ISSN 2229-5518

Fresh Water Production System Design for a 5000 Tonnes Offshore Work Barge

Nitonye Samson

Abstract—The need for fresh water production for the crew and running machinery on board an offshore structure has led to the need for the design of distillation plants. Firstly, the water requirements for the crew and running machinery were estimated and analyzed through the application of Classification Society Rule. Since the need to provide water (for 100 crew, 6 running machinery and other miscellaneous serviceses) for the offshore vessel with a plant that will distill as much quantity of fresh water from brackish sea water with good quality is very vital, this research therefore looked at using mathematical models to design a distillation plant (Multistage Flash evaporator Plant). Since the design of the production plant is for the Niger Delta region of Nigeria in Africa, the total water consumption for the crew per day is estimated at 15,000 liters and that for the machinery and other uses are put at 120 liters. The design cost, material availability, maintainability, durability, production capacity, space occupied and other considerations made, has chosen the Multistage Flash Evaporator Plant to be the best option for greater capacity to produce as much quantity of fresh water needed on board with profit maximization for crew and machinery purposes. All designs were done in accordance with the rules of the classification society and a computer programming written for Multistage Flash evaporator.

Index Terms—Offshore Work Barge, Distilation Plants, Evaporators, Multistage Flash Evaporator Plant, Tubes, Effects and Salt Water.

1 Introduction

THE design of a 5000 tonnes Offshore Work Barge has given rise to the demand of fresh water production system onboard the vessel. A barge is usually a flat bottom vessel mainly used as cargo tanker, equipment supply carriers, crane platform and support accommodation bases in offshore drilling [1]. This offshore structure is capable of accommodating hundred personals that will carry out offshore services simultaneously. To provide adequate potable water for the daily need on board becomes necessary, this will also enhace the hull strength design [2] and the stress analysis of the barge [3].

Since the offshore vessel is not expected to return to shore to get regular supply of water, other sources of water production have to be employed. Looking at several ways of distilling salt water, there is a need to choose an option and optimize it for the purpose of design, cost, maintainability, durability, production capacity, space occupied and other considerations. Not forgetting the stability analysis of the vessel [1][4]. Figure 1 shows a simple water production system that is capable of meeting the water need of the offshore work barge.

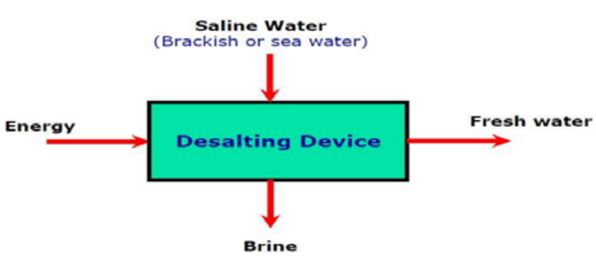

Figure 1: Simple representation of a distillation System

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The basic principle of the desalination is almost the same in every currently used method. As seen in figure 1 the objective of the different desalination processes is to separate the brackish sea water feed with a certain percentage of salinity in two separate flows. The way how this separation of the inflow is obtained in the desalting device is the counting point for the distinction of the desalination methods. The different stages of distillation could be summarized as thermal based methods like distillation or freezing, physical based methods using membrane separation and electrical based methods similar to electro dialysis (ED). On the basis of the economic efficiency the mostly used methods are the multistage flash (MSF) method, the multiple effect distillation MED and the reverse osmosis (RO) [5].

Also Cipollina et al, classified desalination into thermal and membrane desalination processes. Thermal desalination processes include MSF, MED and mechanical vapor compression (MVC). On the other hand, membrane desalination is dominated by RO, while the ED process is found on a very limited scale. The MSF dominates the desalination industry and this is due to its reliable performance and its large unit capacity [6].

1.1 Multi Stage Flash Destilation Process

The MSF process is based on the evaporation and condensation of heated sea water. As shown in figure 2 the seawater feed is getting heated up in the heating section and is filled in a series arrangement of tanks with certain temperatures and pressure values. The combination of thermal conditioning and pressure in the tanks allows a continuing steam production even with decreasing temperatures due to the decreasing pressure values in the different stage tanks [7]. Each tank contains a collector for the condensate that is produced through the cooling function of a heat exchanger. This collector or exchanger is powered by the cold seawater inflow [8].

The efficiency of the desalination process can be increased by the number of stages. As a result of the counter current of the

International Journal of Scientific & Engineering Research, Volume 7, Issue 4, April-2016
ISSN 2229-5518

module the cold seawater can be heated up step by step in each stage before it reaches the actual heating section. As part of this pre-heating, the amount of energy that is needed in the heating section can be decreased [9]. That circumstance has a direct effect of the energy cost of the MSF-module. Modern, large MSF-plants have up to 28 stages [10]. If considered the stages could be less than this for the offshore vessel under consideration.

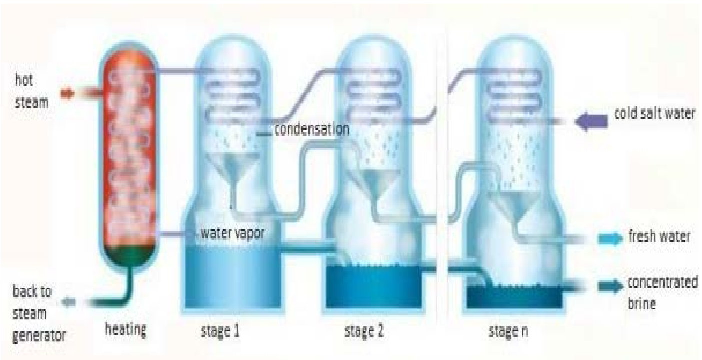

Figure 2: Multi Stage Flash Distillation Processes [11]

MED plants work very similarly to MSF distillation plants. MED, however, has lower energy consumption, which reduces utility costs, and they can handle a wider range of seawater properties with minimal changes to plant operations. These advantages make MED one of the desirable system for this project. However MED is not without its limitations and drawbacks, and it must be properly evaluated against each plant's specific characteristics [12].

MSF is used in desalination plants to convert saltwater by evaporation to potable water or make-up water that is free of impurities. MSF accounts for approximately 85% of commercial desalination worldwide. MSF distillation yields higher production quantities than other desalination methods, such as multi-effect desalination and reverse osmosis separation. GSE's **simulation models** can help operators optimize their controls and processes and discover and solve problems so their multi-stage flash distillation plant operates at peak efficiency. Applications for simulation include:

- Optimizing plant design to maximize the performance ratio of steam input to distillate production;
- Designing operating conditions based on water impurities, mainly salt concentration, and seawater temperature;
- Verifying process dynamics under varied plant loads;
- Understanding impact of scaling on heat transfer efficiency and process dynamics;
- Identification of brine carryover and degradation of product quality; and
- Recognizing the negative effects of non-condensable gases on heat transfer [13].

The two main processes of each stage, heat rejection and heat recovery, are important in determining energy efficiency in the plant. Simulation models of the evaporation stages can ensure that these processes are optimized at all times. Optimization can also help to keep plants online by slowing scaling – the most prevalent cause of maintenance downtime [14]. Figure 3 shows a simple MSF declinator.

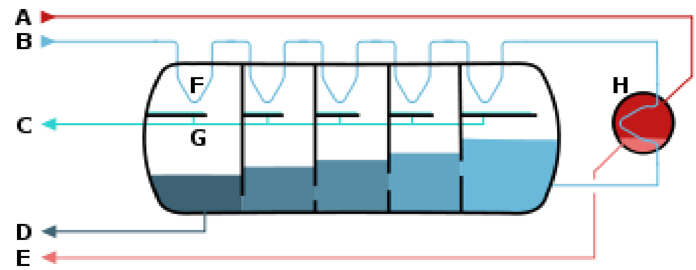

Figure 3: Schematic of a 'once-through' MSF declinator. Legend: A - Steam in, B - Seawater in, C - Potable water out, D - Waste out, E - Steam out, F - Heat exchange, G - Condensation collection, H - Brine heater [15].

2 Materials and Methods

2.1 Determination of Fresh Water Consumption per-Person

The quantity of fresh water needed on board an offshore structure like a 5000 tonnes work barge is not fixed. This is because there are many factors which will be considered before the quantity of water needed on board can be established. These factors are: the size of the vessel, the type of engines on board the vessel (i.e. diesel or steam), the number of crew (persons) on board and the voyage distance or time. Table 1 shows empirical quantities of fresh water needed in some parts of the world [16].

Table 1:
The Quantity of Fresh Water Consumption per Person per Day in Litres at Different Part of the World.

Area	Consumption US gallon/person/ day	Consumption litre/person/ day
USA	100	380
Europe	50	190
Africa	15	150
UN recommended	15	60
Minimum	13	50

Beside the two thermal based methods for desalination, the quality of the water which is produced with MSE depends on several influencing factors. Due to the used amount of heat, the concentration of salinity in the treated seawater, the size and number of tubes can affect the quality of the freshwater outflow [17]. Table 2 shows typical composition of seawater with salinity of 36,000 ppm while Table 3 shows the thermodynamic properties of seawater and fresh water at 25°C.

The main thermal desalination processes include MSF desalination, MED distillation, and MVC. Other thermal desalination processes, e.g., solar stills, humidification dehumidifica-

ISSN 2229-5518

tion, freezing, etc., are only found on a pilot or experimental scale. Thermal desalination processes consume a larger amount of energy than RO; approximately the equivalent of 10–15 kWh/m^3 for thermal processes versus 5 kWh/m^{3}for RO. Irrespective of this; the reliability and massive field experience in thermal desalination keeps its production cost competitive compared to the RO process. MSE has large scale production capacity for a single unit with production capacities of up to 30,000 m^3/day [18] [19].

Table 2:
Typical composition of seawater with salinity of 36,000 ppm [13]

Compound	Composition	Mass Percent	ppm
Chloride	Cl^-	55.03	19810.8
Sodium	Na^+	30.61	11019.6
Sulphate	$(SO_4)^{--}$	7.68	2764.8
Magnesium	Mg^{++}	3.69	1328.4
Calcium	Ca^{++}	1.16	417.6
Potassium	K^+	1.16	147.6
Carbonic Acid	$(CO_3)^-$	0.41	147.6
Bromine	Br^-	0.19	68.4
Boric Acid	$H_3BO_3^-$	0.07	25.2
Strontium	Sr^{++}	0.04	14.4
	Total	**100**	**36,000**

Table 3:
Thermodynamic properties of seawater and fresh water at 25°C

Thermodynamic Property	Seawater (Salinity = 36,000 ppm)	Fresh water (Salinity = 0 ppm)
Density [kg/m3]	1023.8	997.0
Specific Heat [kJ/kg$^\circ$C]	3.99543	4.186172
Viscosity [kg/ms]	0.960499	0.891807
Thermal conductivity (W/m$^\circ$C)	0.608656	0.610584

2.2 Mathematical Modeling Equations for MSE

Design Steps

From the equations below we will analyze the design of the MSE [20]

- First calculate how much amount of product will be obtained using

$$m_p = {(m_f * x)}/{y} \quad (1)$$

Then calculate how much evaporation will take place from

$$m_f = m_p + m_e \quad (2)$$

- Then assume steam economy and calculate amount of steam required to achieve desired separation using

$$m_s = \frac{m_e}{steam\ Economy} \quad (3)$$

- There are two basic equations of mass and energy balance, which are solved for each effect and calculation is made for that after each effect.

$$m_f = m_p + m_e \quad (4)$$
$$Q_F + Q_S = Q_C + Q_P + Q_E \quad (5)$$

These two equations are solved to get m_p *and* m_e

- Concentration per effect is calculated by x new = (feed flow for that effect*x old)/(product flow from that effect)
- Calculation is repeated until desired product concentration is obtained by assuming new value of steam economy each time.
- Then after area of each effect is calculated by

$$Q = U\ x\ A\ x\ \Delta T \text{ and } Q = m_s\ x\ \lambda S \quad (6)$$

$$A = \frac{(m_s\ x\ \lambda S)}{U\ x\ \Delta T} \quad (7)$$

- No of tubes are found by

$$N_t = \frac{A}{\pi DL} \quad (8)$$

- Flow rate of pump can be found by

$$Q_v = Velocity\ x\ Area\ x\ no\ of\ tubes \quad (9)$$

C_F = specific heat of Feed, kcal/kg $^\circ$C
C_{P1}, C_{P2} , C_{P3}, C_{P4} = specific heat of product in effects 1 to 4, kcal/kg $^\circ$C
C_{C1}, C_{C2}, C_{C3}, C_{C4} = specific heat of condensate in effects 1 to 4, kcal/kg$^\circ$C

λS = Latent heat of Steam (to 1st effect), kcal/kg

λC_{E1}, λC_{E2}, λC_{E3}, λC_{E4} = Latent heat of water evaporated, kcal/kg

T_F = Temperature of Feed, $^\circ$C
Ts = saturation temperature of feed to first effect, $^\circ$C
T_1, T_2, T_3, T_4 = Temperature at which evaporation takes place in effects 1 to 4, kJ/kg $^\circ$C

t_1, t_2, t_3, t_4 = Boiling Point Rise in effects 1 to 4, $^\circ$C

T_{P1}, T_{P2}, T_{P3}, T_{P4} = Product outlet temperature in effects 1 to 4, kJ/kg $^\circ$C
m_f = Mass flow rate of feed, kg/hr
x = Initial Total Dissolved Solids
y = Final Total Dissolved Solids

m_p = Mass flow rate Product should be, kg/hr
m_e = Total water evaporated, kg/hr

SE = Steam Economy
m_s = Mass flow rate of steam, kg/hr

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$m_{E1}, m_{E2}, m_{E3}, m_{E4}$ = water removed in effects 1 to 4, kg/hr
$m_{P1}, m_{P2}, m_{P3}, m_{P4}$ = Mass flow rate of Product obtained in effects 1 to 4, kg/hr

$m_{C1}, m_{C2}, m_{C3}, m_{C4}$ = Mass flow rate of condensate obtained in effects 1 to 4, kg/hr

3 Results and Discussions

The amount of product will be obtained by

$$m_p = {}^{(m_f * x)}/_{y} \quad (10)$$

m_f= 800kg/hr
x = 0.05 and y = 0.3
m_p = 666.67kg/hr
To calculate how much evaporation will take place by
$m_f = m_p + m_e$
m_e = (4000 – 666.67) kg/hr = 3333.33kg/hr

Then assume steam economy SE = 3.5
To calculate amount of steam required to achieve desired separation by

$$m_s = \frac{m_e}{steam\ Economy} = \frac{3333.33}{3.5} = 952.38 kg/hr$$

The two basic equations of mass and energy balance will be used, to solved for each effect and calculation is made for that after each effect how much calculation has been achieved.

$$m_f = m_p + m_e \quad (11)$$
$$Q_F + Q_S = Q_C + Q_P + Q_E \quad (12)$$

These two equations are solved to get m_p and m_e
Concentration per effect is calculated by x new = (feed flow for that effect*x old)/(product flow from that effect)
For 1st effect
$m_f = m_{p1} + m_{e1}$ (13)
By simple substitution
$4000 = m_{p1} + m_{E1}$ (14)
$Q_f + Q_s = Q_c + Q_p + Q_E$
$Q_f = (m_f\ x\ C_f\ x\ \Delta T_f)$
$Q_s = (m_s\ x\ \lambda_s)$
$Q_{c1} = (m_{c1}\ x\ C_{c1}\ x\ \Delta T_{c1})$
$Q_{p1} = (m_{p1}\ x\ C_{p1}\ x\ \Delta T_{p1})$
$Q_{E1} = (m_{E1}\ x\ \lambda_{E1})$

285000 + 514218.53 = 96190.38 + 82.81m_{p1} +546.22m_{E1}
703028.15 = 82.81m_{p1} +546.22m_{E1} (15)
Solving equations 14 and 15
$m_{p1} = 3197.71 kg/hr$
$m_{E1} = 802.29 kg/hr$

For 2nd effect
$m_{p1} = m_{p2} + m_{E2}$
By simple substitution
$3197.7 = m_{p2} + m_{e2}$ (16)
$Q_{p1} + Q_{E1} = Q_{c2} + Q_{p2} + Q_{E2}$
Q_{p1} = 3197.71 x 0.91 x 91
Q_{E1} = 802.29 x 546.22
$Q_{c2} = (m_{c2}\ x\ C_{c2}\ x\ \Delta T_{c2})$
$Q_{p2} = (m_{p2}\ x\ C_{p2}\ x\ \Delta T_{p2})$
$Q_s = (m_{E2}\ x\ \lambda_{E2})$

630101.21 = 72.09m_{p2} + 552.34m_{E2} (17)
Solving equations 16 and 17
$m_{p2} = 2365.61 kg/hr$
$m_{E2} = 832.09 kg/hr$

For 3rd effect
$m_{p2} = m_{p3} + m_{e3}$
By simple substitution
$2365.61 = m_{p3} + m_{E3}$ (18)
$Q_{p2} + Q_{E2} = Q_{c3} + Q_{p3} + Q_{E3}$
$Q_{p2} = (m_{p2}\ x\ C_{p2}\ x\ \Delta T_{p2})$
Q_{E2} = 832.09 x 552.34
$Q_{c3} = (m_{c3}\ x\ C_{c3}\ x\ \Delta T_{c3})$
$Q_{p3} = m_{p3}$ x 0.88 x 67
$Q_{E3} = (m_{E3}\ x\ \lambda_{E3})$

562900.52 = 58.96m_{p3} + 561.32m_{E3} (19)
Solving equations 18 and 19
$m_{p3} = 1522.74 kg/hr$
$m_{E3} = 842.87 kg/hr$

For 4th effect
$m_{p3} = m_{p4} + m_{E4}$
By simple substitution
$1522.74 = m_{p4} + m_{E4}$ (20)
$Q_{p3} + Q_{E3} = Q_{c4} + Q_{p4} + Q_{E4}$

Q_{p3} = 1522.74 x 0.88 x 67
$Q_{E3} = (m_{E3}\ x\ \lambda_{E3})$
$Q_{c4} = (m_{c4}\ x\ C_{c4}\ x\ \Delta T_{c4})$
$Q_{p4} = (m_{p4}\ x\ C_{p4}\ x\ \Delta T_{p4})$
$Q_{E4} = m_{E4}$ x 567.18

507566.12 = 50.46m_{p4} + 567.18m_{p4} (21)
Solving equations 20 and 21
$m_{p4} = 689.16 kg/hr$
$m_{E4} = 833.58 kg/hr$

Then after area of each effect is calculated by

$$Q = U\ x\ A\ x\ \Delta T \text{ and } Q = m_s\ x\ \lambda S$$

$$A = \frac{(m_s\ x\ \lambda S)}{U\ x\ \Delta T} \quad (22)$$

$$\text{Note } m_s = \frac{m_E}{steam\ Economy} \quad (23)$$

From equation 23
For 1st effect

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$$A_1 = \frac{(m_{s1}\ x\ \lambda_{s1})}{U_1\ x\ \Delta T_1}$$

$A_1 \approx 12m^2$

For 2nd effect

$$A_2 = \frac{(m_{s2}\ x\ \lambda_{s2})}{U_2\ x\ \Delta T_2}$$

$A_2 \approx 12m^2$

For 3rd effect

$$A_3 = \frac{(m_{s3}\ x\ \lambda_{s3})}{U_3\ x\ \Delta T_3}$$

$A_3 \approx 10m^2$

For 4th effect

$$A_4 = \frac{(m_{s4}\ x\ \lambda_{s4})}{U_4\ x\ \Delta T_4}$$

$A_4 \approx 24m^2$

To calculate the No of tubes

A = $\pi\ x\ no\ of\ tubes\ x\ OD\ of\ tube\ x\ length$

$$N_t = \frac{A}{\pi DL} \quad (24)$$

Take OD of tube 40mm and length of tube = 4m

From equation 24

For 1st effect, No of tubes

$$N_{t1} = \frac{A_1}{\pi DL} = 23.9$$

$$N_{t1}\ \equiv 24\ tubes$$

For 2nd effect, No of tubes

$$N_{t2} = \frac{A_2}{\pi DL} = 23.9$$

$N_{t2}\ \equiv 24\ tubes$

For 3rd effect, No of tubes

$$N_{t3} = \frac{A_3}{\pi DL} = 19.9$$

$N_{t3}\ \equiv 20\ tubes$

For 4th effect, No of tubes

$$N_{t4} = \frac{A_4}{\pi DL} = 47.7$$

$N_{t4}\ \equiv 48\ tubes$

Flow rate of pump can be found using

$$Q_v = Velocity\ x\ Area\ x\ no\ of\ tubes \quad (42)$$

Range of velocity is 0.02 to 0.05m/s

Take v = 0.04

For 1st effect

$$Q_{v1} = 15.36m^3/s$$

For 2nd effect

$$Q_{v2} = 15.36m^3/s$$

For 3rd effect

$$Q_{v3} = 8.00m^3/s$$

For 4th effect

$$Q_{v4} = 46.08m^3/s$$

Figure 4 is a single loop flowchart program written to help obtain the mass of evaporated water, mass flow rate of steam, mass flow rate of product, product flow rate and the discharge. With the help of the flow chart and the program drawn good results are obtained from the calculation process for the MSF design.

With the Program results obtained several graphs were plotted. Tables 4 to 7 are the result of the flowchart for MSF with variations of J_{v_avg}, keeping the production flow rate as constant. Similarly figures 5 to 7 shows the graphs plotted from the flowchart for the MSF design which shows the design to have satisfied all design characteristics.

N_E = Total element number

Q_P = Product flow rate

$J_{V\ ave}$ = Average velocity flux

$(M_A)_E$ = Mean area of element

From the calculation above the area of effects will range from 10m² and 24m² while the Flow rate or discharge of pumps in the effect will range from 8m³/s to 46m³/s and the number of tubes will fall into the range of 20 to 48 to enable the system produce about 16,000 litres per day for the 5000 tonnes offshore work barge. Q_P = 667 liters per hour and $J_{V\ ave}$ is between 12 to 16

Figure 8 shows the Computer presentation of Results from Flow Chart for MSE

Table 4:
Program results for MSF with constant J_{v_avg} of 13

Q_P	J_{V_avg}	M_{AE}	N_E
667	13	10	5.13
667	13	11	4.66
667	13	12	4.28
667	13	13	3.95
667	13	14	3.66
667	13	15	3.42
667	13	16	3.21
667	13	17	3.02
667	13	18	2.85
667	13	19	2.70
667	13	20	2.57
667	13	21	2.44
667	13	22	2.33
667	13	23	2.23
667	13	24	2.14

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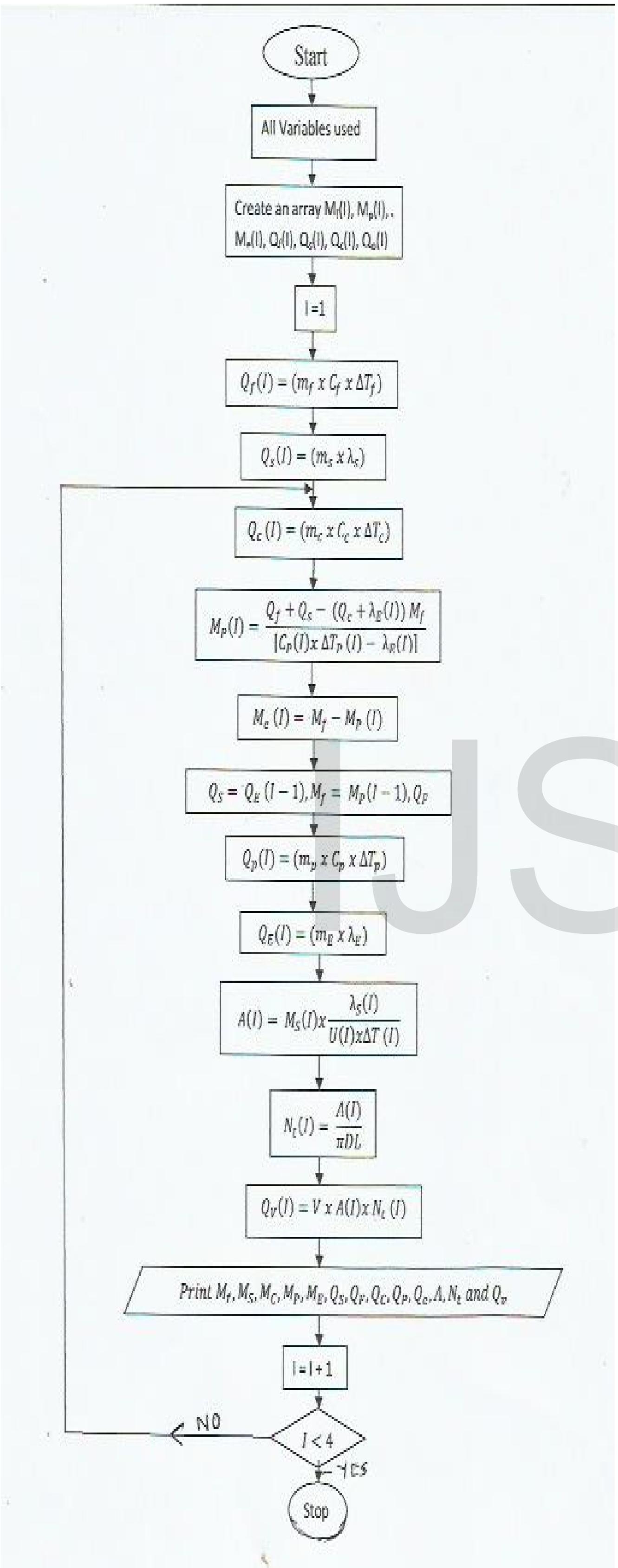

Figure 4: Flow Chart for MSE

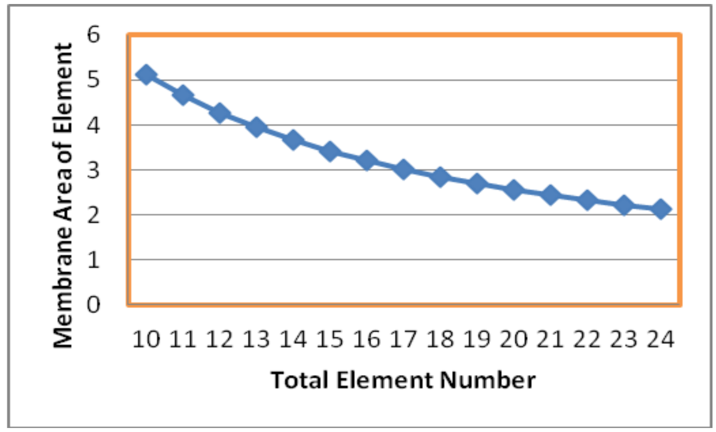

Figure 5: M_{AE} versus N_E for J_{v_avg} = 13

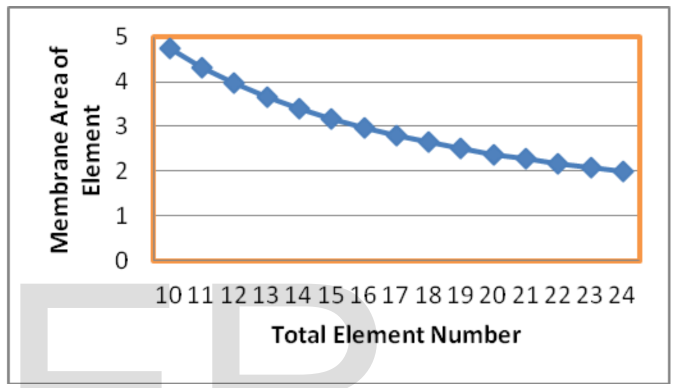

Figure 6: M_{AE} versus N_E for J_{v_avg} = 14

Table 5:
Program results for MED/MSF with constant J_{v_avg} of 14

Q_P	J_{V_avg}	M_{AE}	N_E
667	14	10	4.76
667	14	11	4.33
667	14	12	3.97
667	14	13	3.66
667	14	14	3.4
667	14	15	3.18
667	14	16	2.98
667	14	17	2.8
667	14	18	2.65
667	14	19	2.51
667	14	20	2.38
667	14	21	2.27
667	14	22	2.17
667	14	23	2.07
667	14	24	1.99

Table 6:

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Program results for MSF with constant J_{v_avg} of 14 with a varied Q_P

Q_P	J_{V_avg}	M_{AE}	N_E
500	14	17	2.1
550	14	17	2.31
600	14	17	2.52
650	14	17	2.73
700	14	17	2.94
750	14	17	3.15
800	14	17	3.36

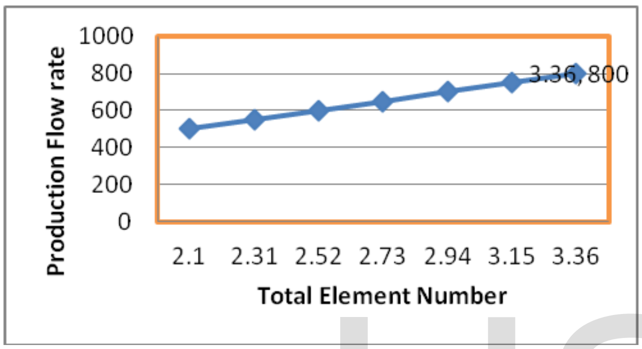

Figure 7: Q_P versus N_E for J_{v_avg} = 14

Table 7:
Program results for MED/MSF with constant J_{v_avg} of 16

Q_P	J_{V_avg}	M_{AE}	N_E
667	16	10	4.17
667	16	11	3.79
667	16	12	3.47
667	16	13	3.21
667	16	14	2.98
667	16	15	2.78
667	16	16	2.61
667	16	17	2.45
667	16	18	2.32
667	16	19	2.19
667	16	20	2.08
667	16	21	1.99
667	16	22	1.89
667	16	23	1.81
667	16	24	1.74

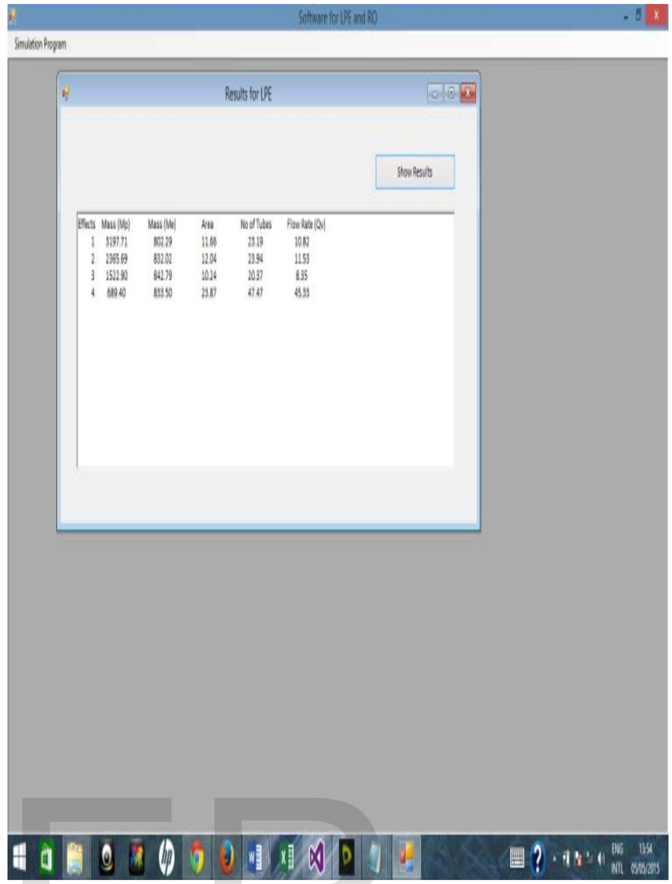

Figure 8: Computer presentation of Results from Flow Chart for MSE

4 Conclusion

The design of fresh water production system for the 5000 tonnes offshore work barge have brought to light the various methods of water production systems. Knowing that water is life then a better way of making life productive on board the vessel was not taken lightly. For proper functioning of the crew and running machinery on board an offshore structure to be archived due comparison of various water production methods and cost for the design of such plants were made, it has been found that the MSE method will be more suitable for the work boat especially in the Niger Delta region of Nigeria. The factors considered for this conclusion included the design cost, material availability, maintainability, durability, production capacity and space occupied. So the MSE is recommended to be the best option because it is also most efficient and has the greater capacity to produce as much quantity of fresh water needed on board with profit maximization for crew and machinery purposes. All designs were done in accordance with the rules of the classification society.

Acknowledgment

The author wishes to thank Prof E. A. Ogbonnaya for his sup-

port and contributions in making this work a success.

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