Design Configuration And Simulation Of A Multi Effects Evaporator For A Desalination Plant

Ethar Ali, Dr. Ahmed Elzain Elhassan, Hamid M. Mustafa, Omer Hassan Abdelrhman Alyas

Abstract: This research is focused on the economic feasibility of using multi-effect evaporators (MEV) for the production of potable water, for the city of Port Sudan, the main port of Sudan. Port Sudan city suffers from chronic shortage of potable water. The study has shown that five effect evaporator plant in Port Sudan can produce 1.41*106 m3/year at a unit cost of 5$/m3 with a pay-back period of 7 years. A simulation of the MEV has been performed using Aspen Hysys (version 7.3) and produced results were very much similar to these obtained manually.

Index Terms: Desalination, Economic, Multi effect evaporators, Port Sudan, Potable water, Simulation.

1 Introduction

Water is the most essential element for sustaining all life on the planet. That alone makes it a worthy subject for a single-topic issue. But there are also many issues swirling around this most precious resource about access to clean water, usage, availability, and control. Nearly a billion people do not have access to clean drinking water, and two billion lack adequate sanitation, leading thousands to die from waterborne diseases. Many experts believe that future global conflicts may ultimately be fights over water access, rights, and usage. Drinking water, and that this proportion will increase due to population growth relative to water resources. The worst-affected areas are the arid and semiarid rEGIONS OF ASIA AND NORTH AFRICA [1].

2 Procedure and Calculation

2.1 Seawater Desalination

Seawater is the largest water source available. Compared with existing fresh water natural resources, its availability is essentially unlimited in the foreseeable future. Seawater is still relatively unpolluted compared with natural fresh water sources and in many parts of the world fresh water is not easily available, whereas brackish water and seawater are readily available [2]. Many desalination technologies have been suggested based on different Principles of separation. Some of them have been successfully developed and become matured technologies. Some of these technologies include: Membrane Processes: (Reverse Osmosis (RO), Nano-Filtration, Ultra-Filtration and Micro-Filtration), Electro-dialysis Multi-Stage Flash, Multi-Effect Distillation and Multi-Effect Evaporator [3]. I chose multi effect evaporator (MEV) as part of my PhD research to look into the economic feasibility of this technology.

2.2 Material Balance:

The objective is production of 160000 kg/hr drinking water from 200000 kg/hr Sea water for the city of Port Sudan [4]. The salinity of red sea water is 2.4% salt (NaCl) and figure 1 show block flow diagram of the forward MEV.

- *Ethar Ali: Currently pursuing Doctorate Degree for Chemical Engineering from Karary University, Sudan. Email: ayaomer289@hotmail.com.*

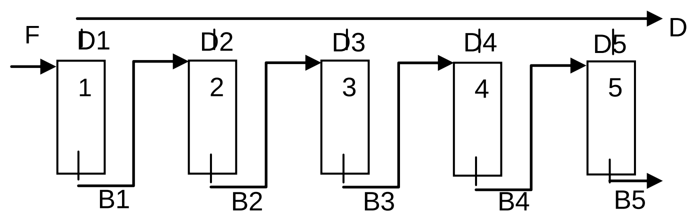

Figure 1: *Block flow diagram of the forward MEV, Where F is the feed in (kg/hr), D1, D2, D3, D4, D5, D is the distillates (kg/hr) and B1, B2, B3, B4, B5 is the bottoms (kg/hr).*

The basis for our choice for the number of effects is based on economic consideration. The economic parameter is the unit cost of producing 1 m^3 of potable water. We included the cost of steam, the capital fixed cost, depreciation to calculate how much cost for producing 1m^3 of potable water. The table 1 shows the unit cost calculation for 6 effects. The last column in the table is obtained by the total cost in column six by total production 3850$/$m^3$. When we plotted the unit cost against the number of effect as shown in figure 2**,** the unit cost decreases sharply from 1 effect to 5 effects. However, we found a marginal difference between 5 and 6 effects. For 5 effects the unit cost is 0.76 $/$m^3$, while the cost is 0.64$/m^3 for 6 effects. Therefore we decide to choose 5 effects for the desalination plant instead of 6 effects. To calculate the material balance for 5-effect MEV, Firstly we were assumed same distillate amount from each effect, F = 200000 kg/hr, D = 160000 kg/hr, and all vapor in each effect is the same. The results of material balance calculation are shown in table 2.

No of effect	steam cost	fixed charge – deprecation	Deprecation	Labor	Total	cost of unit $/m^3$
1	14080.00	12	06	40	14138.00	3.67
2	07040.00	24	12	40	07116.00	1.84
3	04693.33	36	18	40	04787.33	1.24
4	03520.00	48	24	40	03632.00	0.94
5	02816.00	60	30	40	02946.00	0.76
6	02346.66	72	36	40	02494.67	0.64

Table 1: *Unit cost calculation in each effect.*

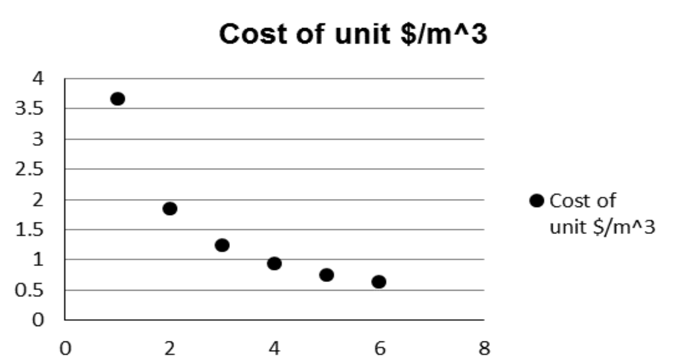

Figure 2: *The relation between the unit cost and the effect.*

2.3 Energy Balance

To do energy balance calculations we made the following assumptions:

i. In each effect there is negligible boiling point rise.
ii. Temperature of steam TS = 121° C
iii. Temperature in the last effect Tout = 40° C
iv. Heat transfer coefficient for 1st effect =2400

To calculate the overall heat transfer coefficient in each effect U_I, using the equation below [5]:

$$U_{i+1} = 0.95\, U_I \quad (1)$$

U_1 (W/m^2 °C)	U_2 (W/m^2 °C)	U_3 (W/m^2 °C)	U_4 (W/m^2 °C)	U_5 (W/m^2 °C)
2400	2280	2160	2057.7	1954.8

To calculate the temperature difference for each effect [5], . where ΔT_t is the temperature difference between the first and last effects:

Effect no.	Distillate (D) kg/hr	Bottom (B) kg/hr	Solid (mass fraction)
1	32000	168000	0. 02381
2	32000	136000	0. 02940
3	32000	104000	0. 03840
4	32000	072000	0. 05546
5	32000	040000	0. 09980

Table 2: *Material balance for MEV.*

$$\Delta T_i = \Delta T_{i-1} * \frac{U_{i-1}}{U_i}$$

ΔT_1(°C)	ΔT_2(°C)	ΔT_3(°C)	ΔT_4(°C)	ΔT_5(°C)
14.57	15.37	16.19	16.99	17.89

To calculate the temperature in each effect [5]:

$$T_i = T_{i-1} - \Delta T_i$$

$$D_i = D * \left(1 + \frac{ʎ_{v1}}{ʎ_{v2}} + \frac{ʎ_{v1}}{ʎ_{v3}} + \frac{ʎ_{v1}}{ʎ_{v4}} + \frac{ʎ_{v1}}{ʎ_{v5}} + \frac{ʎ_{v1}}{ʎ_{v6}}\right) \quad (5)$$

To calculate the value of latent heat of vaporization ($ʎ_{v1}$) in each effect [5], the latent heat can be obtained from the steam table or given correlation:

$ʎ_s = 2499.5698 - 2.204864 * T - 2.304 * 10^{-3} * T^2$ (4)

$ʎ_s$ (kJ/kg)	$ʎ_{v1}$ (kJ/kg)	$ʎ_{v2}$ (kJ/kg)	$ʎ_{v3}$ (kJ/kg)	$ʎ_{v4}$ (kJ/kg)	$ʎ_{v5}$ (kJ/kg)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]407.69

$$A_i = \frac{ʎ_{v1} * D_1}{U_i * (Ts - T_i)} \text{[6]} \quad (6)$$

: Total product flow rate = 160000 kg/hr.

D_1 (kg/hr)	D_2 (kg/hr)	D_3 (kg/hr)	D_4 (kg/hr)	D_5 (kg/hr)
33171.05	32577.84	31990.46	31413.38	30847.26

Initially we were assumed equal values for distillates from each effect but now after using energy balance calculations, these values was re-evaluated and given above. To calculate the area of heat transfer coefficient in each effect [5]:

Thus the total amount of steam needed:

A_1 (m^2)	A_2 (m^2)	A_3 (m^2)	A_4 (m^2)	A_5 (m^2)
589.99	589.87	589.95	590.11	589.93

$Q_1 = U_1 * A_1 * \Delta T_1 = ʎ_s * S$ (7)

$= 2400 W/m^2 °C * 589.99\ m^2 * 14.57°C = 20630770.32\ W$

Where S is steam and Q_1 is amount of heat duty in first effect. Thus table 3 show the actual amount of distillate, bottom, and solid mass fraction for each effect:

$$S = \frac{20630770.32\ J/s}{1000 * 2199.048 J/kg} * \frac{3600s}{hr} = 33774.06\ kg/hr$$

Effect no.	Distillate (D) kg/hr	Bottom (B) kg/hr	Solid mass fraction
1	33171.05	166828.95	0. 023980
2	32577.84	134251.1	0. 029799
3	31990.46	102260.65	0. 039100
4	31413.38	070847.27	0. 056400
5	30847.26	040000.01	0. 099800

Table 3: The actual amount of distillate, bottom, and solid mass fraction for each effect.

$$\frac{1}{\sum_{i=1}^{5} U_i} = \frac{1}{U_1} + \frac{1}{U_2} + \frac{1}{U_3} + \frac{1}{U_4} + \frac{1}{U_5} \text{[6]} \quad (2)$$

$$\Delta T_1 = \frac{\Delta T_t}{\left(U_1 * \left(\frac{1}{\sum_{i=1}^{5} U_i}\right)\right)} = \frac{81}{2400 * 2.3157 * 10^{-3}} = 14.57^oC \quad (3)$$

2.4 Simulation of MEV

We used Aspen HYSYS (version 7.3) to carry simulation of the multi effect evaporators and compare the simulation results with our manual calculations. We chose NRTL electrolyte as our thermodynamic model [7]. We fed HYSYS with the following input data: Temperature of feed 30°C, feed flow rate 200000kg/hr, NaCl mass Composition in the feed 0.97. Figure 3 shows the work sheet of the 5 effects generated by HYSYS. Each effect is represented by re-boiler absorber and heat exchanger. Table 4 shows the output results produced by HYSYS. They include the fraction of solids, amount of distillate and the temperature in each effect.

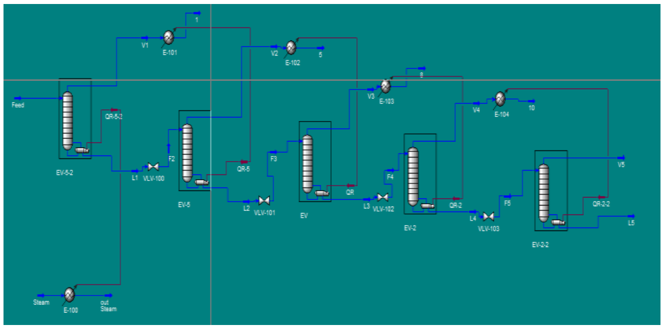

Figure 3: *Aspen HYSYS simulation for desalination process.*

Effect No.	Fraction of solids	Amount of Distillate Kg/hr	Temperature in each effect °C
1	0.0286	24380	133.5
2	0.0344	30000	127.8
3	0.0457	35870	120.6
4	0.0720	42060	111.8
5	0.0906	47660	100.3

Table 4: *HYSYS output results.*

When compared between hand calculation and Aspen HYSYS results, we observed the following regarding the comparison between our hand calculation and that of HYSYS:

i. The mass fractions of the bottom products for all effects are in good agreement. For example in effect #1, the mass fraction for hand calculation is 0. 02398, while it is 0.0286 in Simulation result.
ii. Also we observed good agreement in the amount of vapor produced from each effect. For example the amount produced from effect #3 is 31990.46 kg/hr in hand calculation, while it is 35870 kg/hr in Simulation results.

iii. The only discrepancy between our hand calculations and HYSYS results lies in temperature of each effect. For example, the temperature in the first effect is 106.43° C by hand calculation while it is 133.5° C in Simulation results. We attribute this discrepancy to the fact that the minimum pressure allowed in the Simulation is 1 atmosphere, and we could not lower this pressure below 1 atmosphere.

2.5 Cost Estimation

Cost estimation is a specialized subject and a profession in its own right. The design engineer, however, needs to be able to make quick, rough, cost estimates to decide between alternative designs and for project evaluation. [8] Part of my research work focused on the cost estimation of building a desalination plant in Port Sudan city using the multi effect evaporator Technology. Our effort is to compare the price of existing potable water in Port Sudan to the unit cost of producing the same amount of water from MEV.

Item		Price (2014)
Total cost of equipment	Evaporator+ pump+ boiler	1958684.00$
fixed cost	Depreciation+ insurance+ local taxes	0551720.00$
operating capital	15% of TCI	1390893.00$
total investment	-	7881730.00$
manufacturing cost	0.68TPC+543838	3902339.60$
general expenses	0.091TPC	0449446.54$
total production cost	Direct manufacturing cost+Total fixed charge+ plant overhead+general expenses	1312000.00$
sale (income)	Income of water +Income of salt	6406400.00$/year
Gross profit (before taxes)	Income– TPC	01247312.00$
net profit (after taxes)	Gross profit – (Gross profit * Tax %)	01247312.00$
Internal rate of return (IRR)	Net Profit / TCI	13.4%
payback period	1 / IRR	7 years

Table 5: *Cost estimation calculation. Where TCI is total capital investment and TPC is Total production cost.*

Selling price for water 5$/m3. The real price of bottle (18 liter) of water in Port Sudan is 0.8$ (Produced by reverse osmosis), the selling price of 18 liter bottle produced by MEV is 0.1$.

3 Conclusions

a. The MEV is matured technology that Port Sudan city can rely on to produce potable.
b. Using multi effect evaporators reduce the cost of potable water in Port Sudan RO versus 0.1$ bottle produced by MEV.
c. The salt produced from MEV as a byproduct can be utilized table salt produced.

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