# Thermo-economic Analysis of Seawater Desalination System

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***Abstract:*** *The article is focused on two main methods of seawater desalination. Each method is analyzed separately. Municipal solid waste (MSW) is used as energy source. Coupling of waste to power and seawater desalination plant is discussed in this paper. The case study presents a touristic area where this process could by worthy. The main goal of this article is to calculate the unit product cost as main parameter in desalting plants.*

***Keywords: Desalination, Multi-effect distillation, Reverse Osmosis, Energy, Cost.***

## 1. Introduction

Fresh water is becoming an ever-more precious commodity, again because the arid regions of the world appear to be expanding. This gap is expected to widen in the near future, due mainly to the high rate of population growth and the urbanization. Seawater desalination represents an increasingly interesting solution for the problem of fresh water scarcity. This process consumes large amounts of energy while municipal solid waste (MSW) may be transformed to produce electricity and thermal energy [1]. Waste treatment is an extraneous term in Albanian towns and their thermal utilization in the recent years is encouraged. Seawater desalination can help to resolve local problems of water supply, which, especially in arid areas, can risk the development and the life of people. Nowadays several technologies are available, either thermal (Multi Stage Flash, Multiple Effect Distillation), or mechanical (Reverse Osmosis). Most of them easily achieve the 500 ppm Total Dissolved Solids (TDS) index recommended by the World Health Organization for drinkable water. Since desalination involves high specific consumption of energy per $m^3$ of distilled water, the adoption of economic and efficient desalination technologies is desirable.

## 2. Reverse Osmosis (RO)

Reverse osmosis is a membrane separation process in which the seawater permeates through a membrane by applying a pressure larger than the osmotic pressure of the seawater (Fig.1). The membrane is permeable for water, but not for the dissolved salts. In this way, a separation between a pure water fraction (permeate) and a concentrated brine (the concentrate) is obtained. The membrane is capable of separating salt from water with a rejection of 98–99.5%. Membranes are polymeric thin-film composite membranes, consisting of a very thin separating layer and a number of supporting layers with much lower resistance against mass transport. While they are very permeable for water, their permeability for dissolved substances is very low. By applying a pressure, difference across the membrane and the water contained in the feed is forced to permeate through the membrane. In order to overcome the feed side osmotic pressure, high feed pressure is required. In seawater desalination, it commonly ranges from 5,5 MPa to 7 MPa. The disadvantage of RO is the sensitivity of RO membranes to fouling e.g. by suspended solids, and to damage by oxidized compounds such as chlorine or chlorine oxides. Pretreatment is usually needed to ensure a stable performance of the module; optimization of the pretreatment is one of the most critical aspects of RO [2].

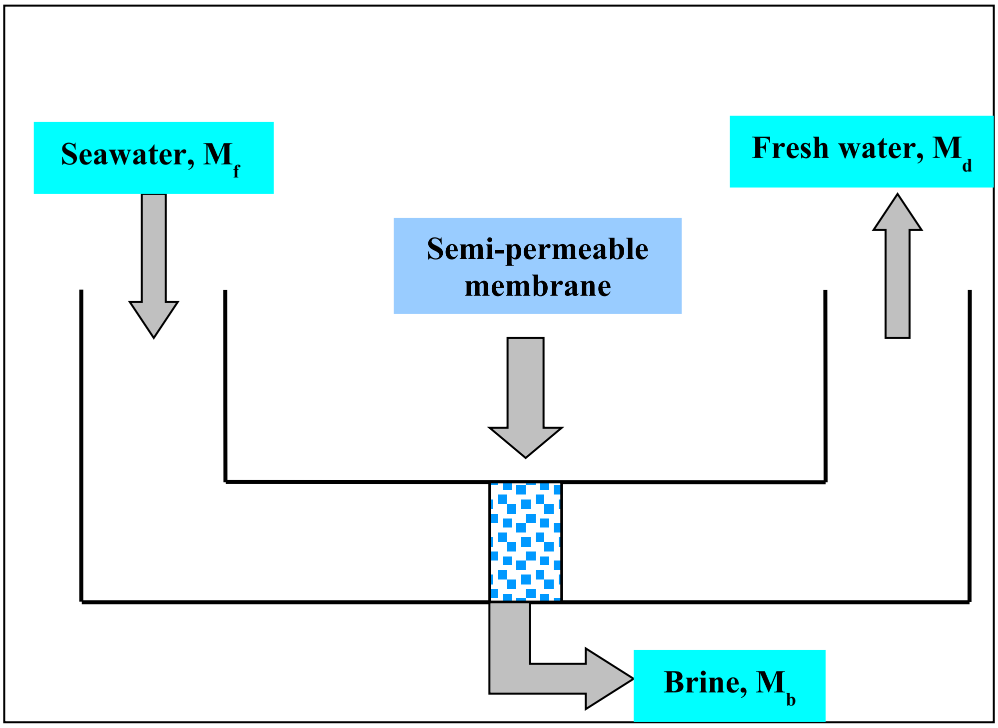

***Fig.1*** *Schematic of RO process*

## 3. Description of Multi-effect distillation (MED)

The Multi-Effect Distillation process takes place in a series of vessels and uses the principle of reducing the ambient pressure in the various effects [3]. In a MED process the feed water enters the first effect and is raised to the boiling point after being preheated in tubes. The tubes are heated by steam from a boiler/turbine which is condensed on the opposite sides of the tubes. The remaining fed water is fed to the second effect, where it is again applied to a tube series. The tubes are in turn being heated by the vapor created in the first effect. The vapor is condensed to distillate while giving up heat to evaporate a portion of remaining feed water in next effect. The main feature of the MED process is that it operates at low top brine temperature 60-70ºC [4].
MED has many variants such as forward feed, parallel feed, mixed feed and backward feed. In the forward feed, both water and heating vapor to the evaporators flow in the same direction; hence the least salinity is at the highest temperature in the first effect. A typical forward feed scheme is shown in Figure 2. Here the cooling water (Mcw) enters the condenser at $T_{in}$ to condense Dn, (last effect vapor output) and leaves at $T_{out}$. Part of the pre-treated Mcw becomes feed (Mf), and is heated successively as it flows in the feed heaters from $T_{out}$ to $Tf_1$, before entering the first effect. The balance ($M_{cw}$-$M_f$) is rejected back to the sea. The supplied stem (Ms) to the first effect heats the feed from $Tf_1$ to the boiling temperature $Tv_1$, and boils $D_1$ out of $M_f$ ($D_1$ is the first effect distillate). Vapor $D_1$ enters the first feed heater $FH_1$, preheats $M_f$, from $T_{f2}$, to $Tf_1$, and then flows as heating vapor to the second effect. The process is repeated to the last effect. Brine $B_1$ enters the second effect as feed, and brine $B_2$ enters as feed effect3 and so on to the last effect. The design of single effect is shown in detail in subchapter 4.2.

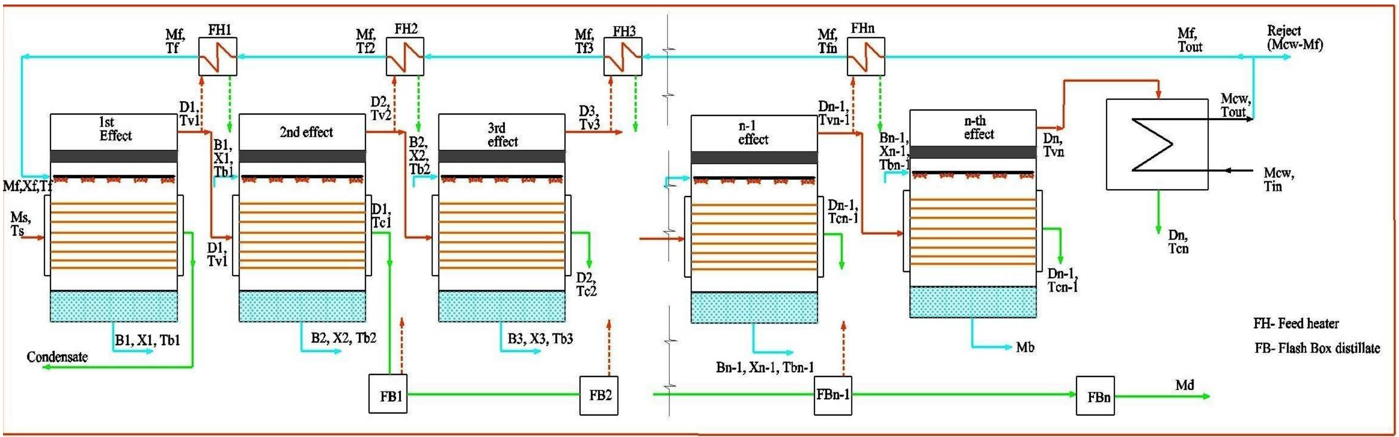


***Fig.2****.Forward feed Multi-effect distillation with feed heaters [4]*

## 4. The Case study

For this case an Albanian touristic area of 100 000 inhabitants has been assumed. The typical present day per capita content of MSW is evaluated 450 – 550 kg/year. MSW calorific value is considerable, 8, 5-13 MJ/kg. For the calculations we have accepted $LHV_{waste}$=11 500 kJ/kg, from which results that nominal thermal power in boiler is $Q_{boiler}$=32,5 $MW_{th}$ and electricity generated E= 9 $MW_{el}$.

### 4.1 Reverse Osmosis powered by waste firing plant

First, we consider that the total energy production of 9 $MW_{el}$ is used to supply RO desalting plant. In order to calculate the unit product cost is necessary to make some assumptions:

- Steady state operation
- Isothermal operation. Therefore the temperatures of the feed, brine and permeate are equal.
- The membrane selectivity is constant and is equal for various types of salts.

In the scheme below is examined a 2 000 $m^3$/d desalination plant. This assumed value is much higher than last achievements in the membrane technology. The main design variables in RO systems are:

- the recovery rate,
- the salt rejection, $S_R$ = 99 %
- the operating pressure,
- the permeate flux, both in terms of overall product rate and specific rate.

For a given salt rejection of the membranes used, technical feasibility of single-stage systems for potable water production is expressed by the following condition:

$$X_d = (1 - S_R / 100) X_f \le 0.5 \qquad (1)$$

$X_f$- salinity of feed water, ≈ 40 [g/kg] [5] (typical value of Mediterranean seawater)
$X_d$- salinity of product water [g/kg]

RO layout and with parameters is shown in **Figure 3**. The cost results from the calculations are summarized in **Table 2**.

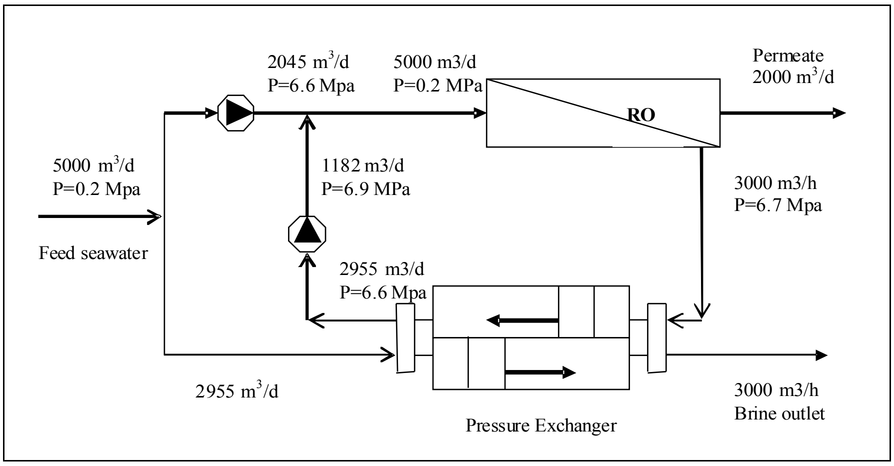


***Fig. 3.*** *Single RO desalination schneme*

In order to decrease the power consumption a pressure exchanger is appropriate for energy recovery. These work exchangers directly transfer brine hydraulic energy to feed hydraulic energy. In any case, cost reduction rarely exceeds 10 % of water cost [6].

### 4.2. Multi-effect distillation process coupled with waste firing plant

In the second assumption the waste firing plant supplies with heat and electricity the MED plant. Desalting capacity is accepted 2 000 $m^3$/d (23.14 kg/s) with 8 effects. Particularly for the MED [4] suggests equal vapor generated by evaporation in each effect (other than $1^{st}$ effect) =βD. Equal temperature drop between effects as well equal specific heat for the brine, and feed water have been assumed. The top brine temperature TBT=70ºC has been accepted, Tn, =38ºC, $T_{cw}$=$T_{in}$=25ºC, $T_{out}$=30ºC, $C_p$=4.2 kJ/kgºC, average latent heat λ=2333 kJ/kg, and feed salinity $X_f$=46 g/kg, and maximum salinity $X_b$=64 g/kg.
Our task is to find: *temperature and salinity distribution, the gain ratio $M_d/M_s$, feed to distillate ratio $M_f/M_d$, cooling water to distillate ratio $M_{cw}/M_d$, and the specific heat transfer area of effects and feed heaters,* if the overall heat transfer coefficient of effects $U_e$= 3 kW/m2ºC, and for feed heaters $U_f$=2.6 kW/m2ºC.

The design of MED parameters starts with the definition of the temperature drop across each effect, which is obtained from equation (2).

$$\Delta T = \frac{TBT - T_{bn}}{n-1} \tag{2}$$

Then,

$$T_{v1} = t_{bn} + (n-1)\Delta T \tag{3}$$

Based on the mathematical models developed by [7] and [10] could be estimated $M^f$

$$\frac{M_f}{M_d} = \frac{X_b}{(X_b - X_f)} \tag{4}$$

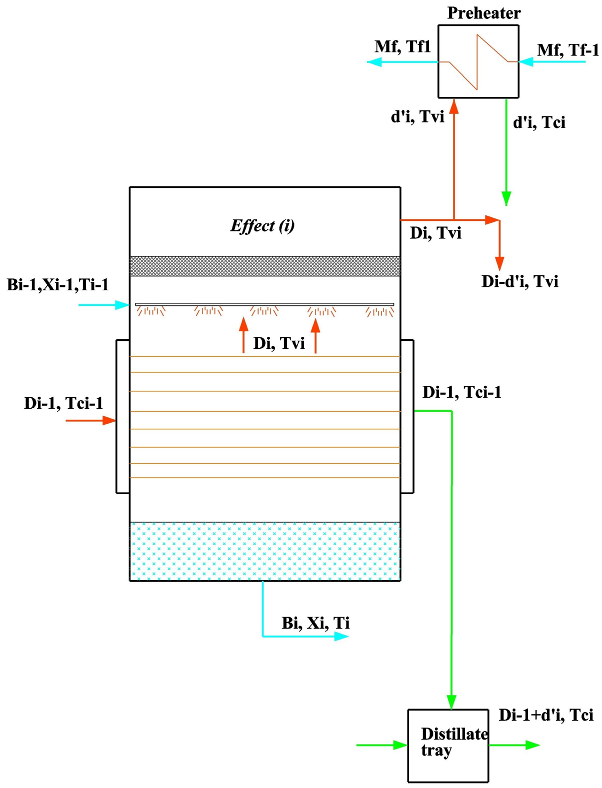


***Fig.4.*** *Layout of detailed model of the $i^{-th}$ effect of MED plant*

The salinity of distillate $X_d$, in this case is neglected.

Part of D1 (vapor) equals d'$_1$ where $d_1' = yM_f$ and $y = \frac{C_p \Delta t}{\lambda}$ is condensed in the $FH_1$ as it heats $M_f$, and the balance ($D_1$-d') enters the second effect to boil the same amount. Since vapor boiled in each effect, except the first, is the same and equal to βD then

$$D_1 = yM_f + \beta D$$

Brine flow rate in effect 1 becomes feed for the second effect, and its temperature $T_{b1}$, drops to $T_{b2}$, by flashing $yB_1$=d'$_2$

$$B_1 = M_f - D_1 = (1-y)M_f - \beta D \quad (5)$$

$$D_2 = \beta D + yB_1 \quad (6)$$

$$B_2 = B_1 - D_2 = B_1 - (\beta D + yB_1) \quad (7)$$

$$B_2 = B_1(1-y) - \beta D = \\ = (1-y)[M_f(1-y) - \beta D] - \beta D \quad (8)$$

$$B_2 = (1-y)^2 M_f - \frac{\beta D}{y}[1-(1-y)^2]$$

(9)

And similarly for the n-th effect,

$$B_n = (1-y)^n M_f - \frac{\beta D}{y}[1-(1-y)^n]$$

(10)

The salinity in second effect $X_2 = X_1 M_f / B_1$

$$X_i = X_{1-1} B_{i-1} / Bi \quad (11)$$

The overall mass balance

$$M_f = M_d + M_b \quad (12)$$

The evaporator heat transfer area, for the first and next effects are written as

$$A_{e1} = \frac{M_s \lambda_s}{U_e (T_s - T_b)} \quad (13)$$

$$A_{ei} = \frac{D_b \lambda}{U_e (\Delta T - BPE)} \quad (14)$$

Where, BPE - boiling point elevation equal to (0.8-1 ºC).

The area of each feed heater derives from balance equation (15)

$$M_f C_p \Delta T = U_f A_f \Delta t_{\ln} \quad (15)$$

The seawater cooling flow rate in the condenser $M_{cw}$ is estimated by the equation of energy balance [8]

$$D_8 \lambda = M_{cw} C_p (T_{out} - T_{in}) \quad (16)$$

and the heat transfer area of the condenser is equal to

$$A_c = \frac{M_{cw} c_p (T_{out} - T_{in})}{U_c . \Delta t_{\ln}} \quad (17)$$

Where the logarithmic mean temperature difference is

$$\Delta t_{\ln} = \frac{T_{out} - T_{in}}{\ln \frac{T_{vn} - T_{out}}{T_{vn} - T_{in}}} \quad (18)$$

Based on [8] the steam consumption is calculated from the relation

$$M_s \lambda_s = M_f c_p (T_1 - T_f) + D_1 \lambda_1 \quad (19)$$

From the calculation has been resulted that gain ratio $\frac{M_d}{M_s} = 7.4$ And cooling water to distillate ratio $\frac{M_{cw}}{M_d} = 5.9$

In Table 1, are shown the results for each effect of designed MED process. As can be seen, for this case the negligible contribution of distillate flashing boxes is not taken into consideration

*Tab.1*. *Main characteristics of MED plant*

| *Effect* | $T_{bi}$ | $T_{vi}$ | *F (kg/s)* | $D_{boiling}$ *(kg/s)* | *d' (kg/s)* | *D (kg/s)* | *B (kg/s)* | *X (g/kg)* | $A_e$ *(m²)* | $A_f$ *(m²)* |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 70 | 65 | 61,55 | 2,963 | 0 | 2,963 | 58,55 | 42,02 | 1619 | |
| 2 | 65,72 | 60,72 | 58,55 | 2,495 | 0,451 | 2,946 | 55,63 | 44,25 | 589 | 50,6 |
| 3 | 61,44 | 56,44 | 55,63 | 2,495 | 0,4284 | 2,9234 | 52,719 | 46,69 | 589 | 50,6 |
| 4 | 57,16 | 52,16 | 52,719 | 2,495 | 0,415 | 2,91 | 49,81 | 49,42 | 589 | 50,6 |
| 5 | 52,88 | 47,88 | 49,81 | 2,495 | 0,39 | 2,885 | 46,936 | 52,44 | 589 | 50,6 |
| 6 | 48,6 | 43,6 | 46,936 | 2,495 | 0,361 | 2,856 | 44,085 | 55,8 | 589 | 50,6 |
| 7 | 44,32 | 39,32 | 44,085 | 2,495 | 0,349 | 2,844 | 41,221 | 59,75 | 589 | 50,6 |
| 8 | 40,04 | 35,04 | 41,221 | 2,495 | 0,3179 | 2,8129 | 38,414 | 63,99 | 589 | 50,6 |
| Total | | | | | | 23,1403 | | | 5742 | 354,2 |

## 5. Some cost aspects of desalination plants

After designing the main parameters of multi-effect distillation, a cost analysis of both plants has been carried out. The evaluation has been considered the two separate plants powered by MSW power plant, including:

- Direct capital cost
- Specific chemical cost
- Specific (operation and maintenance ) cost
- Membrane cost
- Specific steam and electricity cost.

***Tab.2.*** *Unit cost production of fresh water for each desalination process*

| | ***RO unit*** | | ***MED unit*** | |
|---|---|---|---|---|
| Plant capacity, $m^3/d$ | | 2 000 | | 2000 |
| Recovery rate (RO), % and conversion rate (MED), % | | 40 | | 38 |
| Direct capital cost, €$m^3/d$ | | 1350 | | 1400 |
| Chemical consumption, $kg/m^3$ | | 0,28 | | 0,1 |
| Chemical cost, €/kg | | 0,18 | | 0,18 |
| Specific (labour +maintenance), €/$m^3$ | | 0,0645 | | 0,022 |
| Membrane replacement , €/$m^3$ | | 0,034 | | N/A |
| Specific thermal energy consumption, $kWh/m^3$ | | N/A | | 10 |
| Specific electric power consumption, $kWh/m^3$ | | 4,5 | | 2,5 |
| Specific electric energy cost, €/kWh | | 0,05 | | 0,05 |
| Interest rate | 5% | | | 5% |
| The annual fixed cost, €/year | 209 637 | | 168 000 | |
| The annual chemical cost, €/year | 32 256 | | 11808 | |
| The annual operation + maintenance, €/year | 41 280 | | 14432 | |
| The annual membrane cost, €/year | 21 760 | | N/A | |
| The annual energy cost €/year | 144 000 | | 410000 | |
| Total | 448 933 | | 604 240 | |
| ***Unit product cost €/$m^3$*** | ***0,74*** | | ***0,921*** | |

The cost analysis allows us determine the unit product cost of fresh water. Above in Table 2, are summarized the data of cost analysis for each desalination process. The economic analysis is based on cost equation of the total cost $C_t$;

$$C_t = C_c + C_e + C_{ch} + C_l + C_m \tag{20}$$

Where, $C_c$ is the yearly capital cost [€/year]:
$C_e$ - cost of energy [€/year];
$C_{ch}$ - cost of chemicals [€/year];
$C_l$ - the yearly cost of labor [€/year];
$C_m$ - yearly cost of maintenance [€/year].

## 6. Conclusions

Two different methods of desalination have been discussed in this article. RO and MED processes have high energetic requirements. For that purpose the total electricity production of installed 9 $MW_{el}$, from power plant is used for desalination plant in the case one. The second attempt is coupling power plant with MED section. Design parameters of MED and operating parameters derived from the mathematical model have been evaluated. From these calculations results the specific heat transfer area sA=265 $m^2$/kg/s. This value is close to that of other thermal desalination processes.
At last a cost analysis of both plants has been carried out. Unit product cost of RO is slightly lower than thermal desalination unit product cost, due to higher energy requirement of MED. In the end, could say that results are interesting and encouraging mainly, when desalting plants are powered by waste firing plants. In the near future work a combination of MED/RO is considered.

### *Symbols*

| | | |
|---|---|---|
| n | | - Number of effects, |
| A | [$m^2$] | - area |
| B | [kg/s] | - Brine flow rate from each evaporation effect |
| D | [kg/s] | - Amount of vapour formed in each effect |
| d’ | [kg/s] | - vapour generated by flashing |
| F | [kg/s] | - Feed flow to each effect, kg/s |
| M | [kg/s] | - Mass flow rate |
| $T_b$ | [ºC] | - brine temperature, |
| $T_v$ | [ºC] | - vapour temperature in each effect |
| TDS | [g/kg] | - Total Dissolved Solids |
| U | [kW/$m^2$ ºC] | - Heat transfer coefficient |
| X | [g/kg] | - Salinity |
| *Greek letters* | | |
| λ | [kJ/kg] | - Latent heat for evaporation |

*Subscripts*

| | |
|---|---|
| b | - Brine |
| c | - Condenser |
| d | - Distillate |
| e | - Evaporator |
| f | - Feed |
| s | - Steam |

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