives of preservation may be different from that of small vessels. The following methods can be used to preserve fish.

a) Chilling b) Freezing c) Cooling using ice d) Cooling using cooled air

Let us consider freezing in detail as freezing is the basic concept of preservation and the process has number of common features to the other cooling methods of fish.

Process of freezing

Fish contain largely water, normally 60-80% and freezing process converts most of the water into ice. Stages during freezing can be illustrated as given in figure 1.

Stage 1

During the first stage of cooling the temperature falls fairly rapidly to the freezing point of fish around -2^0C.

Stage 2

The bulk of water becomes ice during this stage and the temperature change is very little while the heat to be extracted is almost equal to the latent heat of water. The remaining liquid becomes a stronger solution of salt water and other chemicals naturally present in the fish muscles.

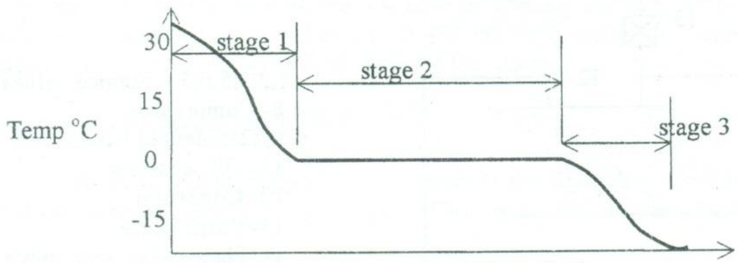


Figure 1. Temperature variation during Freezing

Stage 3

When 75% of water is turned into ice the temperature again begins to fall and during this stage most of the remaining liquid freezes. In this stage a comparatively small amount of heat is removed.

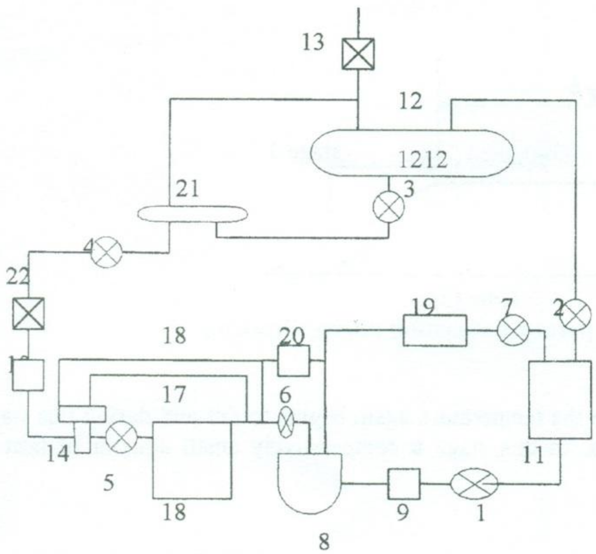
Effect of Cooling Rate

The rate of cooling can be changed by using different methods of freezing. The freezing method and rate of cooling affect the quality and appearance of fish and also cost of freezing. Several theories have been developed on the relative effect of freezing rate on quality of fish.

A block of fish does not freeze uniformly because heat is removed from the out side of the block by any method of freezing. The heat at the center of the block travels outward to the surface thus the block freezes from out side to inward. The rate of freezing depends on the thickness of the block and rate of removal of heat. As the temperature of the fish muscle falls below its freezing point, ice crystal begins to form throughout the tissue. The size of these crystals depends upon the rate of freezing. In fish muscle that cools rapidly from -1 to –10°C, in less than half and hour, for example, very small ice crystals are formed within the structure of cells of the flesh and subsequently very little changes to the flesh when the product is thawed. But prolonged time of freezing may result in much larger ice crystals in the spaces between the cells, disrupting the muscle structure and subsequently damaging the texture after thawing. Tests have shown that the above undesirable change is noticeable only when the time taken to cool the center of a block of fish from -1 to –10°C exceeds four hours.

PROPOSED REFRIGERATION SYSTEM

The proposed refrigeration system is a vapour compression refrigeration system. The system is to be introduced to an ice-cooled fish hold of a 34ft fishing boat. Fish hold extends over the breadth of the boat to 3.8m and approximate volume is15 m^3(5 tonne of fish). The refrigeration system consists of following components.



1,2,3,5,6,7 – Service valves
8- Compressor
9,22-Solenoid valves
11- Oil separator
12- Condenser
13- Purge valve
14-Thermostaic exp. valve
15- Strainer
16-External equalizer
17- Bulb
18-Evaporator
19-Muffler
20-Pressure cutout
21-Purge type receiver
22-Liquid line indicator
23- Equalizer

The project involves the designing of evaporator and condenser depending on the cooling load and heat load. The evaporator, condenser unit and other piping can be produced locally to suit the individual boat configuration. Other accessories are to be purchased from the manufactures.

Design of Evaporator

Estimation of Freezing Time

Modified Plank's equation is used to estimate the freezing time

$$T = [1 + 0.008(t_i - t_f)]\left[\frac{\Delta h.\Delta t}{v}\right]\left[\frac{p\Delta x}{f_g} + R\frac{\Delta x^2}{K}\right]$$

The cooling time depends on many variables and constant as given in the above equation. Some of these variables are uncertain and the effect of these variables on the cooling time T is analyzed and the results are in Table 1. The final temperature t_f is the temperature to be maintained at the end of freezing and it is assumed to be an average between cooling medium temperature and initial freezing temperature.(see appendix for more detail)

Table 1 shows the estimation of T for t_i = 28°C,t_f= -8°C, k = 1.8W/mK, v = 0.001m^3/Kg and Δx = 15cm for different air velocities and assumed cooling medium temperature.

Air Velocity (m/s)	**T (hrs) for different cooling medium temperature -12 °C**	**-14°C**	**-16°C**
1.0	25.624	21.234	18.791
2.0	19.901	16.984	14.597
3.0	16.755	14.231	12.287
4.0	14.774	**12.453**	10.834

Table 1:- Freezing Time for different cooling medium temperature

Freezing time decreases with the increase in cooling medium temperature and the inside air velocity. Freezing time is taken as 12.453 hrs with inside air velocity of 4m/s and cooling medium temperature of –14oC, to continue the design.

Estimation of Cooling Load

The total cooling load required is estimated in the following quantities considering all losses. The associated variables and estimation of heat quantities are described in the appendix.

a) Cooling load of fish above freezing point
b) Latent heat to be removed during freezing
c) Cooling load below freezing point
d) Heat leakage through insulation
e) Infiltration heat load
f) Heat load due to electrical appliances
g) Heat load due to unaccounted losses

Table 2 shows the variation of cooling load with the cooling medium temperature and air velocity inside fish hold. The compressor is selected from the manufacturer's catalogue for refrigeration capacity of 3.762 kW.

Air Velocity (m/s)	**Q (kW) for different Cooling medium temperature**		
	-12 °C	**-14°C**	**-16°C**
1.0	3.702	3.754	3.810
2.0	3.706	3.758	3.815
3.0	3.708	3.760	3.817
4.0	3.709	**3.762**	3.819

Table 2:- Cooling load for different cooling medium temperature

Estimation of Evaporator Tube Dimensions

Evaporator tube diameter and length depend upon the cooling medium temperature and the refrigerant flow rate inside the tubes. Heat removed by the evaporator depends upon inside and outside heat transfer coefficients of tubes and type of evaporator. Appendix explains the calculations involved in design of evaporator and the influence of some variables and constants on the evaporator tube dimensions. Also it is necessary to identify the arrangement of tubes. Selected evaporator is a *two tubes pass plate* type evaporator that fulfills the following requirements.

- To maintain required air velocity at evaporator plates between 2-5m/s to avoid frosting and dehydration of fish.
- To satisfy required cooling time estimated in the previous section
- To satisfy acceptable refrigerant flow rate
- To maintain cooling medium temperature within the evaporator at required level
- Fish hold dimensions

Following table shows the variation of evaporator tube length with inside air velocity, inside temperature for a particular tube diameter and a cooling medium temperature.

For tube Diameter (D) = 15 mm

Air Velocity (m/s)	Length of evaporator tube for cooling medium temp. of –16°C when inside temperature varies from		
	-12°C	-14°C	-15°C
1.0	53.162	107.82	217.330
2.0	28.997	58.815	118.548
3.0	20.340	41.256	83.158
4.0	15.815	32.078	64.658

Table 3:- Variation of length of evaporator-tube with temperature of inside air and inside air velocity

For tube Diameter (D) = 17 mm

Air Velocity (m/s)	Length of evaporator-tube for cooling medium temp. of –16°C when inside temperature varies from		
	-12 °C	-14°C	-15°C
1.0	46.458	94.227	189.922
2.0	25.340	51.398	103.598
3.0	17.775	36.054	72.671
4.0	13.820	28.033	56.504

Table 4:- Variation of length of evaporator-tube with temperature of inside air and inside air velocity

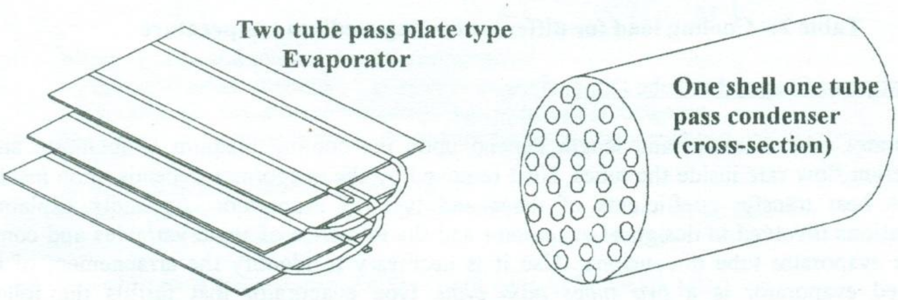


Figure 2:- Arrangement of the Evaporator and Condenser

Design of Condenser

Calculation are carried out to find the dimension of a one shell one tube pass seawater- cooled condenser because it is simple to construct and more effective than multi-pass condenser. Seawater- cooled condenser is smaller in size compared to air-cooled type. Designing involves the determination of diameter and length of the tube and seawater flow rate. Usually the amount of heat to be rejected by the condenser is found by multiplying the system capacity by a factor known as heat rejection factor. This factor depends upon the type of compressor used, the evaporator temperature and the condenser temperature (see appendix).

Selection of Compressor and other Accessories

Compressor and other accessories are selected from manufacture's catalogue. Other accessories receiver, oil separator, liquid indicator, solenoid valve, service valves and high pressure and low -pressure cutout are commonly available in the market.

ECONOMIC FEASIBILITY OF THE PROPOSED SYSTEM

The ice-cooled fish hold to be replaced with the proposed system and the economic feasibility is analyzed against the prevailing method of fish preservation. The cost components given in Table 5 are taken into consideration and the total cost is calculated per annum excluding the building cost of the boat. The total operating costs always depends on the number of trip per annum that in turn depends upon the average speed of operation.

Costs of proposed refrigeration system

	Component	Cost(Rs)
1.	Compressor	68,000.00
2.	Compressor drive	16,000.00
3.	Motor protection & switching	7,000.00
4.	Condenser	20,000.00
5.	Evaporator	80,000.00
6.	2 Fans	10,000.00
7.	Pipes and Fittings	8,000.00
8.	Service/Relief/Solenoid valves	6,500.00
9.	Thermostatic expansion valve	7,000.00
10.	Muffler	6,500.00
11.	Pressure cut-outs	5,000.00
12.	Receiver	4,000.00
13.	Oil separator & drier	15,000.00
14.	Thermostats(2 Nos)	7,000.00
15.	Liquid line indicator	1,000.00
16.	Water pump	7,000.00
17.	Generator	200,000.00
18.	Installation costs	40,000.00
		501,000.00

	Ice cooled fish hold	Refrigerated fish hold
Boat type	34 –feet	34 feet
Engine	50 hp	50 hp
Fuel consumption	7 ltres/hr	7 ltres/hr
Light weight(including fish. Gear)	6.0 tonne	6.7 tonne
Weight consumables	2.5 tonne (except ice)	2.5 tonne
Weight of ice	4.0 tonne	-
Av. Weight at departure condition	*12.50 tonne*	*9.2 tonne*
Av. Speed during departure	7.0 knots	7.84 knots
Distance travel (one way)	800 nautical miles	800 nautical miles
Duration of travel (hrs)	114.25	102.00
Fuel consumption (ltrs)	**799.75**	**714.0**
Duration of fishing (hrs)	72.0	72.0
Fuel consumption during fishing (ltrs)	**250.0**	**258.0 (include. ref. System)**
Weight of fish	5.0 tonne (with 1 tonne of ice)	5.0 tones(without ice)
Av. Weight at arrival condition	*11.5 tonne (1tone of ice remain, 2 tonne of consumable used)*	*12.2 tonne(2 tonne of consumable used)*
Av. Speed during arrival	7.14 knots	7.07 knots
Duration of travel (hrs)	112.0	113.0
Fuel consumption (ltrs)	**784.0**	**791.0**
Total fuel consumption per trip	**1833.75**	**1753.0**
Duration of a trip (days) (with 2 days of idle time)	14.41	13.95
Number of trip per annum	20	22
Annual catch (tonne)	80	110
Fuel cost per annum (Rs) @ 13.2 Rs per ltr	***484176.00***	***509071.00***
Ice cost per annum @ 90 Rs per 50 kg	***144000.00***	--
Maintenance cost of ref. System @ 5% of Building cost	--	***23500.000***
Total operating cost	***628176.00***	***532571.00***
Total operating cost per year per tonne of caught fish	***7852.00***	***4841.00***
Saving per tonne of caught fish		***3011.00***
Fish to be caught to recover the cost of refrigeration unit		***166 tonne***
Duration for recovery		***1.5 years***

Table 5. Comparison of operational costs of two methods.

CONCLUSION

The design and analysis demonstrate the possibility of altering dimensions of the evaporator depending on the fish hold dimensions for optimum utilization of the space allocated for the evaporator coil. The condenser size can also be altered to satisfy any space limitation by changing the pump capacity or number of tubes. In view of the above, there is flexibility in designing the evaporator and condenser satisfying the requirements and limitation of any boat.

It is concluded from the cost benefit analysis that the proposed refrigeration system is very much beneficial to the deep sea fishing boats compared with ice cooled fish hold. Table 5 shows that the cost of the refrigeration unit can be recovered in 18 months of operation of the boat. In addition there are other advantages and benefits that are not quantified on the proposed system of fish preservation. The duration of fishing can be extended until fish hold is fully utilized which is not possible when ice is carried to preserve fish. The fish hold temperature can be maintained at a constant value so that quality of fish remains at highest level. Improved quality of fish increases the return on investment.

References

1. FAO Fisheries Technical Paper No. A 75
2. Small Off-shore fishing boats in Sri lanka-Bay of Bengal Program Rept/61
3. G.H.O. Burgess, C.L. Cuting, S.A. Lovern , Fish Handling & Processing
4. ASHRAE Guide & Data Books on a) Equipment, b)Fundamentals, c) Applications and d) Systems
5. C.P. Arora, Refrigeration and Air Conditioning, Tata, McGRAW-HILL, 1981
6. M.Prasad, Refrigeration and Air Conditioning, WILEY,1983
7. A.R. Trott, Refrigeration and Air Conditioning, London, Butterworths, 1989,2nd Edition.

Appendix

1.0 Estimation of freezing time

Modified Plank's equation is used to estimate the freezing time

$$T = [1 + 0.008(t_i - t_f)]\left[\frac{\Delta h.\Delta t}{v}\right]\left[\frac{p\Delta x}{f_g} + R\frac{\Delta x^2}{K}\right]$$

Where T = Cooling Time, t_i = 28°C- initial temperature of fish,

t_f = (-1-14)/2=-7.5°C- average temperature between freezing temperature and cooling medium temperature

Δh= 250 kJ/kg heat extracted between initial and final temperature

Δt = -1 -(-15) = 14 - temperature difference between initial freezing temperature and cooling medium temperature

Δx = 0.15 m thickness of the product (fish)

P = ¼ for cylindrical shape and is a constant

R = ¼ for cylindrical shape and is a constant depending on the condition of storing fish.

f_g = 25.88 W/m²K - heat transfer coefficient of inside air (depends upon inside air velocity)

k = 10 W/m K - thermal conductivity of fish

v = 1/900 m³/kg specific volume of fish

for above values T =12.453 Hrs

2.0 Estimation of cooling load

a) Cooling load of fish above freezing point is given by

$$Q_1 = mC_1(t_i-t_s)/T = 0.52 \text{ kW}$$

m = 200 kg - catch rate (kg) per T,

C_1 =4.02 kJ/kgK - thermal conductivity of fish above freezing point

t_i =28°C– initial temperature of fish, t_s = -1° C– freezing temperature of fish

T –12.453 hrs - freezing time

b) Latent heat load to be removed during freezing

$$Q_2 = m\,L/T = 1.11 \text{ kW}$$

L =250 kJ/kg– latent heat of fish per kg

c) Cooling load below freezing point

$$Q_3 = m\,C_2\,(t_s - t_f)\,/T = 0.047 \text{ kW}$$

C_2 =1.62 kJ/kg K– thermal conductivity of fish below freezing point

t_f = - 8°C– freezing temperature of fish below freezing point

d) Heat leakage through insulation

$$Q_4 = U\,A\,(t_o - t_i)\,/T = 0.494 \text{ kW}$$

U – overall heat transfer coefficient across the wall of the fish hold

A = 47.029 m² - total surface area of the wall of the fish hold

U =0.292 W/m K for fish hold's wall made out of following layers

Material	Thickness	Thermal Conductivity
FRP	8mm	0.036 W/mK
Polyurethane	100mm	0.042 W/mK
FRP	5mm	0.036 W/mK
Air gap	5mm	0.027 W/mK
FRP	8 mm	0.036 W/mK

e) Infiltration heat load

$$Q_5 = Vn\,(h_o - h_i)\,/v_a = 0.649 \text{ kW}$$

$V = 14.9\ m^3$ - total volume of air inside the fish hold,
$n = 30$ per day – number of air changes (number of openings of the fish hold hatch)
$h_i = 5.1$ kj/kg - enthalphy of inside air, $h_o = 116$ kJ/kg - enthalphy of outside air
$v_a = 0.9\ m^3/kg$ – specific volume of air

f) Heat load due to electrical appliances inside fish hold
Q_6 ==0.6 kW -Total power of appliances inside fish hold
½ kW two blowers and 0.1 kW 4 bulbs

g) Heat load due to unaccounted losses
Q_7 = 10% of the total load =0.1 x 3.42 = 0.342 kW

Total cooling load required $Q = \sum_{1}^{7} Q_i$ = **3.762 kW**

The refrigeration capacity of 3.762 kW and the evaporator temperature can be used to select the appropriate compressor for the system.

3.0 Evaporator design.

3.1 Heat transfer coefficient between refrigerant and evaporator tubes

Heat transfer coefficient inside evaporator tube $h_i = Ch_f \left[\frac{1}{I_t}\right]^n$

Where $I_t = \left[\frac{1-x}{x}\right]^{0.9} \left[\frac{\mu_f}{\mu_g}\right]^{0.9} \left[\frac{\rho_g}{\rho_f}\right]^{0.5}$ and $h_f = 0.023\ \text{Re}^{0.8}\ \text{Pr}^{0.3} \frac{k}{D}$

μ_f and μ_g - viscosity of liquid and gaseous refrigerant
ρ_f and ρ_g – density of liquid and gaseous refrigerant
x - dryness fraction, C - 3.5 for R-12, Pr - Prandtl number
Re- Reynolds number, k - thermal conductivity of refrigerant, D - pipe diameter

3.2 Heat transfer coefficient between evaporator tubes and surrounding air

Heat transfer coefficient outside evaporator tube $h_o = C_1 \left[\frac{V_{max} D}{\nu}\right]^n \text{Pr}^{0.33} \frac{k_a}{D}$

Where $V_{max} = \frac{s}{s-D} V$

$C = 0.396$ and n=0.584 are depend upon the arrangement of the evaporator
ν - kinematic viscosity of refrigerant, V- inside air velocity and k_a- thermal conductivity of air
s - vertical distance between tubes

3.3 Overall heat transfer coefficient (U) between refrigerant and surrounding air

$$\frac{1}{U} = \frac{1}{h_i} + \frac{r}{k_t} + \frac{1}{h_o}$$

k_t - thermal conductivity of tube material and r – wall thickness of the tube
h_i and h_o are inside and outside heat transfer coefficients of the media.

3.4 Length of evaporator tubes

If the evaporator tube length is given by L, the total cooling load to be transmitted

$$Q = \pi D^2 L\, U(t_o - t_m)$$

Selecting a two tube-plate type evaporator

Cooling load without plate = Cooling load with plate x K

Where $$K = \tanh \left(u \sqrt{\frac{2\, h_i}{k_a t}} \right) / \left(\frac{h_i A}{k_a p} \right)^{1/2}$$

A-Cross sectional area of plate, t - thickness of plate, p - perimeter of plate and
$u = 5D$ – width of plate

Following table shows the variation of evaporator tube length with inside air velocity, inside temperature for a particular tube diameter and cooling medium temperature.

5.0 Condenser design

Heat to be rejected = Heat rejection factor x System cooling load capacity
Heat rejection factor depends upon type of compressor, evaporating temperature and condensing temperature. This factor was selected as 1.32 for a condenser temperature of 40°C.

Water side heat transfer coefficient $$h_i = 0.023\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.3}\ \frac{k}{D}$$

Shell side heat transfer coefficient $$h_o = 0.725 \left[\frac{k_f^3 . \rho_f^3 . g . h_{fg}}{N.D.\mu_f.\Delta t} \right]^{0.25}$$

Where k_f - thermal conductivity of liquid refrigerant
ρ_f - density of liquid refrigerant , g- acceleration of gravity
μ_r - dynamic viscosity of liquid refrigerant, h_{fg} - latent heat of refrigerant
Δt – temperature different between tube wall and the condensing temperature

To find tube wall temperature $Q = A(t_w - t_b)/f_c$
Q – heat to be removed, A – surface area of tubes, t_w – tube wall temperature
t_b – bulk mean temperature of sea water., f_c – sea water fauling factor = 9×10^{-3} m^2.°C/W

To find length of the condenser tube $Q = U\, A[(t_c-t_i)-(t_c-t_f)/\ln\{(t_c-t_i)/(t_c-t_f)\}]$
Where t_c – condenser temperature, t_I - sea water inlet temperature, t_f – sea water outlet temperature