Modelling Of Multi-Stage Flash Process for the Production of Potable Water from Seawater

by

Ahmad Zulhusni Bin Abdollah

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

MAY 2011

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Modelling Of Multi-Stage Flash Process for the Production of Potable Water from Seawater

by

Ahmad Zulhusni bin Abdollah

A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

____

(Dr. Shuhaimi Mahadzir)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained here have not been undertaken or done by unspecified sources or persons.

AHMAD ZULHUSNI BIN ABDOLLAH

Abstract

Nowadays people are moving towards renewable source to ensure the sustainable development. Many new green technologies have been introduce in order to sustain the development had been done by human. There are a few method of desalination that is multi stage flash desalination, multiple effect distillation, and reverse osmosis. In this paper, we have discussed one of method to produce potable water from sea water, which is multistage flash desalination. The main focus in this paper is the modelling of multistage flash desalination process. This is because MSF is applied in real world compare to other type of desalination. Many papers had been published for MSF in the Middles East but none had been done for South East Asia. This paper is focused on environment in Malaysia, using the characteristic of the Malaysia seawater at different temperature, pressure and salinity. Moving on we have study the market price of water in Malaysia and the price for desalination water. After that we had develop the simulation of multistage flash desalination using mathematical method with the aid of Microsoft Excel, MATLAB. We started the modelling by developing a mathematical method. Next we set the parameters and run the modelling. The total distillate yield is 1653m^3 /hr that are 16.53% of the initial water intake. In the final part we had discuss the thing that can be improve this model.

Acknowledgement

First and foremost, I would like to thank Allah the Almighty for constantly strengthen and enlighten the every step through the project and make all things possible in the end.

I wish to express our sincere gratitude to my Supervisor, Dr Shuhaimi Mahadzir, for his invaluable knowledge, guidance, and support during my final year project. He had done a tremendous job in monitoring and guiding me throughout the project which I have learnt many things from him throughout my FYP.

Besides that I would like to thanks to chemical engineering department lecturers especially to all the external and internal examiners whom assessing my project for their willingness to help and guide me in their area of specialty. Their experience, knowledge and view on the project have given me a better outlook in my FYP.

Last but not least, I was really indebted to all individuals has contributed and has been a great aid to the completion of the project. Hence, I would like to take the opportunity to express my sincere appreciation and gratitude to whom that has been supportive and helpful.

Thank You

Contents

Appendices

List of Figures

List of Tables

Abbreviation and Nomenclatures

MSF = Multi Stage Flash Desalination

M = Seawater flowrate

T = Seawater temperature

X = Salinity of seawater

P= Pressure of system

Q= Heat

BPE=Boiling Point Elevation

NEA= Non Equilibrium Allowance

S =Salinity

CHAPTER 1

INTRODUCTION

1.1 Background

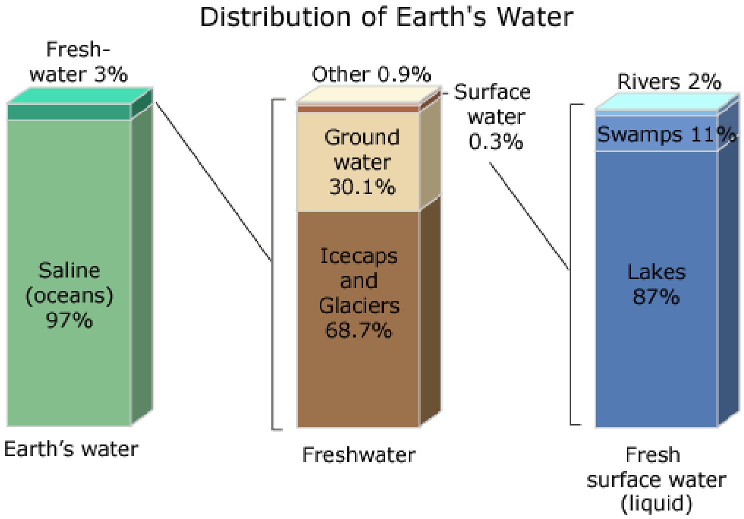


Figure 1: Global Water Distribution[10]

Water has always been earth's most valuable resource. All ecosystems such as animals, plants, and humans depend on water for their daily activities such as for food, cleaning, process plant and etc. Although the world is covered by 71% of water, the access for the fresh water is limited because 97.5% of the global stock of water is saline and only 2.5% is fresh water. Furthermore out of 2.5% fresh water that is available, 80% of this global freshwater stock is locked up in polar icecaps or combined as soil moisture. (See Figure 1) The main sectors that consume water are:

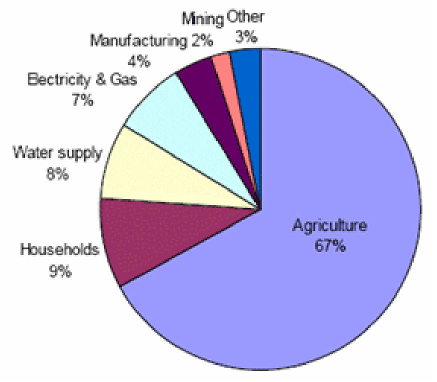


Figure 2 : Pattern of Water Consumption

From figure 2 we can see that agriculture has consumes most of water that is 67 and industrial has come to second with total 24%. By increasing in the number of population and growth of industries this kind of trend was expected to be change. In order to show their effort on to conserve the natural resources use a few global companies has started to report their total water consumption in their sustainability report to show their commitment to ensure the supply of water is can sustain much longer. Figure 3 shows PETRONAS domestic operation water consumption as per reported in their 2010 Sustainability Report.

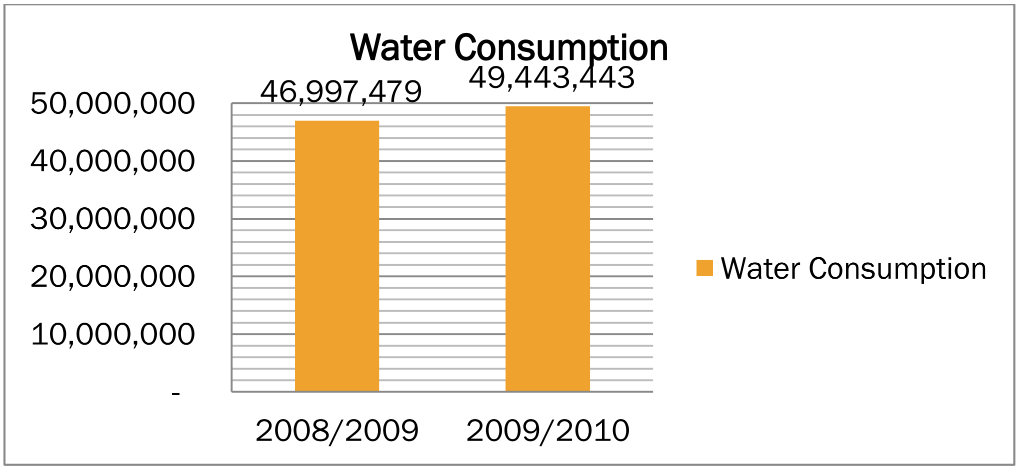


Figure 3: PETRONAS Water Consumption for 2 Years [9]

Human has invented in desalination using a few method s that are:

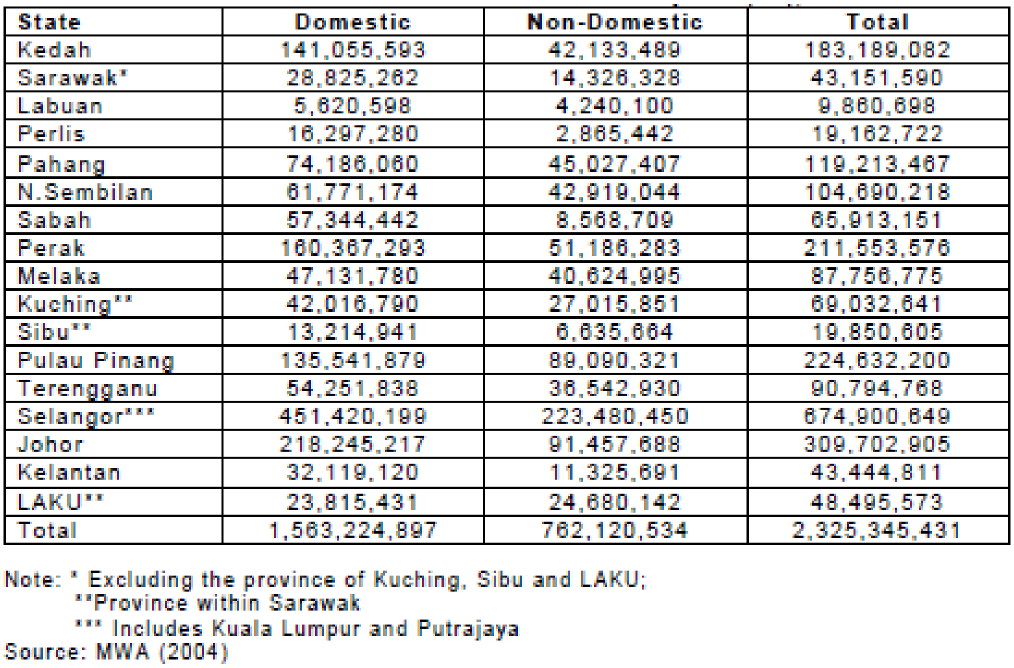
1. Multi Stage Flash Desalination
2. Multiple Effect Distillation
3. Reverse Osmosis

In this paper we will further discuss on the Multi Stage Flash Desalination process.

1.2 Problem Statement

The number of populations and industries are increasing from year to year and the world will be expecting to face shortage in fresh water supply. Since 1900, more than 50% of the world's wetlands have disappeared .By the year 2025, 48 countries will be affected by water stress or scarcity, affecting around 35% of the projected global population in that year. Only 64 of the world's 177 large rivers (1,000km and longer) remain free-flowing, unimpeded by dams or other barriers [7]. Table 1 show the water consumption in Malaysia in m^3 according to state.

Table 1 :Malaysia Water Consumption According to State



State	Domestic	Non-Domestic	Total
Kedah	141,055,593	42,133,489	183,189,082
Sarawak*	28,825,262	14,326,328	43,151,590
Labuan	5,620,598	4,240,100	9,860,698
Perlis	16,297,280	2,865,442	19,162,722
Pahang	74,186,060	45,027,407	119,213,467
N.Sembilan	61,771,174	42,919,044	104,690,218
Sabah	57,344,442	8,568,709	65,913,151
Perak	160,367,293	51,186,283	211,553,576
Melaka	47,131,780	40,624,995	87,756,775
Kuching**	42,016,790	27,015,851	69,032,641
Sibu**	13,214,941	6,635,664	19,850,605
Pulau Pinang	135,541,879	89,090,321	224,632,200
Terengganu	54,251,838	36,542,930	90,794,768
Selangor***	451,420,199	223,480,450	674,900,649
Johor	218,245,217	91,457,688	309,702,905
Kelantan	32,119,120	11,325,691	43,444,811
LAKU**	23,815,431	24,680,142	48,495,573
Total	1,563,224,897	762,120,534	2,325,345,431

Note: * Excluding the province of Kuching, Sibu and LAKU;
**Province within Sarawak
*** Includes Kuala Lumpur and Putrajaya
Source: MWA (2004)

With the 70% of the world is being covered by seawater, studies had been made to produce fresh water from sea water. Multi stage flash is one of the desalination processes to produced fresh water from seawater. At Malaysia there is still no study had been done on MSF. In order to develop the model of MSF first we have to study the characteristic of the sea water as it change due to the salinity and the temperature.

1.2 Objective and Scope of Study

The objectives of this study are:

1. The study on characteristic of seawater and it properties
    - We will study on:
        a. Vapor Saturation Pressure
        b. Boiling Point Elevation
        c. Latent Heat of Evaporation
        d. Specific Enthalpy
        e. Specific Heat at Constant Pressure
2. To design multistage flash desalination process that focused on the total distillate yield, final temperature and salinity of the brine.
3. To find potential improvement in MSF in term of cost, method, or energy efficiencies.

CHAPTER 2

LITERATURE REVIEW

2.1 Seawater Properties

To undergo this project first we need to know the properties of the seawater and different temperature, pressure and salinity.

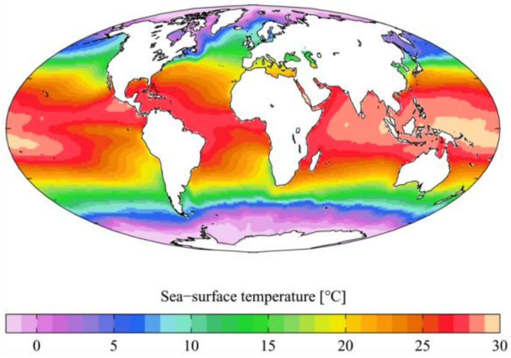


Figure 4 : World Sea-Water Temperature Plot

Figure 4 shows the plot of world sea water temperature. From figure 4 we can see that Malaysia is located at the area with temperature >30^{0}C. From that it had been agreed to take Malaysia sea water temperature is 32^{0}C.

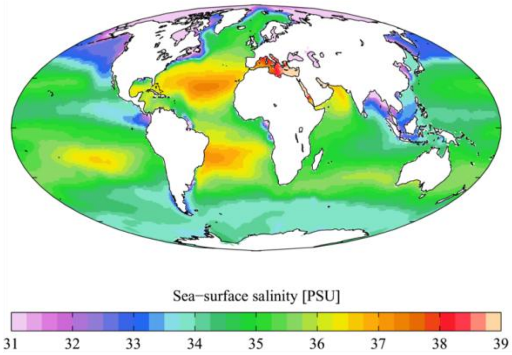


Figure 5 : World Sea-Water Salinilty Plot

Figure 5 shows the plot of salinity for world sea water. From figure 5 we can see that Malaysia is located at the area with salinity between the range (33-35)g/kg. From that it had been agreed to take Malaysia salinity is 35g/kg.

Table 2: Malaysia Sea Water Properties

Malaysia Sea-Water Properties	
Temperature	32 °C
Salinity	35 g/kg

For Malaysia area we can see the average temperature and salinity from table 2. These mean that every kg of seawater there is 35g of dissolved salt that contributed from different elements. Due this dissolved salt the seawater become denser compared to fresh water.

Table 3 : Component and Percentage in Sea Water Salinity

Component	Concentration in ppm	% of Total Salinity
Chloride	19.345	55.03
Sodium	10.752	30.59
Sulfate	2.701	7.68
Magnesium	1.295	3.68
Calcium	0.416	1.18
Potassium	0.390	1.11
Bicarbonate	0.145	0.41
Bromide	0.066	0.19
Borate	0.027	0.08
Strontium	0.013	0.04
Flouride	0.001	0.003
Other	<0.001	<0.001

From table 3 we can see the components that contribute to the salinity of seawater. We can see that chloride has the highest mass percentage that contributes to the salinity of seawater. Besides that another factors that contributes to the salinity of seawater is the rate of evaporation or precipitation in an area. If there is more evaporation than precipitation then the salinity increase meanwhile if there is more rain in an area the salinity will decreases. So to produce fresh water from seawater we need to reduce the salinity to <0.5g/kg as shown in figure 6.

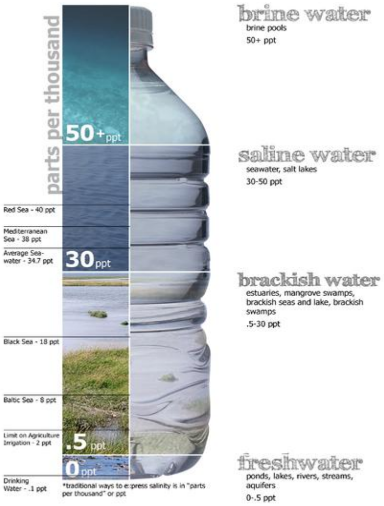


Figure 6 : Water Type According to Salinity

After we know the temperature and the salinity of the seawater, we need to know the physical properties of seawater such as, specific heat, latent heat of vaporization, saturated pressure and Boiling Point Elevation. All of these properties were important in order to model a MSF.

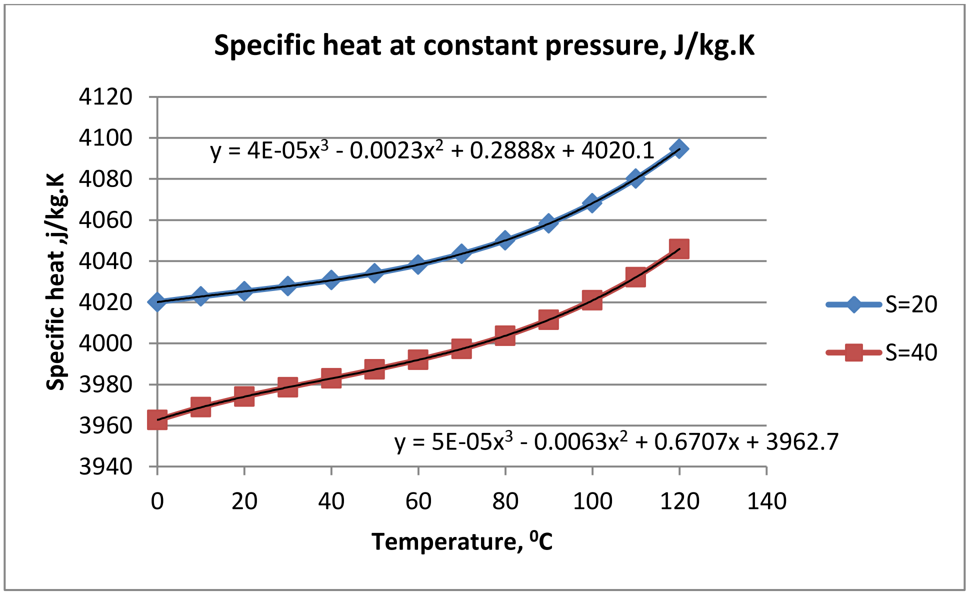


Figure 7 : Specific Heat at Constant Pressure [8]

Specific heat is the measurable physical quantity that characterizes the amount of heat required to change a substance's temperature by a given amount. In SI unit the unit of specific heat is J/kg.k. In modeling a MSF plant specific heat was very important in order to calculate the heat required to heat up the seawater to top brine temperature. Figure 7 show the graph for specific heat at constant pressure against temperature for seawater.

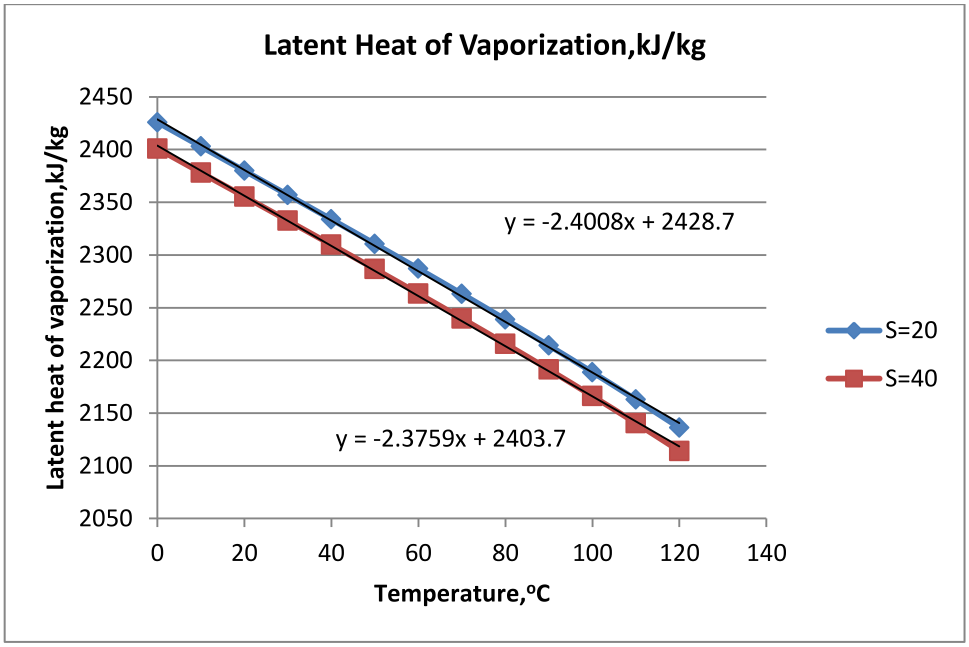


Figure 8 : Latent Heat of Vaporization [8]

Latent heat of vaporization is the heat absorbed by a chemical substance or a thermodynamic system during a change of state that occurs without a change in temperature, meaning a phase transition from liquid to gas. In this modeling the latent heat of vaporization was very important in order to determine the mass of flash vapor. Figure 8 shows the graph for latent heat of vaporization against temperature for seawater.

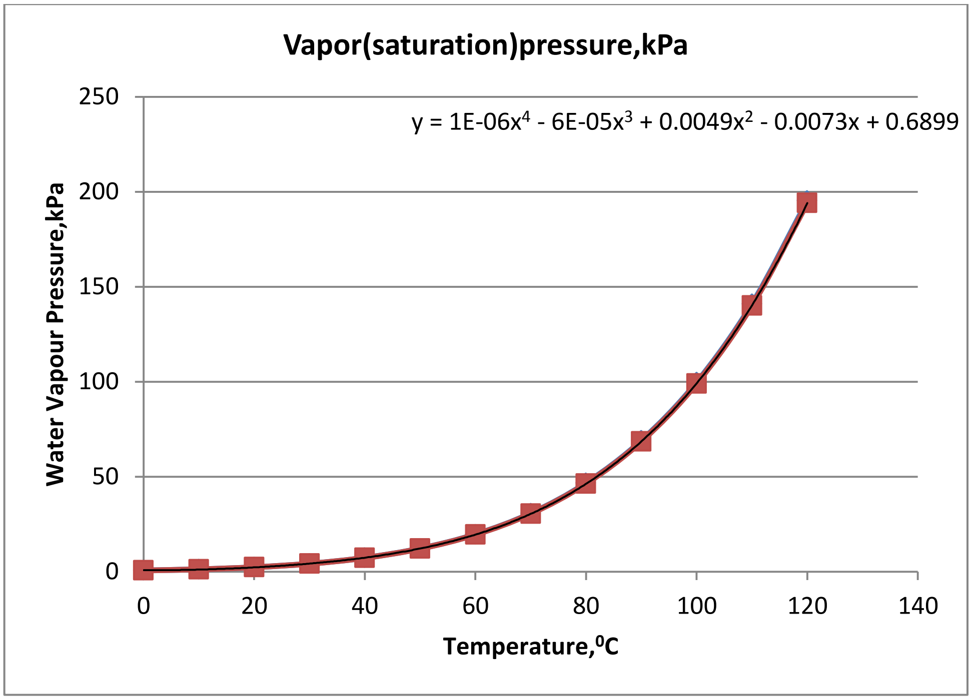


Figure 9 : Vapor (saturation) Pressure [8]

Vapor (saturation) pressure is the pressure of a vapor in thermodynamic equilibrium with its condensed phases in a closed system. All liquids have a tendency to evaporate, and some solids can sublimate into a gaseous form. Vice versa, all gases have a tendency to condense back to their liquid form, or deposit back to solid form, as long as the temperature is below their critical temperature or decomposition temperature. In plain terms, a liquid will evaporate at all pressures below its vapor pressure while remaining stable at pressure above the vapor pressure. Figure 9 is a graph fresh water vapor (saturation) pressure against temperature. In order to get sea water vapor (saturation) pressure we need to insert the salinity and the vapor (saturation) pressure at certain temperature in Equation 2.1.

$$\frac{p_{v,w}}{p_{v,sw}} = 1 + 0.57357 \times \left(\frac{S}{1000-S}\right) \qquad (2.1)$$

Another importance property is BPE. BPE is a phenomenon where boiling points become higher due to appearance of others compound in this case it was salinity. To calculate the BPE we can use equation 2.2

$$BPE=AX+BX^2+CX^3 \qquad (2.2)$$

Where $A = (8.325x10^{-2}+1.883x10^{-4}T+4.02x10^{-5}T^2)$

$B = (-7.625x10^{-4}+9.02x10^{-5}T-5.2x10^{-7}T^2)$

$C = (1.522x10-^{4}-3x10^{-6}T-3x10-8T^2)$

2.2 Overall Process

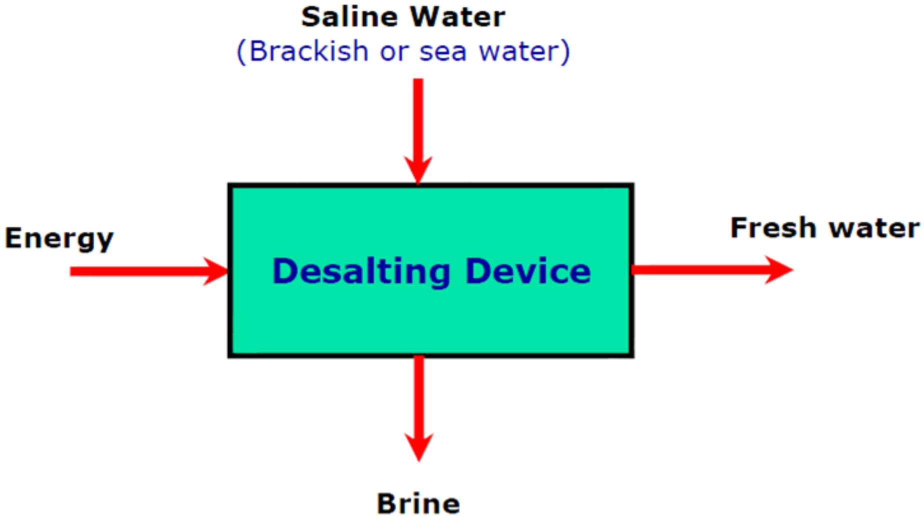


Figure 10 :Overall Flow of Desalination[10]

Desalination is a process that removes salt from sea water. Water is desalinated in order to produce fresh water to suit human consumption. In order to desalinate the water energy was required. In MSF fossil fuel is use as source of energy to heat up the water to top brine temperature.

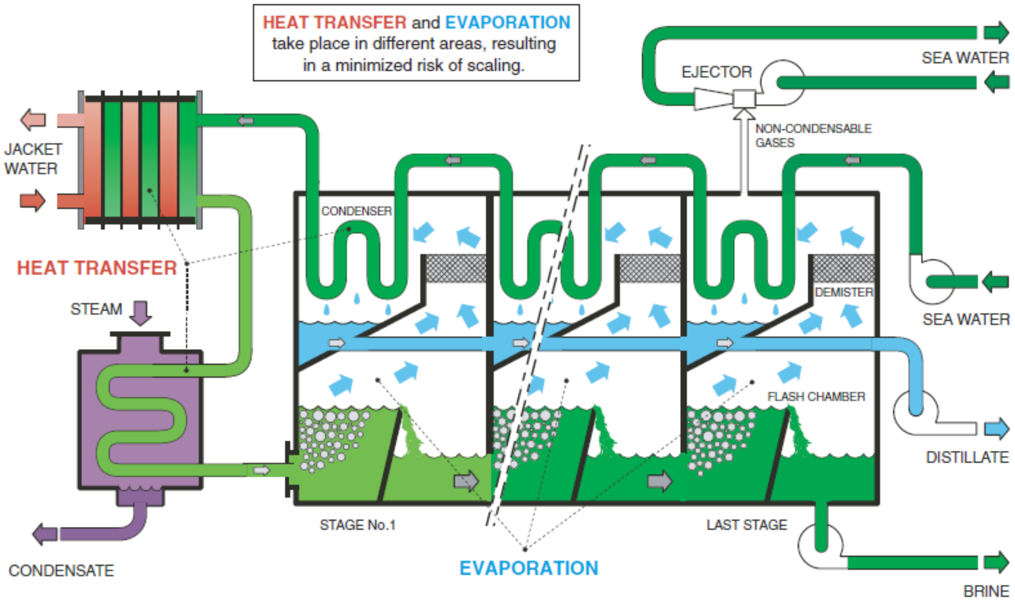
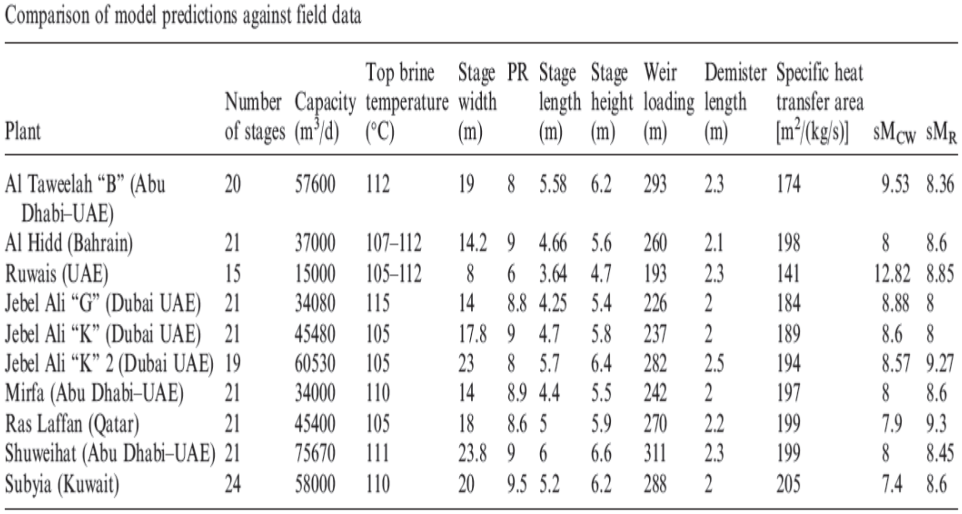


Figure 11:Flow Diagram of MSF

Figure 11 sows the process for MSF. The main components of the plant is the heat rejection, recovery section, and brine heater. The process starts when the seawater is pumped from the source that is sea. After that it will go through along heat exchanger that was heated by hot steam of distillate that produces at every stage. After going pass through the 1st stage the seawater will be heated until it meet the top brine temperature. The water will be flash at every stage due to pressure drop at every stage. The process will go through the stage until the last stage [1][2][3][4][5]. Table 4 show the real plant condition of an MSF plant.

Table 4 : Real Plant Condition



Comparison of model predictions against field data

Plant	Number of stages	Capacity (m^3/d)	Top brine temperature (°C)	Stage width (m)	PR	Stage length (m)	Stage height (m)	Weir loading (m)	Demister length (m)	Specific heat transfer area [m^2/(kg/s)]	sM_{CW}	sM_R
Al Taweelah "B" (Abu Dhabi–UAE)	20	57600	112	19	8	5.58	6.2	293	2.3	174	9.53	8.36
Al Hidd (Bahrain)	21	37000	107–112	14.2	9	4.66	5.6	260	2.1	198	8	8.6
Ruwais (UAE)	15	15000	105–112	8	6	3.64	4.7	193	2.3	141	12.82	8.85
Jebel Ali "G" (Dubai UAE)	21	34080	115	14	8.8	4.25	5.4	226	2	184	8.88	8
Jebel Ali "K" (Dubai UAE)	21	45480	105	17.8	9	4.7	5.8	237	2	189	8.6	8
Jebel Ali "K" 2 (Dubai UAE)	19	60530	105	23	8	5.7	6.4	282	2.5	194	8.57	9.27
Mirfa (Abu Dhabi–UAE)	21	34000	110	14	8.9	4.4	5.5	242	2	197	8	8.6
Ras Laffan (Qatar)	21	45400	105	18	8.6	5	5.9	270	2.2	199	7.9	9.3
Shuweihat (Abu Dhabi–UAE)	21	75670	111	23.8	9	6	6.6	311	2.3	199	8	8.45
Subyia (Kuwait)	24	58000	110	20	9.5	5.2	6.2	288	2	205	7.4	8.6

2.3 Cost Estimation

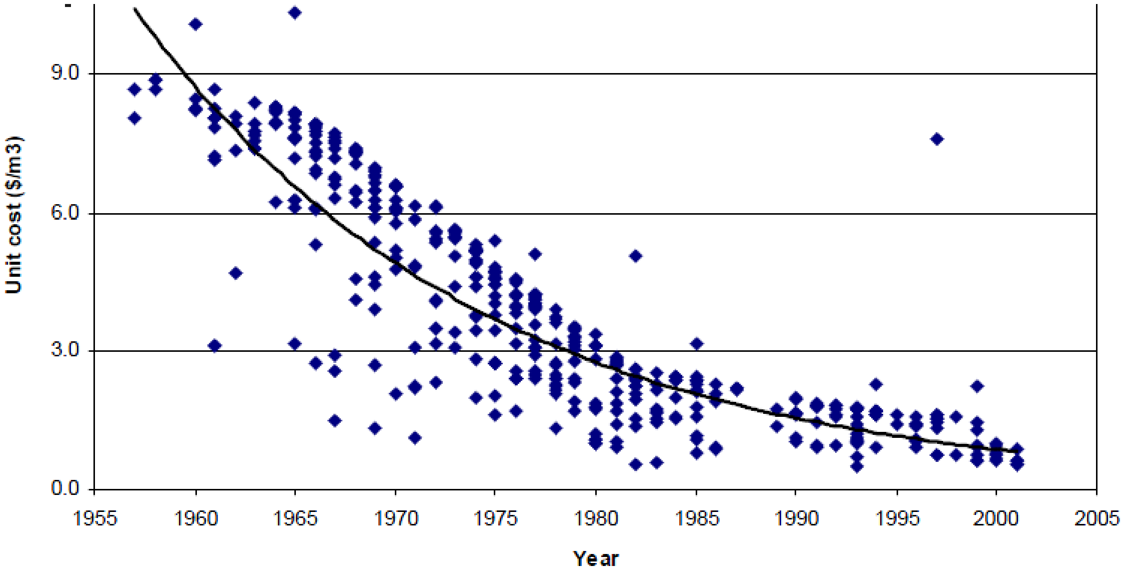
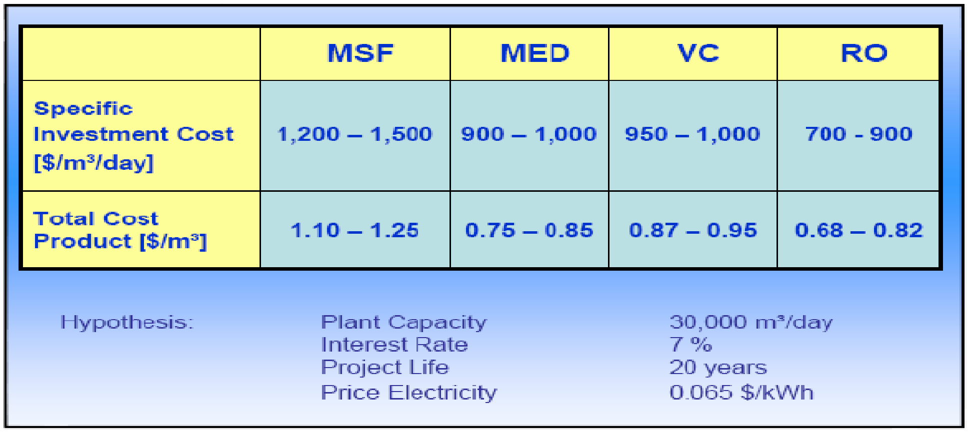


Figure 12 :Cost Analysis of MSF [10]

MSF at early of its innovation the cost per m^3 is as high as USD 9 but as innovation has been done by years to years the cost of fresh water that been produced has reduced to around USD1-2 per m^3 as per what we can see in figure 12.

Table 5 : Economis of Desalination [10]



	MSF	MED	VC	RO
Specific Investment Cost [$/m³/day]	1,200 – 1,500	900 – 1,000	950 – 1,000	700 - 900
Total Cost Product [$/m³]	1.10 – 1.25	0.75 – 0.85	0.87 – 0.95	0.68 – 0.82

Hypothesis:

Plant Capacity	30,000 m³/day
Interest Rate	7 %
Project Life	20 years
Price Electricity	0.065 $/kWh

Source: Kaufler

From Table 5 we can see that the total cost of fresh water from MSF is about USD 1.25 and in Malaysian Ringgit it is RM 3.58. In Malaysia the normal water charge is between RM 1-2. The water charge is depends to the state companies that give water services. Table 6 shows the water charge according to the state in Malaysia.

Table 6 : Malaysia Water Charge per State

State	Water Charge per m^3 (RM)
Johor	2.96
Kedah	1.80
Kelantan	1.25
Melaka	1.47
Negeri Sembilan	1.60
Pahang	0.84
Penang	1.00
Perlis	1.30
Sabah & Labuan	1.20
Sarawak	1.21
Selangor	2.28
Terengganu	1.15

CHAPTER 3
Methodology

3.1 Project Activities

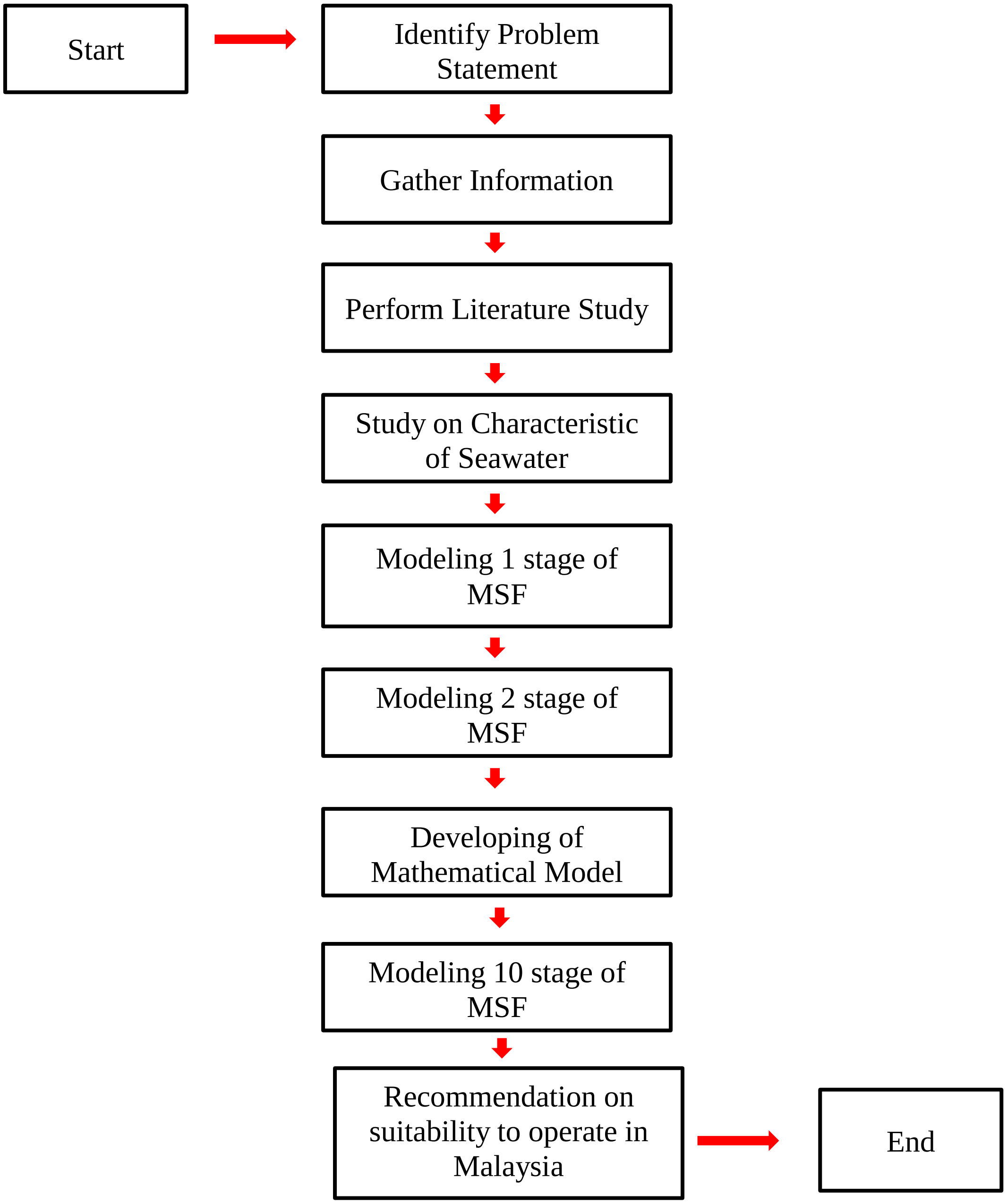


Figure 13 : Project Activities

For this project we have start with studying the background of this project and gather all the information needed to run the modelling. After that we continue with the study on characteristics of sea water. We have study the difference properties of seawater at difference salinity and temperature that is:

- Vapor Saturation Pressure
- Boiling Point Elevation
- Latent Heat of Evaporation
- Specific Enthalpy
- Specific Heat at Constant Pressure

After that we continue with developing the model. First we understand the concept of the mass balance and energy balance. After that we develop a model of single stage MSF. We need to understand the relationship between all the data. Moving on we start to develop second stage of the MSF. When the 2 stage of MSF have been developed we start to develop the mathematical model that will assist us in order to finish the modeling of MSF.

3.1.1 Mass Balance and Energy Balance

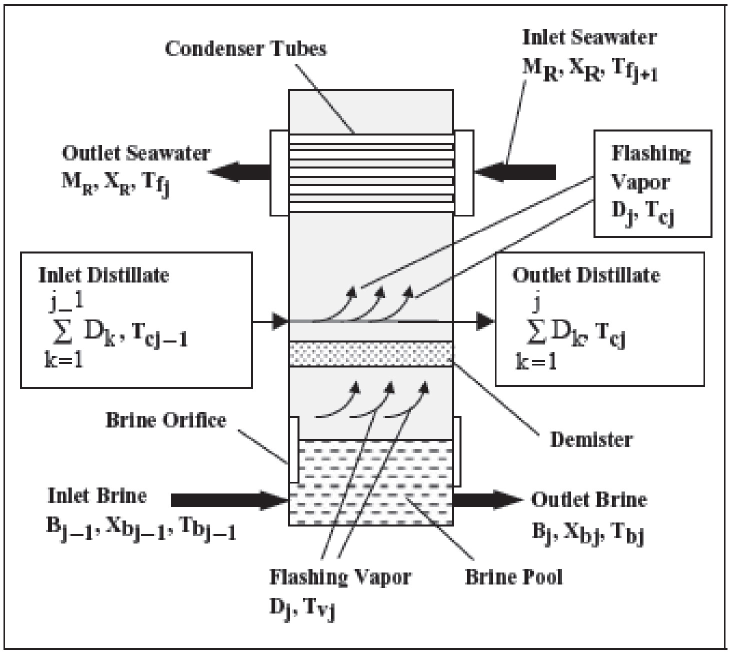


Figure 14: Mass Balance for 1 Stage [2]

In order to develop a model first we need to know the mass and energy balances of the process. The process of a stage in a flash desalination is shown in figure14 and the overall mass balance and energy balance was shown in figure 15 [2]. In this part it will discuss on the mass transfer and heat transfer in a stage for a flash desalination plant. The overall mass balance for a stage is given by

$$B_{j-1} + \sum_{k=1}^{j-1} D_k = B_j + \sum_{k=1}^{j} D_k \qquad (3.1)$$

It should be noted that for the first stage the value B_{j-1} is equal to M_R and the term $\sum_{k=1}^{j-1} D_k$ is equal to zero. Therefore the equation (3.1) can be reduce to following

$$M_R = D_1 + B_1 \qquad (3.2)$$

And for the salt concentration for each stage is given by

$$X_{bj-1}\, B_{j-1} = X_{bj} B_j \qquad (3.3)$$

It should be noted that B_{j-1} is equal to M_R and X_{bj-1} is equal to X_R for the first stage. Thus the equation can be reduce to

$$X_R M_R = X_{b1} B_1 \qquad (3.4)$$

The energy balance for the flashing brine is given by

$$D_j \lambda_{Vj} = B_{j-1} Cp_b (T_{bj-1} - T_{bj}) \qquad (3.5)$$

It should be noted that for the first stage B_{j-1} is equal to M_R and T_{bj-1} is equal to T_{b0}. Thus the equation can be reduce to

$$D_1 \lambda_{V1} = M_R\, Cp_b (T_{b0} - T_{b1}) \qquad (3.6)$$

The temperature for the unevaporated brine flowing to the next stage is related to the saturation temperature of the formed vapour, boiling point elevation (BPE) and nonequilibrium allowance (NEA). The equation is given by

$$T_{bj} = T_{vj} + BPE_j + NEA_j \qquad (3.7)$$

NEA is a measure of the thermal efficiency. The equation is given by

$$NEA_{10} = (0.9877)^{T0}(15.7378)^{H}(1.377)^{Wx10-6} \qquad (3.8)$$

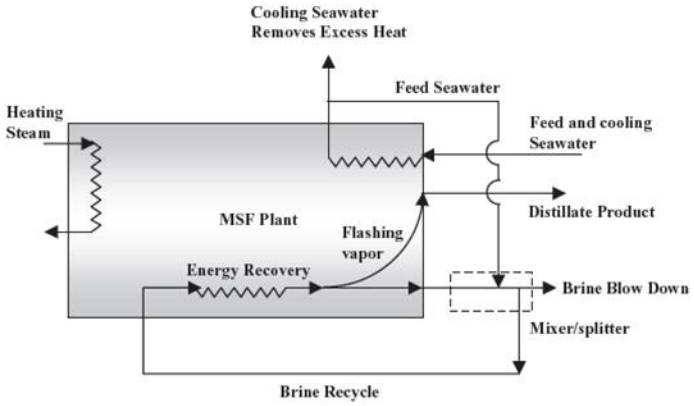


Figure 15 : Overall Mass & Energy Balance

3.2.2 Mathematical model

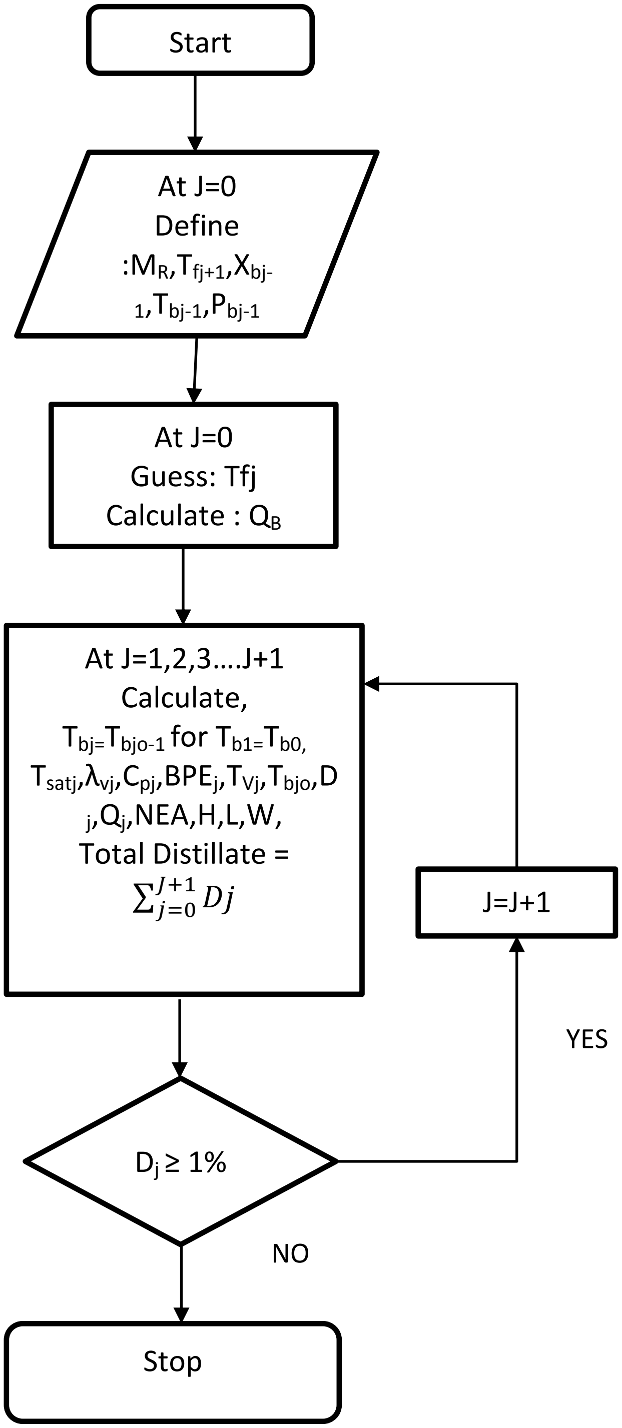


Figure 16 : Mathematical Model for MSF

In this mathematical model a few assumption has been made that is:

- This operation is a steady state operation
- Heat loss to the surrounding are negligible
- The heat capacities for feed seawater, brine and distillate product depend on temperature and composition.
- The distillate is product salt free.

As shown in the figure 14, first we need to define seawater intake (M_R), inlet seawater temperature (T_{fj+1}), inlet seawater salinity (X_{bj-1}), top brine temperature (T_{bj-1}) and top brine pressure (P_{bj-1}). After that we need to guess the seawater temperature through a condenser at stage 1(T_{fj}) and then we can calculate the heat required by the brine heater (Q_B).

For every stage we need to calculate the brine temperature (T_{bj}) using equation 3.7, flash vapor temperature (T_{vj}) , distillate flowrate(Dj) using equation 3.5,NEA using equation 3.8 and $\sum_{j=0}^{J+1} Dj$. The modeling will stop if Dj is less than 1% the inlet water flowrate or $\sum_{j=0}^{J+1} Dj$ is between 10-20% of the water intake flowrate and the number of stage is greater than 10. This is because due to economical restriction.

For the modeling of MSF there software that will be need to us is:

1. Microsoft Office Excel
2. MATLAB

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Result & Discussion

4.1.1 MSF Design

Operating Variable	
Seawater Flow rate	$10000m^3/hr$
Seawater Temperature	32^0C
Seawater Salinity	35g/kg
Top Brine Temperature	120^0C
Height	5.8m
Length	4.86m
Width	15.4m
Number of Stage	10

Table 7 : Operating Variable for MSF

The dimension of the MSF plant is same for every stage. This is because we had made the assumption that all stage has the same heat transfer area. We also had stop the modeling at stage number 10 because it has reach the %yield between 10-20 that is 16%

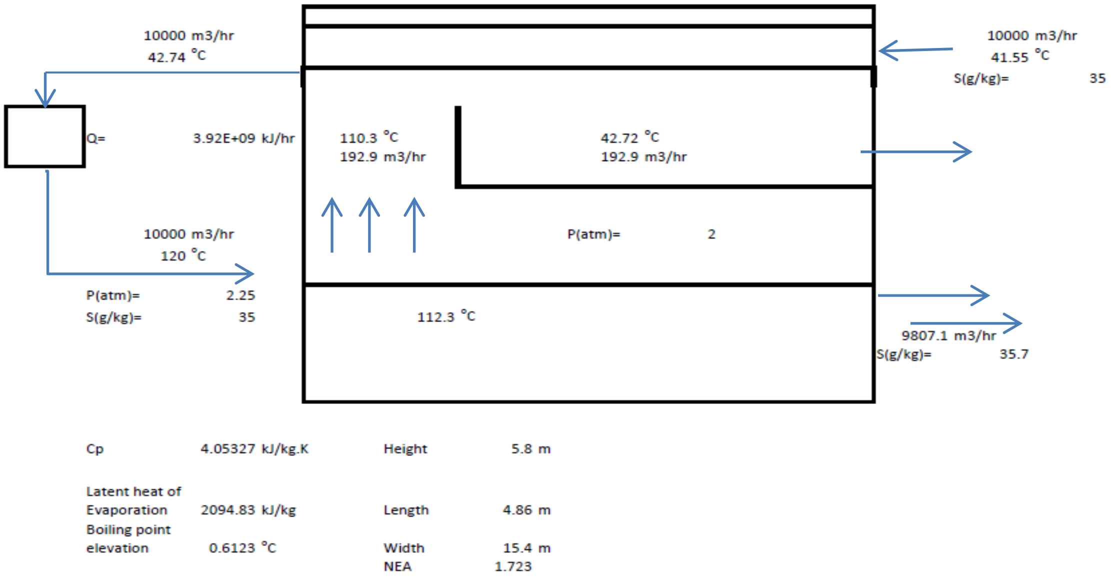


Figure 17 : 1st stage of MSF

Operation Conditions										
	Stage									
	1	2	3	4	5	6	7	8	9	10
Brine Inlet Temperature(^{O}C)	120	112.3	104.6	96.3	88.5	80.8	72.4	64.7	58.3	50.4
Brine Outlet Temperature(^{O}C)	112.3	104.6	96.3	88.5	80.8	72.4	64.7	58.3	50.4	42.9
Flash Water Temperature(^{O}C)	110.3	102.7	94.2	86.6	78.6	70.2	62.3	56.8	48.9	40.4
Distillate Temperature(^{O}C)	42.74	41.55	40.37	39.37	38.43	37.65	36.6	35.6	34.3	32.1
Inlet Flowrate (m^3/hr)	10000	9807.1	9623.8	9442.2	9267.8	9096.8	8930.4	8771.6	8647.2	8495.6
Brine Flowrate (m^3/hr)	9807.1	9623.8	9442.2	9267.8	9096.8	8930.4	8771.6	8647.2	8495.6	8346.1
Distillate Flowrate (m^3/hr)	192.9	183.3	180.6	175.3	170.1	165.4	159.8	123.4	151.6	148.5
Inlet Salinity(g/kg)	35.0	35.7	36.4	37.1	37.8	38.5	39.2	39.9	40.5	41.2
Brine Salinity(g/kg)	35.7	36.4	37.1	37.8	38.5	39.2	39.9	40.5	41.2	41.9
Distillate Yield(%)	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.4	1.8	1.7

Table 8: Operating Conditions of MSF

By using the mathematical model that we have discussed in methodology we have finally setup a model as per shown at Table 8. In order to build up the model there are a few thing that should be take note that is:

- The top brine temperature is 120^0C
- The inlet water intake is 10000m^3/hr
- The inlet water salinity is 35g/kg
- The heat transfer area for is stage is constant.

After the modeling had been done we can see that:

- The heat needed to heat up the seawater to top brine heater is $3.92X10^9$kJ/hr
- The average distillate yield at every stage is 1.65% and the total distillate yield is 16.52% that is 1653m^3/hr that equivalent to 39672m^3/day
- The number of stage is 10
- The final temperature of the brine blowdown is 42.9^0C
- The final salinity of the brine is 41.9g/kg

From the result that we have obtained we can see that the brine temperature is higher compared to normal sea water that is 35^0C. Another main concern is the salinity of the brine that is 41.9g/kg compared to normal that is 35g/kg. These two properties were very important because by increase the salinity the density of the seawater will increase and make it less soluble to carbon dioxide.

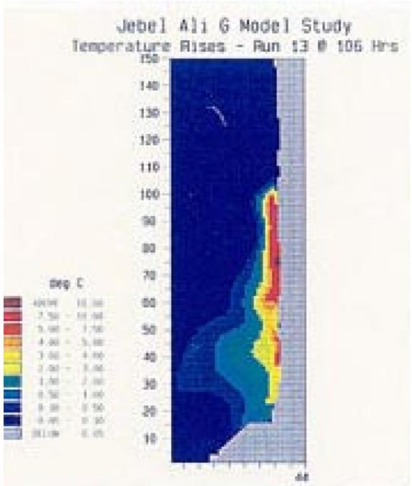
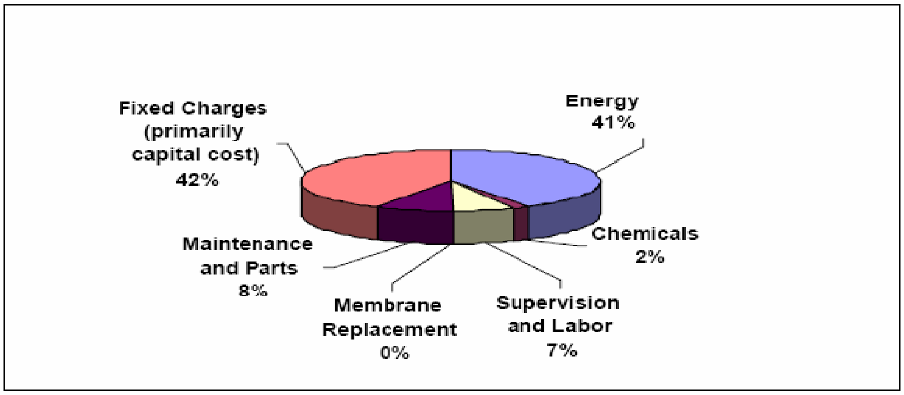


Figure 18: Temperature Plot At Al -Jebel Plant

4.2 Recommendation

There are some improvements that still can be done that is

1. Energy efficiency



Source: Ebensperger and Phyllis Isley (2005)

Figure 19 :Cost Segregation for MSF

From figure 19 we can see that almost half of the cost of to produce fresh water is from energy consumption that is 41%. So if the cost of production to be reduces it must be reduce from the energy use. One of the methods to reduce the energy use is by changing to membrane process. It has been prove that by using membrane process it can reduce the energy use to 20 %. [10]

CHAPTER 5
CONCLUSION

From the result that we obtain we have studied the characteristic of the sea water that varies on different salinities and temperature. The sea water properties that had been studies is vapour saturation pressure, latent heat of vaporization, specific heat at constant pressure, boiling point elevation.

After that a MSF model with 10 stages has been model using all of the properties that had been studied before. 1653m^3 that is equal to 16.53% of fresh water had been yield out of 10000m3 of the inlet flowrate. The modeling was done by using the Microsoft Excel and MATLAB.

In the end a few improvement was suggested to improve the efficiency and reduce the cost per m3 of produce fresh water that is improvement in energy efficiency by suggesting a new method of desalination has been suggested that is membrane process that have been proved can reduce the energy consumption

References

1. El-Dessouky.H, Shaban G. I. and Al- Ramadan,H., *Multi-Stage Flash Desalination Process : A Thermal Analysis*

2. Abdel-Jabbar,N.M., Qiblawey,H.M., Mjalli,F.S., Ettouney,H., *Simulation of large capacity MSF brine circulation plants.*

3. Abduljawad,M**.,** *Steady State Simulation*

4. McCreery,K., Khurshid,M., Yoon,S., Rowland,W**.,** *Introduction to Civil Engineering 2008on of MSF Desalination Plant*

5. Junjie,Y., Shufeng,S., Jinhua,W., Jiping,L., *Improvement of a multi stage flash seawater desalination for cogeneration power plants*

6. Gleick, P. H., 1996: *Water resources. In Encyclopedia of Climate and Weather, ed. by S. H. Schneider,* Oxford University Press, New York, vol. 2, pp.817-823

7. World Health Organization, <http://www.who.int/features/factfiles/water/en/>

8. Sharqawy, M.H., Lienhard V,J.H., and Zubair,S.M., "*Thermophysical properties of seawater: A review of existing correlations and data," Desalination and Water Treatment,* Vol. 16, pp.354-380, April 2011

9. Lee,C.**,** *Water Taarif and Development,Case In Malaysia*

10. Banat,F., *Economic and Technical Assessment of Desalination Technologies*, June 2007

11. Conceptual design of chemical processes by James M. Douglas, McGraw Hill, 1988

12. Douglas,J.M., Total Capital Investment and Total Product Costs, Conceptual

13. Design of Chemical Processes, McGraw-Hill International Edition, 1988.

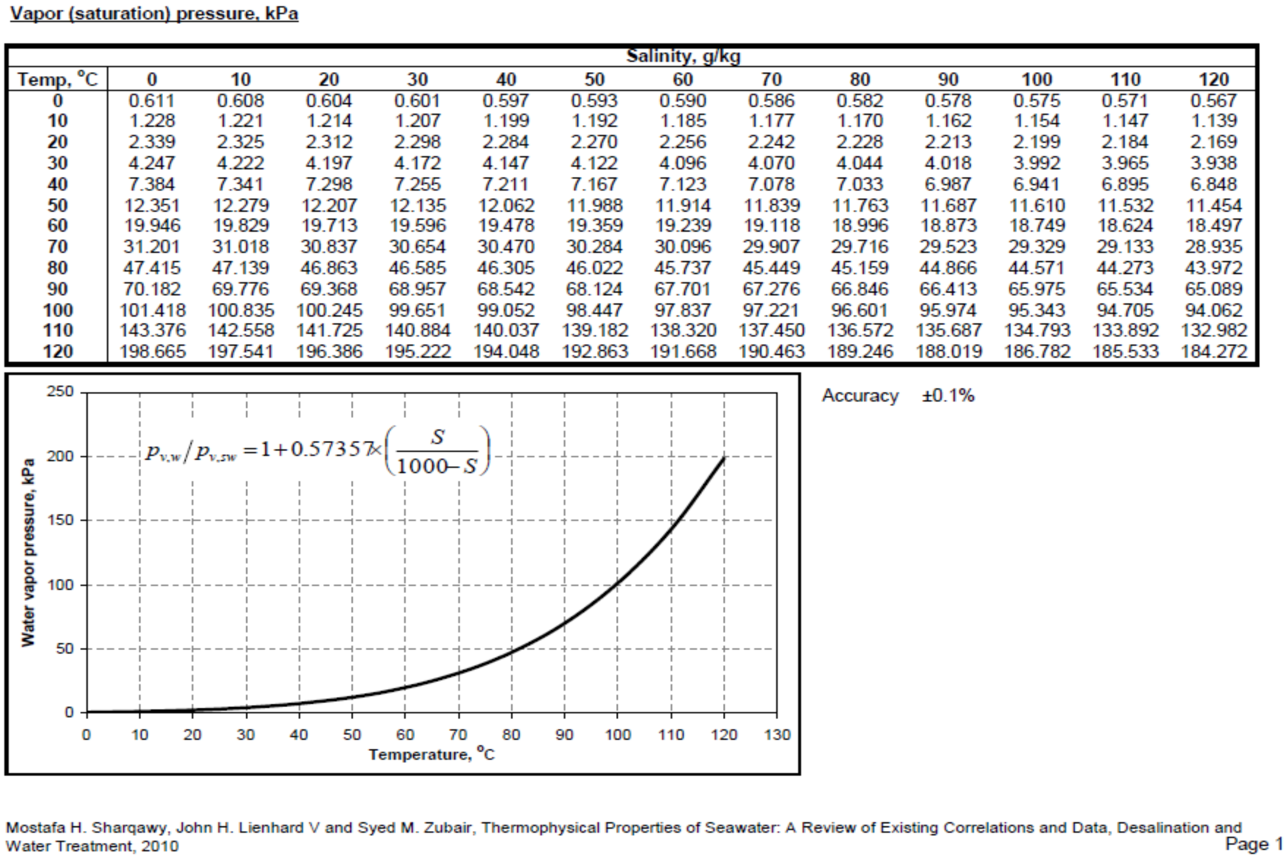
14. Coulson & Richardson (1994), Chemical Engineering, Volume 3, Chemical &

15. Biochemical Reactors & Process Control, 3rd Edition, Pergamon, Wiltshire.

16. Max S.Peters, Klaus D.Timmerhaus, 1991, Plant Design and Economics, MCGraw-Hill, Inc
17. Douglas J., Conceptual Design of Chemical Processes, International Edition, (1988),Mc Graw Hill Inc, New York
18. Shell Sustainability Report 2008
19. BP Sustainability Report 2008
20. TOTAL Sustainability Report 2008
21. PETRONAS Sustainability Report 2009

APPENDIX A

Vapor Saturation Pressure



Vapor (saturation) pressure, kPa

Temp, °C	Salinity, g/kg 0	10	20	30	40	50	60	70	80	90	100	110	120
0	0.611	0.608	0.604	0.601	0.597	0.593	0.590	0.586	0.582	0.578	0.575	0.571	0.567
10	1.228	1.221	1.214	1.207	1.199	1.192	1.185	1.177	1.170	1.162	1.154	1.147	1.139
20	2.339	2.325	2.312	2.298	2.284	2.270	2.256	2.242	2.228	2.213	2.199	2.184	2.169
30	4.247	4.222	4.197	4.172	4.147	4.122	4.096	4.070	4.044	4.018	3.992	3.965	3.938
40	7.384	7.341	7.298	7.255	7.211	7.167	7.123	7.078	7.033	6.987	6.941	6.895	6.848
50	12.351	12.279	12.207	12.135	12.062	11.988	11.914	11.839	11.763	11.687	11.610	11.532	11.454
60	19.946	19.829	19.713	19.596	19.478	19.359	19.239	19.118	18.996	18.873	18.749	18.624	18.497
70	31.201	31.018	30.837	30.654	30.470	30.284	30.096	29.907	29.716	29.523	29.329	29.133	28.935
80	47.415	47.139	46.863	46.585	46.305	46.022	45.737	45.449	45.159	44.866	44.571	44.273	43.972
90	70.182	69.776	69.368	68.957	68.542	68.124	67.701	67.276	66.846	66.413	65.975	65.534	65.089
100	101.418	100.835	100.245	99.651	99.052	98.447	97.837	97.221	96.601	95.974	95.343	94.705	94.062
110	143.376	142.558	141.725	140.884	140.037	139.182	138.320	137.450	136.572	135.687	134.793	133.892	132.982
120	198.665	197.541	196.386	195.222	194.048	192.863	191.668	190.463	189.246	188.019	186.782	185.533	184.272

Accuracy ±0.1%

Mostafa H. Sharqawy, John H. Lienhard V and Syed M. Zubair, Thermophysical Properties of Seawater: A Review of Existing Correlations and Data, Desalination and Water Treatment, 2010

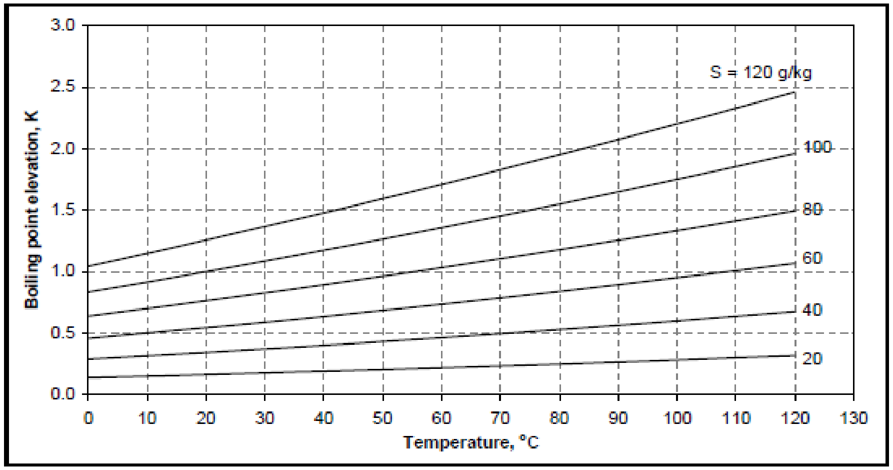
Page 1

APPENDIX B

Boiling Point Elevation

Boiling point elevation, K

	Salinity, g/kg												
Temp, °C	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
0	0.000	0.067	0.138	0.213	0.291	0.373	0.458	0.547	0.640	0.736	0.836	0.939	1.046
10	0.000	0.073	0.150	0.232	0.317	0.407	0.501	0.599	0.701	0.807	0.917	1.032	1.151
20	0.000	0.079	0.163	0.251	0.344	0.442	0.545	0.652	0.764	0.880	1.002	1.128	1.258
30	0.000	0.085	0.176	0.272	0.373	0.479	0.590	0.707	0.829	0.956	1.088	1.225	1.368
40	0.000	0.092	0.190	0.293	0.402	0.517	0.637	0.764	0.895	1.033	1.176	1.325	1.480
50	0.000	0.099	0.204	0.315	0.433	0.556	0.686	0.822	0.964	1.112	1.267	1.428	1.595
60	0.000	0.106	0.219	0.338	0.464	0.597	0.736	0.882	1.035	1.194	1.360	1.532	1.711
70	0.000	0.114	0.234	0.362	0.497	0.639	0.788	0.944	1.107	1.277	1.455	1.639	1.831
80	0.000	0.121	0.250	0.387	0.530	0.682	0.841	1.007	1.181	1.363	1.552	1.748	1.952
90	0.000	0.129	0.267	0.412	0.565	0.726	0.895	1.072	1.257	1.450	1.651	1.860	2.076
100	0.000	0.138	0.284	0.438	0.601	0.772	0.952	1.139	1.335	1.540	1.752	1.973	2.203
110	0.000	0.146	0.302	0.465	0.638	0.819	1.009	1.208	1.415	1.631	1.856	2.089	2.331
120	0.000	0.155	0.320	0.493	0.676	0.868	1.068	1.278	1.497	1.725	1.962	2.207	2.462

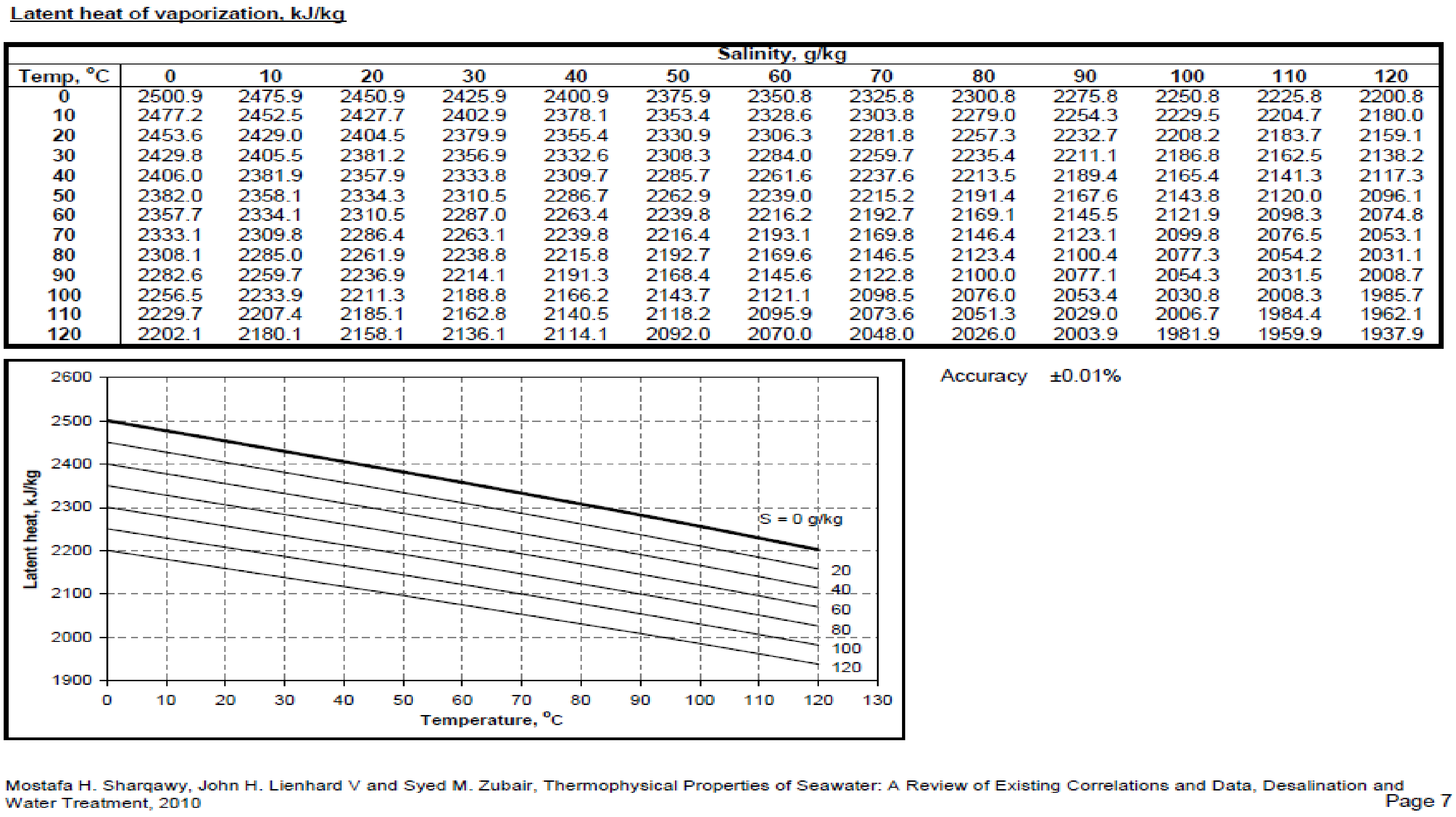


Accuracy ±0.018 K

Mostafa H. Sharqawy, John H. Lienhard V and Syed M. Zubair, Thermophysical Properties of Seawater: A Review of Existing Correlations and Data, Desalination and Water Treatment, 2010

APPENDIX C

Latent Heat of Vaporization



Latent heat of vaporization, kJ/kg

	Salinity, g/kg												
Temp, °C	0	10	20	30	40	50	60	70	80	90	100	110	120
0	2500.9	2475.9	2450.9	2425.9	2400.9	2375.9	2350.8	2325.8	2300.8	2275.8	2250.8	2225.8	2200.8
10	2477.2	2452.5	2427.7	2402.9	2378.1	2353.4	2328.6	2303.8	2279.0	2254.3	2229.5	2204.7	2180.0
20	2453.6	2429.0	2404.5	2379.9	2355.4	2330.9	2306.3	2281.8	2257.3	2232.7	2208.2	2183.7	2159.1
30	2429.8	2405.5	2381.2	2356.9	2332.6	2308.3	2284.0	2259.7	2235.4	2211.1	2186.8	2162.5	2138.2
40	2406.0	2381.9	2357.9	2333.8	2309.7	2285.7	2261.6	2237.6	2213.5	2189.4	2165.4	2141.3	2117.3
50	2382.0	2358.1	2334.3	2310.5	2286.7	2262.9	2239.0	2215.2	2191.4	2167.6	2143.8	2120.0	2096.1
60	2357.7	2334.1	2310.5	2287.0	2263.4	2239.8	2216.2	2192.7	2169.1	2145.5	2121.9	2098.3	2074.8
70	2333.1	2309.8	2286.4	2263.1	2239.8	2216.4	2193.1	2169.8	2146.4	2123.1	2099.8	2076.5	2053.1
80	2308.1	2285.0	2261.9	2238.8	2215.8	2192.7	2169.6	2146.5	2123.4	2100.4	2077.3	2054.2	2031.1
90	2282.6	2259.7	2236.9	2214.1	2191.3	2168.4	2145.6	2122.8	2100.0	2077.1	2054.3	2031.5	2008.7
100	2256.5	2233.9	2211.3	2188.8	2166.2	2143.7	2121.1	2098.5	2076.0	2053.4	2030.8	2008.3	1985.7
110	2229.7	2207.4	2185.1	2162.8	2140.5	2118.2	2095.9	2073.6	2051.3	2029.0	2006.7	1984.4	1962.1
120	2202.1	2180.1	2158.1	2136.1	2114.1	2092.0	2070.0	2048.0	2026.0	2003.9	1981.9	1959.9	1937.9

Accuracy ±0.01%

Mostafa H. Sharqawy, John H. Lienhard V and Syed M. Zubair, Thermophysical Properties of Seawater: A Review of Existing Correlations and Data, Desalination and Water Treatment, 2010

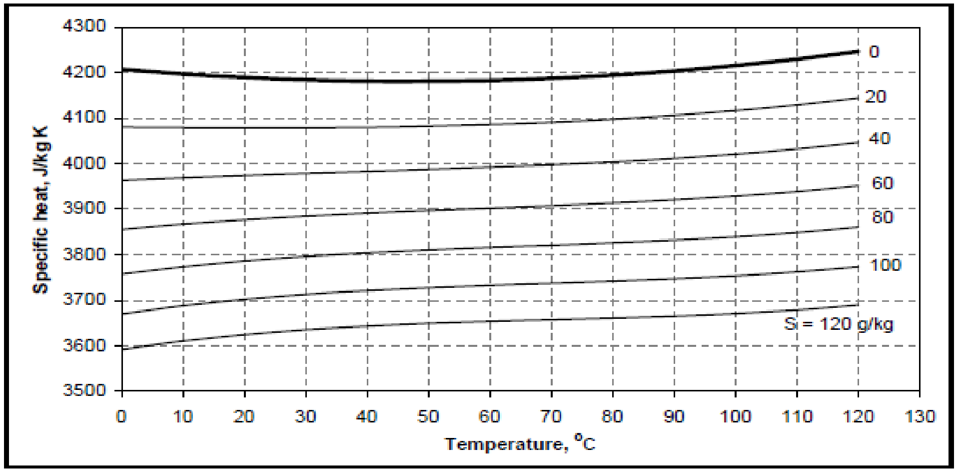
Page 7

APPENDIX D

Specific Heat At Constant Pressure

Specific heat at constant pressure, J/kg K

Temp, °C	Salinity, g/kg												
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
0	4206.8	4142.1	4079.9	4020.1	3962.7	3907.8	3855.3	3805.2	3757.6	3712.4	3669.7	3629.3	3591.5
10	4196.7	4136.7	4078.8	4022.8	3968.9	3916.9	3867.1	3819.2	3773.3	3729.5	3687.7	3647.9	3610.1
20	4189.1	4132.8	4078.2	4025.3	3974.1	3924.5	3876.6	3830.4	3785.9	3743.0	3701.8	3662.3	3624.5
30	4183.9	4130.5	4078.5	4027.8	3978.6	3930.8	3884.4	3839.4	3795.8	3753.6	3712.7	3673.3	3635.3
40	4181.0	4129.7	4079.6	4030.7	3982.9	3936.4	3891.0	3846.7	3803.7	3761.8	3721.1	3681.6	3643.2
50	4180.6	4130.8	4081.9	4034.1	3987.3	3941.5	3896.6	3852.9	3810.1	3768.3	3727.5	3687.8	3649.0
60	4182.7	4133.7	4085.5	4038.3	3992.0	3946.5	3902.0	3858.3	3815.5	3773.7	3732.7	3692.6	3653.4
70	4187.1	4138.5	4090.6	4043.6	3997.3	3951.9	3907.4	3863.6	3820.6	3778.5	3737.2	3696.7	3657.0
80	4194.0	4145.3	4097.3	4050.1	4003.7	3958.1	3913.3	3869.2	3825.9	3783.5	3741.7	3700.8	3660.7
90	4203.4	4154.2	4105.9	4058.3	4011.5	3965.4	3920.2	3875.7	3832.0	3789.1	3746.9	3705.6	3665.0
100	4215.2	4165.4	4116.4	4068.2	4020.9	3974.3	3928.5	3883.6	3839.4	3796.0	3753.5	3711.7	3670.8
110	4229.4	4178.8	4129.1	4080.2	4032.2	3985.1	3938.7	3893.3	3848.6	3804.9	3761.9	3719.9	3678.6
120	4246.1	4194.7	4144.2	4094.6	4045.9	3998.2	3951.3	3905.4	3860.3	3816.2	3773.0	3730.7	3689.4



Accuracy ±0.28%

Mostafa H. Sharqawy, John H. Lienhard V and Syed M. Zubair, Thermophysical Properties of Seawater: A Review of Existing Correlations and Data, Desalination and Water Treatment, 2010

Page 9