

## **EXERGY AND THERMO-ECONOMICS INVESTIGATION OF MULTI EFFECT EVAPORATION (MEE) AND HYBRID MULTI EFFECT EVAPORATION – MULTI STAGE FLASH (MEE-MSF) SYSTEMS**

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### **ABSTRACT**

In this investigation, a number of comparisons for Multi Effect Evaporation (MEE) as well as hybrid Multi Effect Evaporation – Multi Stage Flash (MEE-MSF) systems have been performed using the exergy and thermoeconomics analysis. The comparison is performed based on the same platform and working under the same operating conditions. Thermoeconomics analysis is applied to account for both energy and cost simultaneously. The best of the MEE and MEE-MSF studied configurations, from the economical point of view, is obtained. The numerical results reveal that the unit product cost of forward feed FF-MEE configuration is 25 % less than that of the parallel/cross P/C-MEE configuration. A comparison between two hybrid configurations of MEE\_MSFF systems showed that the unit product cost of the once through (MEE-MSF-OT) is 5 % less than the mixing brine (MEE-MSF-M) system.

Thermoeconomics results of the comparison between the forward feed FF-MEE, and the combined MEE-MSF-OT showed that the combined system has a unit product cost of 7 % less than that of the FF-MEE under the same operating conditions.

**Key words:** MEE, MSF, Hybrid MSF-MEE, Exergy, Thermoeconomics.

### **INTRODUCTION**

Multiple Effect Evaporation (MEE) process is one of the main and most effective thermal desalination techniques. The race for the second generation of the sea water desalination systems has been settled with RO and low temperature MEE of horizontal tube evaporators. Both systems are characterized by their low energy consumption as compared to the Multi Stage Flash (MSF) system, Darwish [1]. Many configurations of MEE process can be obtained by changing the feed pre-heater arrangement and feed

flow patterns. Bleeding steam as heating source, heat recovery from condensate, distillate flash box and combination with Multi-Stage Flash (MSF) process as a feed pre-heater are different techniques for MEE feed preheating.

Using thin brine film evaporation outside the horizontal tubes, in MEE systems, increase the heat transfer coefficient especially with corrugated tubes. This also decrease the resident time required for the scale formation. The recent trend is to use horizontal tube evaporators connected inside a large vessel with inside gates and ducts to direct streams between effects. These arrangements avoid the problem of using many connections at many effects, Darwish [1]. Many configurations of MEE process can be arranged and schemed by changing the feed pre-heater arrangement and types.

Different methods of MEE feed preheating are considered, Nafey [2]. Bleeding steam as heating source, heat recovery from condensate, distillate flash box and combination with Multi-Stage Flash (MSF) as a feed pre-heater are available techniques for MEE feed preheating. Also, many feed flow patterns such as forward feed, parallel feed and parallel/cross feed are examined [3]. Most of the previous works are carried out to reduce the energy consumption cost by enhancing the steam economy (kg product/kg steam) (performance ratio) [1, 2, 3]. However, reducing the steam consumption flow rate increase the required heating surface area to give the same distilled output. Five different configurations of MEE process were solved by Nafey [2] under the same operating and design conditions. Nafey (1988) showed that the configuration shown in Fig.1 which preheats the feed by vapor bleed through external heat exchangers has the higher performance ratio. Performance analysis was conducted by El-Dessouky *et al.* [3] for the Parallel and parallel/cross flow patterns of MEE process. Results indicated that better performance is obtained by parallel/cross feed of Fig.2. In the work of Krebs *et al.* [4], a combined Multi stage Flash and Vertical Tube Evaporators (MSF-VTE) process was investigated. In this process a forward-fed, multiple-effect, falling film is arranged in parallel with MSF stages as shown in Fig. 3. The performance of the combined processes was investigated under variety of operating modes. A multi purpose plant was described by Kuenstle and Brunner [5]. This plant produces drinking water and chemicals from sea water. A combined MSF-VTE has high economy ratio and produce high concentration of the brine. In this process, the VTE evaporators units are arranged in parallel to the MSF stages. Each module consists of two MSF stages and one VTE evaporator unit as shown in Fig. 4.

The review mentioned above showed that different MEE configurations were considered, and different preheating techniques were used. Number of comparisons has been made based on the first law of thermodynamics [2, 3, 4, 5]. However the economical comparison of these configurations based on the second law computations (Thermo-economics) is still required. Second law analysis computations allow engineers to distribute energy resources at the boundary of the system of interest to each part of the system. Thermoconomics distribute the expenses on the plant boundary in each unit streams based on the exergy not energy. The exergy destruction was estimated by Spiegler *et al.* [6] for specific operating conditions of MEE unit and MSF stage. The results showed that the exergy destruction of the MEE effect is lower

than that of the flash chamber. To determine the best of these of MEE configurations, from the economical point of view, a comparison should be performed based on the same platform and working under the same operating conditions. Based on the exergy and thermoeconomics analysis methodology, the developed Visual Design and Simulation (VDS) package has been developed by the authors [7, 8], and will be used in the present work for these comparisons. Energy, Exergy and Thermo-economics calculations are sequentially performed to obtain the performance ratio, exergetic efficiency and the product water cost respectively.

The following procedures are followed to carry out the comparison between the considered configurations. Firstly, a comparison between the forward feed FF-MEE of Fig.1 and parallel/cross feed P/C-MEE of Fig. 2 is carried out. Secondly, once through combined MEE-MSF-OT of Fig.3 and brine mixing MEE-MSF-M of Fig.4 are compared. The economical analysis from the first and the second steps will be the best configuration of pre-heater feed technique for MEE plant. The horizontal falling film evaporator is considered in all MEE configurations. The same operating conditions such as steam temperature, the distillate output, the salt concentration in the feed and the reject lines are fixed for all the considered configurations.

## **PROCESS CONFIGURATIONS**

### **(i) Forward Feed - Multi Effect Evaporation (FF-MEE) System**

Fig.1 shows the process flowsheet of the forward feed multi effect evaporation (FF-MEE) system as presented in Nafey [2]. The hot end is at the left side however the cold end is at the right side, at the last effect. The vapor flows from left to right, in the direction of falling pressure, while the sea water feed flows in opposite direction. The brine stream leaves the first stage to the second stage, where it sprayed on the evaporator tubes. The system contains a number (n) of evaporators (effects) and a train of (n-1) condensers which use the bleeding steam as a heating medium for the feed stream, a train of (n-1) feed/distillate heat exchangers and a down condenser.

### **(ii) Parallel/Cross Feed - Multi Effect Evaporation (P/C-MEE) System**

Fig.2 shows parallel/cross feed multi effect evaporation system as presented in El-Dessouky et. al. [3]. The hot end is at the left side and the cold end is at the right side, at the last effect. The vapor flows from left to right, in the direction of falling pressure, while the sea water feed flows in a perpendicular direction. The brine stream leaves the first effect to the second effect, where it flashes and mixes with the feed seawater. The system contains a number (n) of evaporators (effect) and a train of (n-1) flashing tanks, and a down condenser.

### (iii) Hybrid MEE and Once Through MSF (MEE-MSF-OT) System

The proposed hybrid configuration is shown in Fig.3 in which the MEE evaporators are arranged in parallel to MSF evaporators. Each MSF stage together with an MEE evaporator forms a module. A brine heater and desuperheater are utilized in the oriented configuration. The sea water feed is preheated in the MSF evaporators before it is introduced to the brine heater. The exit stream from brine heater is divided into two streams; the first stream is fed to the first MEE evaporator where vapor is formed by utilizing external heating steam. The exit brine stream of the first MEE evaporator is then mixed with the second stream out of the brine heater. The mixed brine stream is then fed to the first stage of MSF where the vapor is formed by flashing. The exit brine stream from the first MSF stage is again divided into two streams; the first stream is directed to the second MEE evaporator to produce another amount of vapor using the formed vapor of the first effect. The exit brine stream is then mixed with the second one before entering the second MSF stage. This stream situation is repeated for all modules. The vapor of the last MEE evaporator is condensed in a separate condenser using cooling sea water. Equal feed flow rate and equal heating surface area of MEE evaporators are considered in this process. As the sea water is directly introduced to the last stage of the MSF, this configuration is denoted by once through MEE-MSF-OT.

### (iv) Hybrid MEE and Mixed Brine MSF (MEE-MSF-M) System

Fig.4 shows another configuration for the hybrid MEE-MSF systems. This configuration is similar to that in Fig. 3 in the relative position of the main units. However the sea water feed is mixed with a blend of the rejected stream before proceeding into the last stage of the MSF preheater.

## EXERGY AND THERMO-ECONOMICS ANALYSIS

Mathematical models of mass and energy balance equations are illustrated in details by Nafey [2] and El-Dessouky *et al.* [3]. Here only the exergy and thermoeconomic analysis are presented.

### 1. Exergy Mathematical Model

The method of exergy is the most visible and established techniques to analyse the plant losses and the units cause losses. Exergy analysis is a method that uses the mass and energy conservation principles together with the second law of thermodynamics (entropy equations) for the design and analysis of desalination processes. The exergy of saline water, vapor and distilled water are presented by the authors in [8]. Exergy balance analysis of each unit in the considered configurations is performed based on the following equation:

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \quad (1)$$

The rate of fuel exergy ( $\dot{E}_F$ ) represents the resources expended to generate the product  $\dot{E}_p$ . The difference between the fuel and product is mainly due to exergy destruction within the system ( $\dot{E}_D$ ) and the exergy loss out of the process ( $\dot{E}_L$ ), [9].

The exergy balance equation for most employed components in the present configurations are illustrated in details in [8]. As an illustrated example, the exergy balance of the Forward Feed evaporator and parallel/Cross feed evaporator are explained in the following section.

**a. Forward Feed Evaporator, Fig. 5**

To simplify the exergy analysis of the evaporator, it may be considered as two subunits; preheater/condenser exchanger and flash tank splitter, which are operating simultaneously as shown in Fig. (5).

**(2) Heat exchanger of the evaporator:**

$$\dot{E}_{steam,in} - \dot{E}_{condensate,out} = \dot{E}_{b,2} - \dot{E}_{b,1} + \dot{E}_{D,exchanger} \tag{2}$$

**(ii) Splitter (brine pool) of the flash tank:**

$$\dot{E}_{b,2} - \dot{E}_{b,3} = \dot{E}_{vapor} + \dot{E}_{D,splitter} \tag{3}$$

By summing (2), and (3), the exergy destruction in the forward feed evaporator is obtained as :

$$\dot{E}_D = \dot{E}_{steam,in} - \dot{E}_{condensate,out} + \dot{E}_{b,1} - \dot{E}_{b,3} - \dot{E}_{vapor} \tag{4}$$

The exergetic efficiency of the evaporator unit is written as follows:

$$\eta_{II} = \frac{\dot{E}_{b,3} - \dot{E}_{b,1} + \dot{E}_{vapor}}{\dot{E}_{steam,in} - \dot{E}_{condensate,out}} \tag{5}$$

**b. Parallel/Cross Feed Evaporator, Fig. 6:**

**(2) Heat exchanger of the evaporator:**

$$\dot{E}_{steam,in} - \dot{E}_{condensate,out} = \dot{E}_{b,2} - \dot{E}_{feed,1} + \dot{E}_{D,exchanger} \tag{6}$$

**(ii) Splitter (brine pool) of the flash tank:**

$$\dot{E}_{b,2} + \dot{E}_{b,3} - \dot{E}_{b,4} = \dot{E}_{vapor} + \dot{E}_{D,splitter} \tag{7}$$

By summing (6) and (7), the exergy destruction in the forward feed evaporator is obtained as:

$$\dot{E}_D = \dot{E}_{steam,in} - \dot{E}_{condensate,out} + \dot{E}_{feed,1} + \dot{E}_{b,3} - \dot{E}_{b,4} - \dot{E}_{vapor} \tag{8}$$

The exergetic efficiency of the evaporator unit is:

$$\eta_{II} = \frac{\dot{E}_{b,4} - \dot{E}_{feed,1} - \dot{E}_{b,3} + \dot{E}_{vapor}}{\dot{E}_{steam,in} - \dot{E}_{condensate,out}} \quad (9)$$

## 2. Thermo-Economics Mathematical Model

The cost balance of the equipment relates the rate of the expenditures made to generate the product. The general cost balance equation can be written as follows [9]:

$$\dot{C}_p = \dot{C}_F + \dot{Z}^{CI+OM} \quad (10)$$

The above equation expresses that the cost rate associated with the product of the stream  $\dot{C}_p$  equals the total rate expenditures made to generate the product, namely the fuel cost rate  $\dot{C}_F$  and the cost rates associated with capital investment and operating & maintenance  $\dot{Z}^{CI+OM}$ .

The cost balance equations for most of the unit employed in the present configurations are illustrated in details in [8]. Here due to space limitation only the evaporator is illustrated as an example:

### a. Forward Feed Evaporator, Fig.5:

#### (i) Preheater/condenser:

The incoming feed temperature is increased at the expense of the condensation of the heating steam.

$$\dot{C}_{b,2} - \dot{C}_{b,1} = \dot{C}_{steam} - \dot{C}_{condensate} + \dot{Z}_{hx}^{(CI+OM)} \quad (11)$$

#### (ii) Splitter (pool brine):

Since the inlet brine is partly vaporized and the remaining brine leaves the pool with higher salt concentration; so  $\dot{C}_p = \dot{C}_{vapor}$  &  $\dot{C}_F = \dot{C}_{b,2} - \dot{C}_{b,3}$  which leads to the following equation:

$$\dot{C}_{vapor} = \dot{C}_{b,2} - \dot{C}_{b,3} + \dot{Z}_{splitter}^{(CI+OM)} \quad (12)$$

Summing equations (11) and (12), the evaporator cost balance is written as follows:

$$\dot{C}_{vapor} + \dot{C}_{b,3} - \dot{C}_{b,1} = \dot{C}_{steam} - \dot{C}_{condensate} + \dot{Z}_{evaporator}^{CI+OM} \quad (13)$$

As there are three outlet streams from evaporator, two additional auxiliary equations are required. The first auxiliary equation states the equality of the average cost of the inlet feed and exit brine.

$$\frac{\dot{C}_{b,1}}{\dot{E}_{b,1}} - \frac{\dot{C}_{b,3}}{\dot{E}_{b,3}} = 0 \tag{14}$$

The second auxiliary equation states the equal average cost of the heating steam and its condensate; i.e.

$$\frac{\dot{C}_{\text{vapor}}}{\dot{E}_{\text{vapor}}} - \frac{\dot{C}_{\text{condensate}}}{\dot{E}_{\text{condensate}}} = 0 \tag{15}$$

**b. Parallel/Cross Feed Evaporator, Fig.6:**

**(i) Preheater/condenser:**

The incoming feed temperature is increased at the expense of the condensation of the heating steam.

$$\dot{C}_{b,2} - \dot{C}_{\text{feed},1} = \dot{C}_{\text{steam}} - \dot{C}_{\text{condensate}} + Z_{hx}^{(CI+OM)} \tag{16}$$

**(ii) Splitter (pool brine):**

Since the inlet brine is partly vaporized and the remaining brine leaves the pool with higher salt concentration; so  $\dot{C}_p = \dot{C}_{\text{vapor}}$  &  $\dot{C}_F = \dot{C}_{b,2} + \dot{C}_{b,3} - \dot{C}_{b,4}$  which leads to the following equation:

$$\dot{C}_{\text{vapor}} = \dot{C}_{b,2} + \dot{C}_{b,3} - \dot{C}_{b,4} + Z_{\text{splitter}}^{(CI+OM)} \tag{17}$$

Summing equations (16) and (17), the evaporator cost balance is written as follows:

$$\dot{C}_{\text{vapor}} + \dot{C}_{b,4} - \dot{C}_{\text{feed},1} - \dot{C}_{b,3} = \dot{C}_{\text{steam}} - \dot{C}_{\text{condensate}} + Z_{\text{evaporator}}^{CI+OM} \tag{18}$$

Two additional auxiliary equations are required. The first auxiliary equation states the equality of the average cost of the inlet feed and exit brine.

$$\frac{\dot{C}_{\text{feed},1}}{\dot{E}_{\text{feed},1}} - \frac{\dot{C}_{b,4}}{\dot{E}_{b,4}} = 0 \tag{19}$$

The second auxiliary equation states the equal average cost of the heating steam and its condensate; i.e.

$$\frac{\dot{C}_{\text{vapor}}}{\dot{E}_{\text{vapor}}} - \frac{\dot{C}_{\text{condensate}}}{\dot{E}_{\text{condensate}}} = 0 \tag{20}$$

The capital investment and operating & maintenance term of the right hand side of the above equations  $Z^{CI+OM}$  is calculated using the illustrated relations in Table (1).

The total annual investment cost of each process unit is calculated according the following relation, [9]:

$$\text{Annual Investment} = \text{Present value} \times \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad (21)$$

Using an interest rate,  $i = 7\%$  and the amortization year,  $n = 10$  years; then, the hourly cost equals to  $= \frac{\text{annual investment}}{365 \times 24 \times 0.9}$  \$/hr. This cost is fed to the program as a capital cost for each process unit.

The VDS package, developed by the authors [7], uses the designed and operating variables of Table (2) to solve mass, pressure, energy balance equations. Then the exergy flow rate of the streams is calculated. The process cost balance equation model is solved to obtain the monetary cost flow rate of the streams. Then the following parameters are calculated for the overall plant performance analysis:

$$\text{- Performance ratio, PR} = \frac{\text{distilled flow rate}}{\text{steam flow rate}} = \frac{\dot{m}_d}{\dot{m}_s} \quad (22)$$

$$\text{- Plant Exergetic efficiency, } \eta_{II} = \frac{\dot{E}_{\text{distilled-water}}}{(\dot{E}_{\text{steam}} - \dot{E}_{\text{condensate}}) + \dot{E}_{\text{feed}} + \dot{E}_{\text{pumping-power}}} \quad (23)$$

$$\text{- Unit product cost, } \$/\text{m}^3, \dot{C}_w = \frac{\dot{C}_{\text{distilled}} + \dot{C}_{\text{loss}} (\$/\text{hr})}{\text{Distilled flow rate (T/hr)}} = \frac{\dot{C}_p + \dot{C}_L}{\dot{m}_d} \quad (24)$$

$$\text{- Specific heat transfer area, SA} = \frac{\text{Heat transfer area}}{\text{Distilled out put flow rate}} \quad (25)$$

## RESULTS AND DISCUSSION

Figure 7 shows comparison between the forward feed (FF-MEE) and the parallel cross feed (P/C-MEE) multi effect evaporator at different evaporator number. Figure (7.a) shows that the performance ratio of the FF-MEE and P/C-MEE configurations increases as the number of evaporator (effects) increase. The increase in the performance ratio for larger number of effects is a result of increasing the number of vapor reuse in the system. The system performance ratio of the FF-MEE is 25 % higher than that of P/C-MEE system. Figure (7.b) shows that the specific heat transfer area for the two systems increases with increase of the evaporator numbers. The increase in the specific heat transfer is caused by the reduction in the driving force for heat transfer, or the temperature drop per effect. Figures (7.a & 7.b) show that the Forward Feed system has higher performance ratio and lower specific heat transfer area than the Parallel/Cross system. Figure (7.c) shows that the exergetic efficiency for the two systems increases as the evaporators number increases. Although, the exergy out of the system is fixed, the exergetic efficiency is increased. This is owing to the decrease in the consumed steam flow rate and the required of pumping power. The lower input exergy is a result of the reduction in the exergy destruction and exergy loss. Figure (7.c) shows also that the FF\_MEE system is more exergetic than the P/C-MEE. Figure (7.d) shows that the unit product cost of the distillate decreases as the



evaporator numbers increase. The unit product cost reduction is caused by the decrease in the operating cost (steam consumption, electrical) despite the increase in the cost of the surface area. Figure (7.d) shows also that the unit product cost in the FF-MEE configuration is lower than that of the P/C-MEE. The input invested cost in the FF-MEE system is small due to the lower cost of the destruction energy (or lower loss cost) which associated with the rejected streams. The numerical results reveal that the unit product cost of FF-MEE configuration 25 % less than that of the P/C-MEE for eight evaporators. The conclusion drawn from the above discussion is that the forward feed FF-MEE configuration is preferable.

Two configurations of combined of MEE and MSF in parallel arrangement, shown in Fig.3 and Fig.4, are conducted under different evaporators (effects) number. Fig. 8 illustrates the energy, exergy and thermoeconomic results for the two configurations MEE-MSF-OT and MEE-MSF-M. Equal feed flow rate to each evaporator is maintained as well as equal heat transfer area of each evaporator is considered. The performance ratio, the exergetic efficiency and the specific heat transfer area increase as the number of effects increase. The pumping power decreases as the evaporator number increases. This reduction is owing to the reduction in the cooling water flow rate. The thermoeconomic results reveal that the total input cost decreases as the evaporator number increases as shown in Fig. (8.d). This because the reduction in the operating cost (steam and electrical cost) is more dominant than the capital investment (heat transfer surface area). The unit product cost decreases as the evaporator number increases that is due lower input cost (or lower in the sum of both destruction cost and loss cost). The results showed that the unit product cost of the MEE-MSF-OT is 5 % less than the MEE-MSF-M system. This is mainly owing to the lower specific area as shown in Fig. (8.b).

Figure 9 shows the comparison between the forward feed FF-MEE (8 effects) and the combined MEE-MSF-OT (8 effects + 8stages) at different heating steam temperature. Figure (9.a) shows that the performance ratio variation of the two systems is slightly decrease as the heating temperature increase. This figure indicates that the MEE-MSF-OT configuration has the higher performance ratio. Figure (9.b) shows that the specific heat transfer decreases in the two systems as the heating steam temperature increase. This is because the increase in the temperature drop per stage, which enlarges the driving forces for heat transfer. Also, at higher temperatures the value of the overall heat transfer coefficient augments causing the decrease in the heat transfer area. This figure indicates that the specific heat transfer area for the FF-MEE and MEE-MSF-OT are identical. Figure (9.c) shows that the exergetic efficiency variation at different heating steam temperature. Figure (9.d) shows that the unit product cost decreases for the two systems as the heating steam temperature increases. The combined MEE-MSF-OT has the lower unit cost than the FF-MEE due to the higher in the performance ratio, the lower in the specific heat transfer area and lower in the pumping power. The numerical results of the thermoeconomic analysis reveal that the unit product cost for the two systems FF-MEE and MEE-MSF-OT are 1.08 and 1.0  $\$/\text{m}^3$  respectively at the heating steam temperature of 110°C and 5000  $\text{m}^3/\text{day}$

capacity. The combined system MEE-MSF-OT has a unit product of 7% less than that of FF-MEE at the same operating conditions.

## CONCLUSIONS

1. The numerical results reveal that the unit product cost of Forward Feed Multi Effect Evaporation (FF-MEE) configuration is 25 % less than that of the Parallel Cross Multi Effect Evaporation (P/C-MEE) for eight evaporators (effects). In addition, the (FF-MEE) performance ratio is also 25 % higher than that of (P/C-MEE) system. FF-MEE configuration is, therefore, preferable than P/C-MEE.
2. Comparison between the two hybrid configurations of (MEE-MSF-OT) and (MEE-MSF-M) showed that the cost of the heat transfer area is more effect rather than the steam consumption cost. The unit product cost of the once through (MEE-MSF-OT) is 5 % less than the mixing brine (MEE-MSF-M) system.
3. The hybrid (MEE-MSF-OT) system has the lower unit cost than the (FF-MEE) system, due to its higher performance ratio, lower specific heat transfer area and lower required pumping power. The hybrid (MEE-MSF-OT) system has a unit product cost of 7 % less than that of FF-MEE at the same operating conditions.

## NOMENCLATURE

- $\dot{C}$  : cost flow rate, \$/hr  
 $c$  : cost per unit exergy, \$/GJ  
 $\dot{E}$  : Exergy flow rate, MW  
 $\dot{m}$  : Mass flow rate, kg/s  
 $\dot{Z}$  : Rate of the capital cost
- Superscripts:**  
 $CI$  : Capital investment  
 $OM$  : Operating & Maintenance
- Subscripts:**  
 $b$  : Brine water  
 $D$  : Destruction  
 $d$  : Distillate  
 $L$  : Loss  
 $F$  : Fuel  
 $P$  : Product
- Greek Letters**  
 $\eta_{II}$  : Exergetic efficiency

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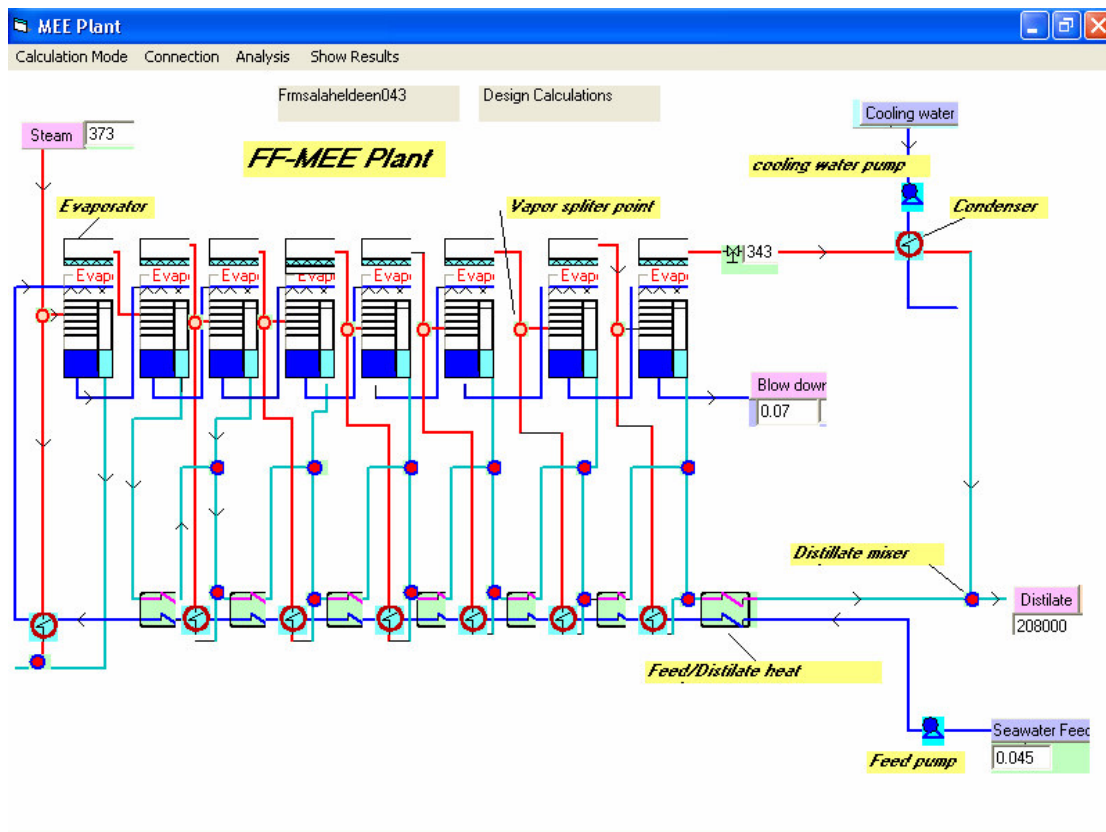
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**Table (1): Cost data of the process unit**

Unit	Equation	Reference
Evaporator, \$	$4135 \times A^{0.786} \Rightarrow A: \text{area (m}^2\text{)}$	Nafey (1988),[2]
Pump, \$	$65 \times Q^{0.825} \Rightarrow Q: \text{m}^3 / \text{hr}$	Nafey (1988),[2]
Heat exchanger, \$	$1224 \times A^{0.57} \Rightarrow A: \text{m}^2$ or $57 \times A \Rightarrow A: \text{m}^2$	Nafey (1988),[2] El_Dessouky (1999),[3]
Steam cost, \$/ton	3.5	Bejan, [9 ]
Intake cost, \$/hr	3	Nafey et al. (2004),[8]

**Table (2): Specified variable used for design calculation**

Specified Variable	Value	Units
Sea water temperature, $T_f$	27	$^{\circ}\text{C}$
Salt concentration in feed, $X_f$	0.045	kg/kg
Required Distillate	208	Ton/hr
Vapor temperature at the last evaporator	47	$^{\circ}\text{C}$
Salt concentration at the reject stream	0.07	kg/kg
Heating steam temperature	90,100,110	$^{\circ}\text{C}$
$\Delta T$ , approach for heat exchanger	2.778	$^{\circ}\text{C}$



**Fig. 1: Forward Feed Multi Effect Evaporation (FF-MEE) System**

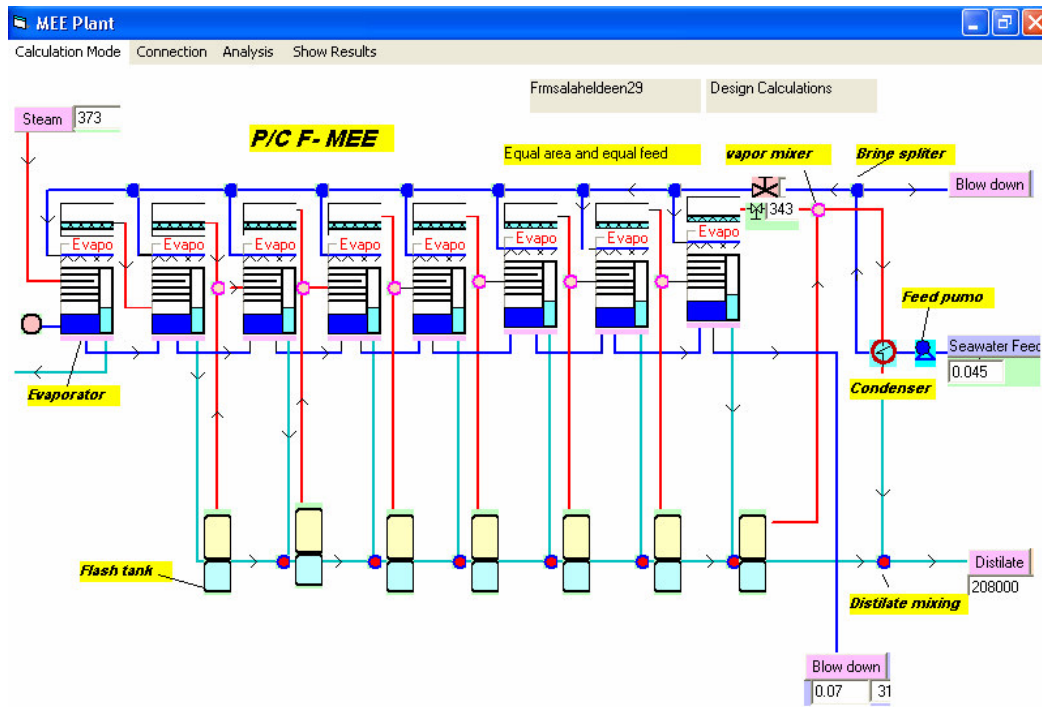


Fig. 2: Parallel/Cross Feed Multiple Evaporation (P/C-MEE) System

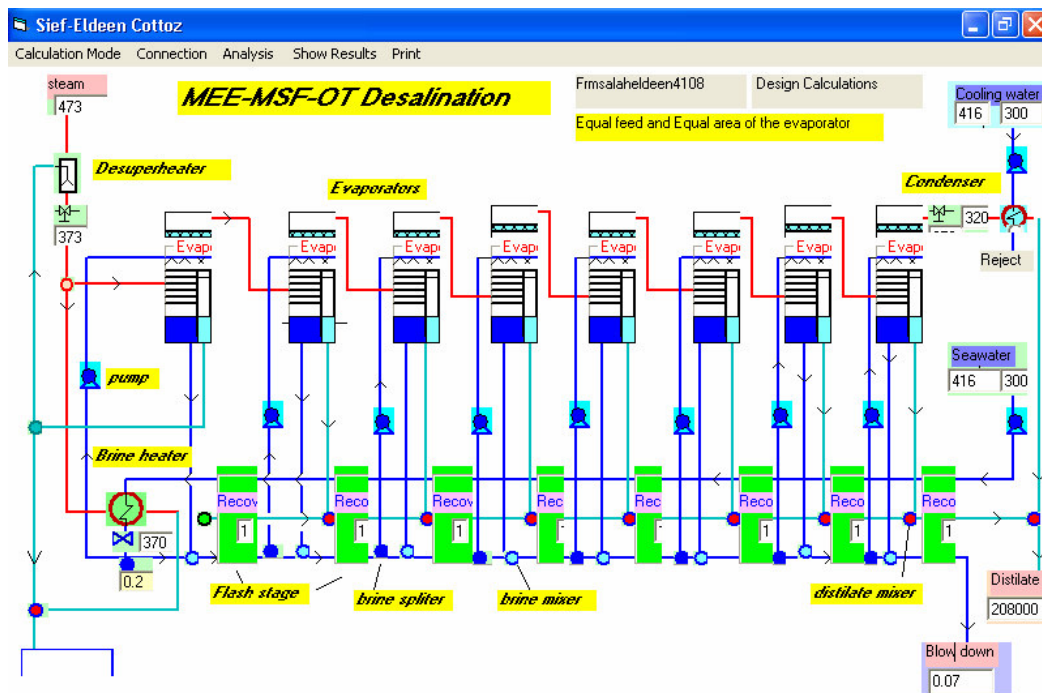
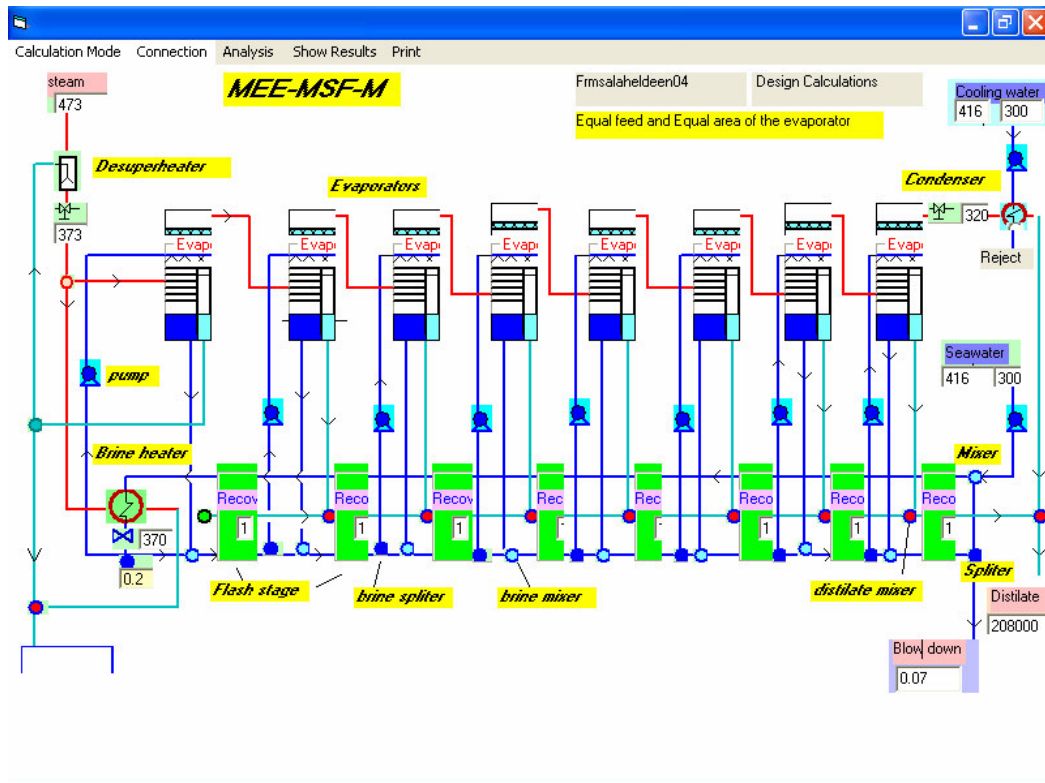
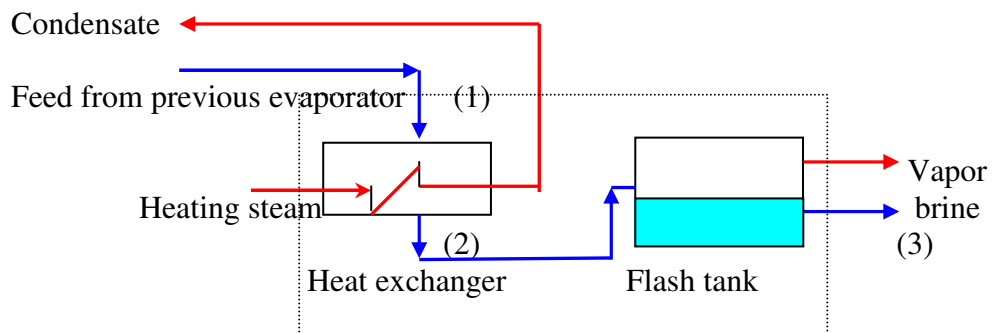


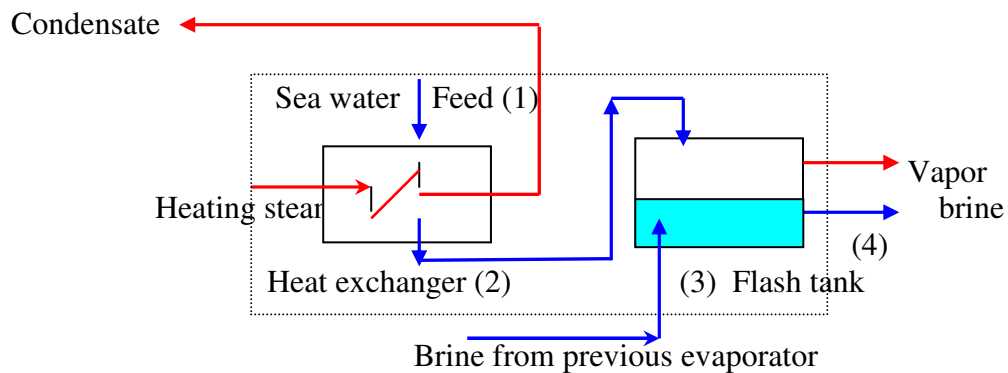
Fig. 3: Hybrid Multi Effect and Once Through MSF (MEE-MSF-OT) System



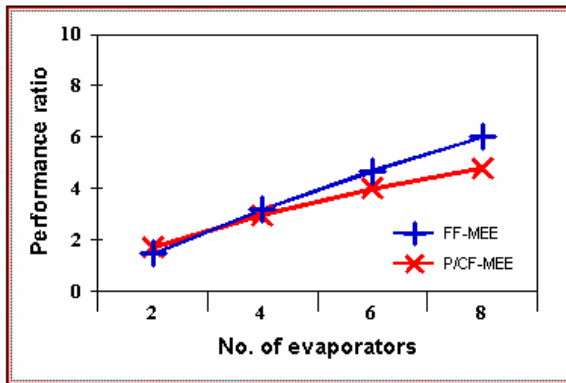
**Fig. 4: Hybrid Multi Effect and Mixed brine MSF (MEE-MSF-M) System**



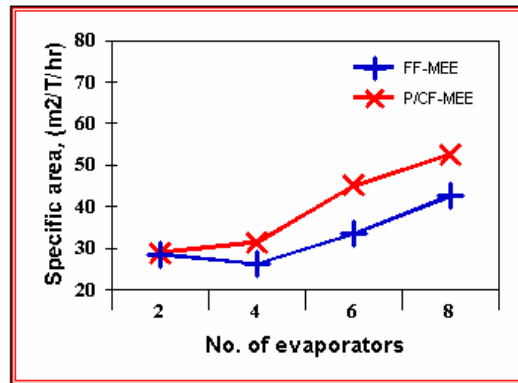
**Fig. 5: Simple flow sheet of Forward Feed Evaporator**



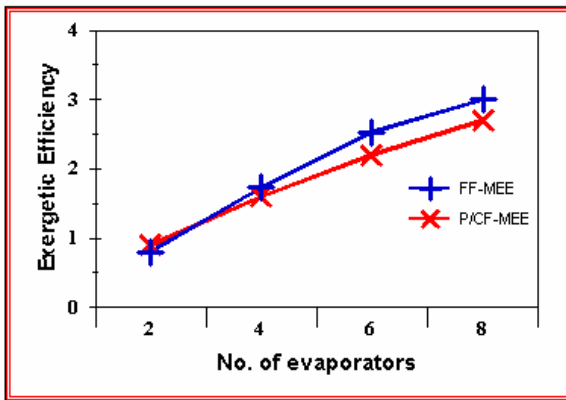
**Fig. 6: Simple flow sheet of Parallel/Cross Feed Evaporator**



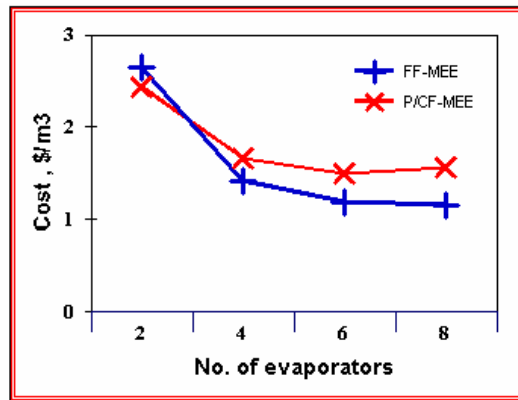
(a) Performance ratio



(b) Specific area

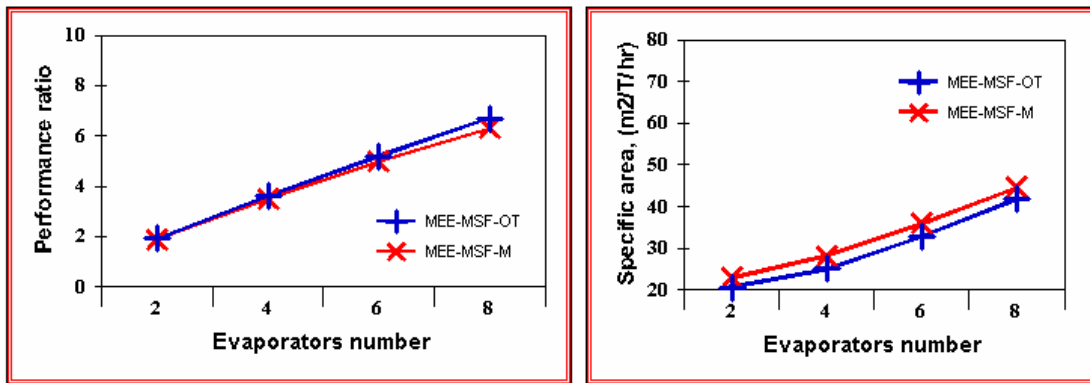


(c) Exergetic efficiency



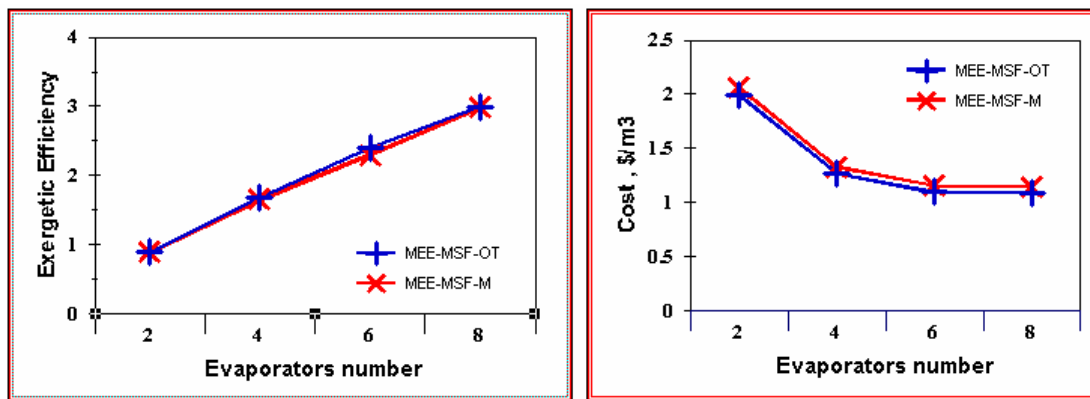
(d) Product Unit Cost

Figure (7) Performance Comparison between (FF-MEE) and (P/C-MEE) Systems



(a) Performance ratio

(b) Specific area

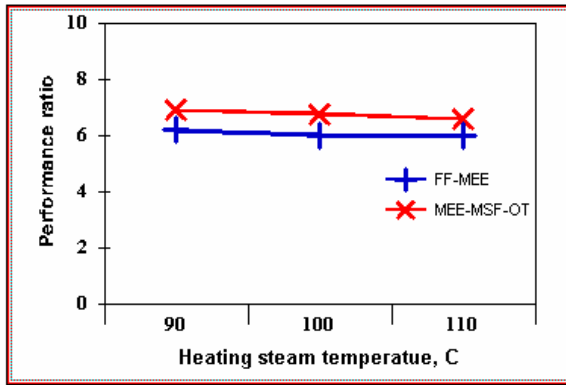


(c) Exergetic efficiency

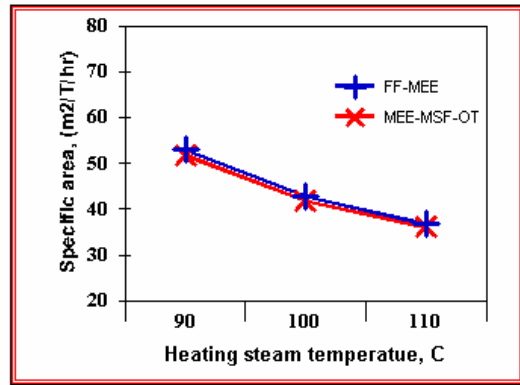
(d) Product Unit Cost

**Figure (8) Performance Comparison between (MEE-MSF-OT) and (MEE-MSF-M) Hybrid Systems**

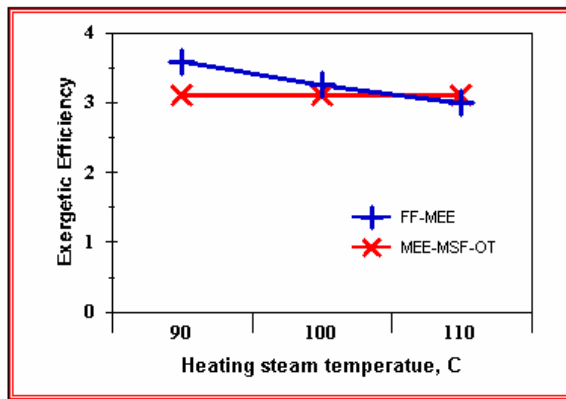




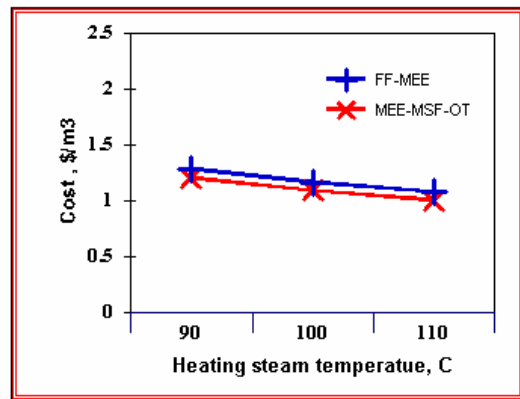
(a) Performance ratio



(b) Specific area



(c) Exergetic efficiency



(d) Product Unit Cost

Figure (9) Performance Comparison between (FF-MEE) and (MEE-MSF-OT) Systems