Determination of the Criteria for Comparative Analysis of Desalination Plant

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Abstract. The problem of fresh water lack can be solved by desalination of the seawater. Distillation of the seawater can be accomplished by several methods. Comparative analysis of distillation desalination plant requires certain criteria. This criterion must take into account both energy consumption and seawater salinity. Relation of the minimal work required for seawater desalination to energy consumption was selected as such criterion. Four types of the distillation plants were considered: Multi-effect distillation plants (MED), multi-effect distillation plants with mechanical vapor compression (MVC) plants, MVC desalination plants have the best multi-effect distillation plant with thermal vapor compression (TVC) plants and Multistage flash distillation plants (MSF). MSF plants gave dependency that their efficiency rise along the gain ratio. That may be explained by the fact that its steam consumption does not depend on seawater consumption. TVC plants have slightly higher efficiency than MED plants. Thus, MVC plants can be recommended to use if there is no heat source, MSF plants – if there is heat source and plant must have a high gain ratio and TVC plant in the rest cases.

1. Introduction
Lack of the fresh water became a problem in recent years. According to researches, in 2025 about half of the states will suffer fresh water deficit [1]. Growing worldwide deficit of the fresh water can be compensated by desalination of the water with high (more than 10 g/litre) and medium (2-10 g/litre) salinity of the oceanic, sea and underground water which is 98% of total water storage on Earth.

Distillation or thermal desalination is mostly distributed method of seawater desalination. Distillation is seawater heating up to its evaporation temperature with further evaporation and then resulted steam is cooled and transfer back to liquid condition. Resulted distillate is considered a fresh water. Seawater evaporation is possible by both boiling and without boiling. In last case seawater is heated at higher pressure in comparison with pressure in evaporation chamber where water is directed. Because water temperature is higher than evaporation temperature corresponding to pressure in the evaporation chamber, part of the charged water is transformed into steam which is later condensate in distillate. Heat, which is contained in the evaporating water, is used for evaporation. Water itself in this case is cooled down to evaporation temperature. Main thermodynamic difference between the processes is that during boiling process heat is added from external source and keep evaporation temperature during given pressure in evaporator, i.e. process is isothermal. During process without boiling heat is added to seawater without boiling up to temperature higher than evaporation.
temperature corresponding to pressure in evaporation and, consequently, evaporation is performed by internal energy and can be considered adiabatic.

2. Main types of distillation plants used for seawater desalination

Multiple effect distillation plant (MED)

Multiple effect evaporator consists of several consequent stage. Every stage has lower pressure and temperature in comparison to previous one. Every stage mainly consists of pack of horizontal tubes. Seawater is dispersed on the upper layer of the tubes, then it flows down under gravity (figure 1).

Heating steam is charged inside the tubes. Tubes are cooled by seawater flow and as result of this, steam is condensed to distillate, falling seawater is heated and partially evaporated by the means of condensation heat. Due to evaporation, salt concentration in seawater is increased and seawater flow to the down side of the stage. Resulted steam has temperature lower in comparison with heating steam and become heating steam itself for a next stage. Pressure decrease from stage to stage allows to utilize brine and distillate in further stages for additional steam generation at lower pressure. This additional steam will condensate to distillate inside the next stage. This process is repeated from stage to stage (Multiple Effect Distillation). In last stage steam is condensed in a heat exchanger. This heat exchanger is called distillate condenser, it is cooled by seawater. Passing through condenser, part of the heated seawater is used as initial water, another part is returned to the sea. Brine and distillate, received in the stage, are charged from the last stage by the means of centrifugal pumps.

![Figure 1. Scheme of the Multiple effect distillation plant](image1)

Thermal efficiency of such evaporator can be quantitatively determined as a relation of the mass of resulted distillate on mass of the steam charged in to system (Gain Output Ratio).

Multiple Effect Distillation with thermal vapour compression (MED-TVC)

For increase of the plant efficiency, ejector can be implemented between steam source and one of the stages. Ejector sucked part of the low or medium pressure steam and mixed with steam of higher pressure to use it as initial steam for the first stages. Principal scheme of multiple Effect Distillation plant with thermal vapour compression is presented on figure 2.

![Figure 2. Scheme of the multiple effect distillation plant with thermal vapour compression](image2)
Multiple effect distillation plant with mechanical vapour compression (MED-MVC)

In conditions, where there is no external heat source (steam), mechanical compressor is used. Steam recirculate from the last stage to first one through centrifugal compressor driven by electric motor (figure 3). Energy consumption of such system usually varies from 8 to 16 kWh/m$^3$.

![Figure 3. Scheme of the Multiple Effect Distillation with Mechanical Vapour Compression](image)

Multistage Flash distillation (MSF).

Desalination plants with Multistage Flash distillation (MSF) (Figure 4) seawater consequently pass through condensers inserted in evaporation chambers, heating from the condensation heat, than it enters main heater and is heated above evaporation temperature on the first evaporation chamber, where evaporation occurs. Then steam is condensed on the surface of the condenser tubes and condensate flows to condenser and pumped to a consumer. Non-evaporated water flow through hydraulic seal and enter next chamber with lower pressure, where it evaporated again etc.

![Figure 4. Scheme of the Multistage Flash distillation plant](image)

3. Estimation of the energy efficiency of the distillation plants

Correct estimation of plant efficiency suited for seawater desalination, required complex accounting for a factors which influence energy efficiency and quality of outcoming water.
For example, most simple and understandable parameter – conversion ratio, which shows relation of the distillate output to seawater consumption, does not account neither energy cost nor seawater parameters such as salinity and temperature. Such criterion can be used only for approximate calculation or comparative analysis of the plants with similar energy consumptions:

\[ \tau = \frac{G_d}{G_{sw}}, \]  

(1)

where \( G_d \) – distillate output, \( G_{sw} \) – seawater consumption.

Real plant efficiency can be determined similarly to compressor efficiency, where minimal theoretic work, which can be used to increase pressure of the working fluid, is related to work, corresponding to a given compressor. Then, in this case, efficiency of the desalination plant will be determined as relation of the minimal work desalination \( L_{min} \) to energy consumption of given plant \( \sum L_{con} \):

\[ \eta_{des} = \frac{L_{min}}{\sum L_{con}}. \]  

(2)

Calculation of the energy consumption of the plant is not difficult (power of compressor and pump drives, added heat (if presented), in case of initial water temperature difference from temperature of environment – exergy of initial water). Determination of minimal theoretic work requires certain thermodynamic analysis.

Salination process is executed with grow of entropy. Reverse process of desalination is connected with loss of exergetically meaningful energy.

In case of reversible separation of solution to freshwater and brine, energy consumption will be minimal \( L_{min} \). Independently from the type of technical device and desalination method, this parameter will be determined only by initial and final working fluid condition and parameters of environment. For separation process, minimal work can be determined by Gouy-Stodola expression:

\[ L_{min} = T_0 \Delta s, \]  

(3)

where \( \Delta s \) – total change of the entropy during salts separation, \( T_0 \) – temperature of the separation process.

Usually, minimal work is calculation by the change of the partial thermodynamic potential \( F \) during isothermal transfer of the clear water from solution with one concentration to solution with another concentration:

\[ -L_{min} = RT_0 \ln \frac{a}{a'}, \]  

(4)

where \( a \) and \( a' \) – water activity in initial and final conditions, \( R \) – specific gas constant. Final Freshwater was selected as final condition for which \( a' = 1 \).

Given expression is fair only for a first moment of separation process. During freshwater extraction from the solution, its concentration increases, and work of the process is increased. This expression can be interpret as energy consumption rate for a separation process with infinite volume of initial salt solution. If extraction coefficient is higher than zero, minimal work of reversible process of salt solution separation is determined by expressions:

\[ -dL = \Delta F dn \]  

(5)

and

\[ -L_{min} = RT_0 \int_{n_i}^{n_2} \ln a \ dn, \]  

(6)

where \( n_i \) and \( n_2 \) – initial and final number of moles of working fluid.
As it can be seen from this equation, minimal desalination work is determined by media temperature, salinity of initial and final solution (or which is the same, freshwater gain ratio $\tau$).

Figure 5 shows dependencies of minimal separation work depending on extraction ratio, media temperature and initial seawater salinity. As it can be seen, separation work is increased during increase of the media temperature, seawater salinity and gain ratio.

![Figure 5](image)

**Figure 5.** Minimal desalination work dependently on media temperature, seawater salinity and gain ratio [1]

Analysis was performed for a number of articles [2-21]. Results of the analysis are presented on figure 6.

![Figure 6](image)

**Figure 6.** Comparison of the desalination COP of different plants.

4. **Conclusions**

As it can be seen from the figure 6, MVC desalination plants have the best efficiency. MSF plants gave dependency that their efficiency rise along the GR. That may be explained by the fact that its steam consumption does not depend on seawater consumption. TVC plants have slightly higher
efficiency than MED plants. Thus, MVC plants can be recommended to use if there is no heat source, MSF plants – if there is heat source and plant must have a high gain ratio and TVC plant in the rest cases.

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