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Exergy Destruction and Entropy Generation in Desalination Systems

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Abstract: The impetus for new tools for a comprehensive and accurate analysis of energy utilization and industrial systems comes from the need for sustainable development that could be impeded by exhausting energy sources and deteriorating environment. Exergy evaluation provides insight to achieve highest technological efficiency at the lowest cost while meeting the social and legal conditions. Desalination processes are known as major energy consumers and exergy destruction and entropy of these processes is essential for their sustainable development. This paper identifies important areas of exergy destruction and entropy generation in desalination processes including multi-effect distillation (MED), multistage flash (MSF) and reverse osmosis (RO) with case studies and offers recommendations for future efforts in research and development.

Keywords: energy; exergy; entropy; desalination; distillation; membranes; osmosis

1. Introduction

Desalination has now become a promising alternative for freshwater supply due to rapidly increasing demands for freshwater throughout the world. However, since well-established desalination technologies including thermal and membrane processes demand large quantities of energy, providing desalinated water can place a concomitant demand on the limited energy sources. Energy production also involves degradation of environmental quality. Therefore, water, energy, and environment become the most important components for sustainable human development.

Desalination technologies utilize various forms of energy to produce freshwater. While the process efficiency can be reported, in general, by the first law of thermodynamic analysis, this is not a true measure of the process performance since it does not account for all the forms of energy. Accordingly, the second law of thermodynamics has been more useful to evaluate the performance of the desalination systems. Second law of thermodynamics (exergy analysis) accounts for the available forms of energy in the process streams and energy sources with a reference environment and identifies the major losses of energy/exergy destruction. This aids in developing efficient desalination processes by eliminating the hidden losses [1]. This paper elaborates on exergy analysis of desalination processes to evaluate the thermodynamic efficiency of major components and process streams and identifies suitable operating conditions to minimize exergy destruction. Well-established MSF, RO, and Solar distillation were discussed with case studies to illustrate the exergy performances.

2. Materials and Methods

Fundamental mass, energy and exergy balances are discussed below. Definitions for exergy destruction and exergy loss in individual components and complete systems.

Exergy Analysis:

A complete steady-state analysis of energy conversion/utilization processes can be made based on mass, energy, and exergy balances. Ignoring kinetic and potential energy terms, the three balances for a control volume are [50]:

Mass balance:

$$0 = \sum_i \dot{m}_i - \sum_e \dot{m}_e \tag{1}$$

Energy balance:

$$0 = \dot{Q} - \dot{W} + \sum_i \left(\dot{m} \cdot h\right)_i - \sum_e \left(\dot{m} \cdot h\right)_e \tag{2}$$

Exergy balance:

$$0 = \sum_j \left[1 - \frac{T_0}{T_j}\right]\dot{Q}_j - \dot{W} + \sum_i \left(\dot{m} \cdot e\right)_i - \sum_e \left(\dot{m} \cdot e\right)_e - \dot{E}_D \tag{3}$$

The variables are defined in the Appendix.

The terms on the right hand side of the exergy equation represent the exergy associated with heat transfer, j at temperature T_j; the work transfer; the exergy inflow; the exergy outflow; and the exergy destruction, respectively. The exergy inflow and outflow associated with the streams entering and leaving the control volume are quantified in terms of the specific exergy, e, defined as follows:

$$e = \left(h - h_o\right) - T_o\left(s - s_o\right) \tag{4}$$

For a given set of operating conditions and the corresponding properties of the working fluid, the rates of exergy destruction and exergy loss for each component of the process can be computed from the above equations. The following measures can now be defined to assess the thermodynamic performance of the components of a system and the entire system [1]:

Exergy destruction ratio for component c of the system, $y_{D,c}$:

$$y_{D,c} = \frac{\text{Exergy destruction in component, } \dot{E}_{D,c}}{\text{Exergy destruction in system, } \dot{E}_D} \tag{5}$$

Exergy destruction ratio for complete system, y_D:

$$y_D = \frac{\text{Exergy destruction in system, } \dot{E}_D}{\text{Exergy of fuel supplied, } \dot{E}_F} \tag{6}$$

Exergy loss ratio for the complete system y_L:

$$y_L = \frac{\text{Exergy loss in system, } \dot{E}_L}{\text{Exergy of fuel supplied, } \dot{E}_F} \tag{7}$$

Exergetic efficiency, ψ:

$$\psi = 1 - \left(\frac{\dot{E}_D + \dot{E}_L}{\dot{E}_F}\right)$$

The exergy destruction rate (irreversibility) is related to the *entropy generation* rate by the Gouy–Stodola equation as follows:

$$y_D = T_0 \times S_{gen} \tag{8}$$

3. Results and Discussion

Exergy performance of multi-stage flash distillation, reverse osmosis and solar still desalination processes are discussed with case studies in this section followed entropy generation in MED, MSF and RO systems.

3.1. MSF Desalination

A large MSF distillation plant (Al-Jubail) in the Arabian Gulf area was analyzed thermodynamically by Kahraman and Cengel [2] using actual plant data and operation data. Exergy flow rates were evaluated throughout the plant to determine the locations of the highest exergy destruction. The highest exergy destruction occurred within the MSF unit, as expected. The details of the MSF desalination plant are as follows: water production capacity of 8.7×10^5 m^3/d with an integrated power production capacity of 1295 MW. This plant has 40 MSF units each consisting 22 flashing stages. Each MSF unit has a capacity of 23, 500 m^3/d. A general diagram of a MSF unit is shown in Figure 1. Seawater (a flow of 2397 kg/s) at 35°C and a salinity of 46,500 ppm enters the desalination plant. A major portion of the incoming seawater is used as the cooling water and rejected into the sea while the rest (808 kg/s) is supplied through the MSF stages. The saline water is then flashed through the MSF stages at lower pressures in each stage successively with a total pressure drop of 627 kPa. The saline water (brine) is discharged at a flow rate of 536 kg/s and a salinity of about 70,000 ppm.

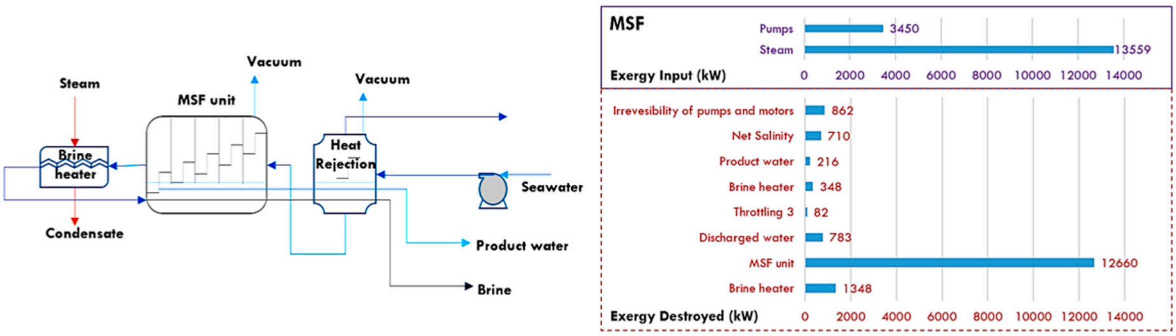

Figure 1. Schematic of a typical MSF distillation unit and exergy balance of the Al-Jubail MSF plant.

The total second law efficiency was 4.2%. Majority of the exergy destruction (78%) occurred in the MSF distillation units, followed by 8.3% of exergy destruction in heat exchangers. Pumps and motors contributed 5.3% and cooling water discharge had an exergy destruction of 4.8%. The remaining 3.8% of the exergy destruction occurred in throttling valves and discharge of the brine and product waters.

3.2. Reverse Osmosis Membrane Process

A reverse osmosis desalination plant with a treatment capacity of 7250 m^3/d was evaluated for its exergy performance [3]. The plant received a brackish water source with a salinity of 1550 ppm and the product water had a salinity of less than 500 ppm. The flow schematic of the reverse osmosis plant is shown in Figure 2. The brackish water is supplied by a low pressure pump from which a partial flow is bypassed as blend. The raw water passes through static mixer to add chemicals to prevent potential scaling and fouling and then it passes through filters to remove the contaminants and suspended solids before it is pumped (high pressure pumps) through the reverse osmosis unit. Permeate from the RO unit will then be blended with the bypass saline water to produce product water with a required salinity of less than 500 ppm. The exergy analysis of the unit is shown in Figure 2. The RO membrane unit accounts for the maximum exergy destruction in this unit which accounts up to 74.1%. Throttling valves contribute to other significant exergy losses and the smallest exergy losses occur in the static mixer and filter. The second law efficiency of the plant was 4.3%. The exergy efficiency was improved to 4.9% with addition of a pressure exchanger which resulted in savings of 19.8 kW.

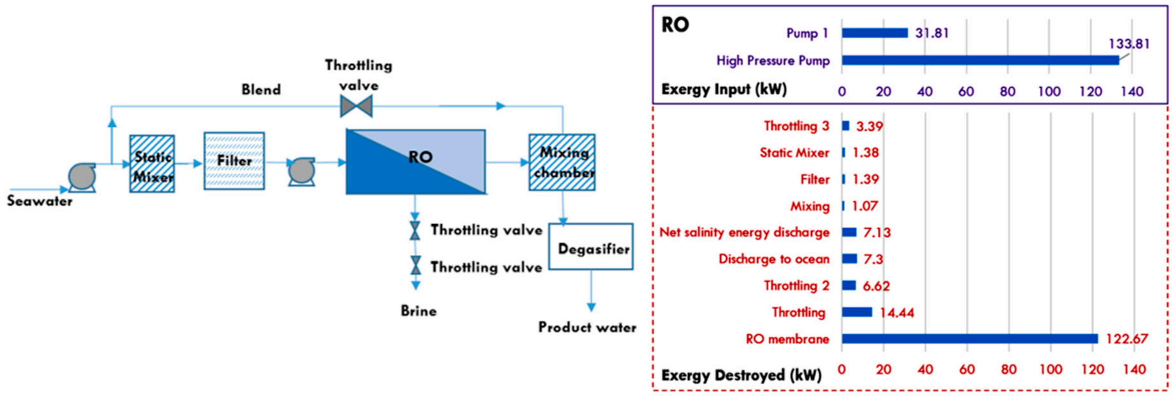

Figure 2. Flow schematic and exergy balance of a reverse osmosis unit receiving brackish water.

In another study, a brackish water desalination plant in Jordan with a salinity of 2500 ppm had two RO units which produced permeates of 90 and 70 ppm respectively [4]. As shown in Figure 2, this unit had pressure filters and cartridge filters followed by RO units, decarbonator and a hydrostatic water tank. Majority of exergy destruction occurred in the throttling valves which accounted up to 56.8% followed by membrane units with 21% of total exergy destruction. The pumps and motors caused 19.6% exergy destruction. The second law efficiency of this plant was 4.1% which was similar to the previous study reported by Cerci [3]. This analysis showed higher exergy efficiencies of filters and suggested that replacement of throttling valves with energy recovery devices and pumps equipped with variable frequency motors might reduce the exergy destruction in the overall RO unit.

3.3. Solar Stills and Solar Desalination Systems

The essential components of a passive solar still are collector plate (absorber), saline water (brine) and glass cover. Passive systems collect solar energy incident on the glass cover directly to cause evaporation of pure water. The exergy efficiency of a passive solar system was reported at 5% [5], that of the absorber and saline water were 12.9% and 6%. During non-sunlight hours, the sensible heat stored in the saline water causes further evaporation of freshwater due to lower ambient temperatures increasing exergy efficiency of saline water to as high as 93%. The highest exergy destruction of 615 W/m^2 was noted for the collector out of a solar exergy input of 935 W/m^2 [5]. Increasing the number of effects in solar stills may improve the exergy efficiency. Sow et al [6] reported exergy analysis of a single, double, and triple effect solar stills. Three important criteria were applied which were water rejection limit of 50%, maximum salinity limit of 5.5% and a minimum solar energy utilization. The exergy efficiency of the triple effect system was between 19 and 26% and that of the double-effect system was between 17% and 20%. The single-effect system had an exergy efficiency less than 4%. Energy storage may also improve the energy and exergy efficiencies in solar desalination systems and low grade heat sources [7].

Tiwari et al [8] conducted a comparative study on the active and passive solar stills. The active solar still was supported by flat panel solar collectors while the passive still was standalone receiving direct solar energy. The freshwater yields were higher for active solar still when compared with passive solar still. The yields for the active still were 3.08 L and 2.85 L for equal and unequal inner and outer glass cover temperatures respectively while the same for the passive solar still were 1.14 L and 1.09 L respectively. The effect of the number of solar collectors on the energy and exergy efficiencies of the active solar still was evaluated. Since the depth of the saline water in the solar still would have significant effect on the process performance, calculations were performed at different saline water depths as shown in Figure 3.

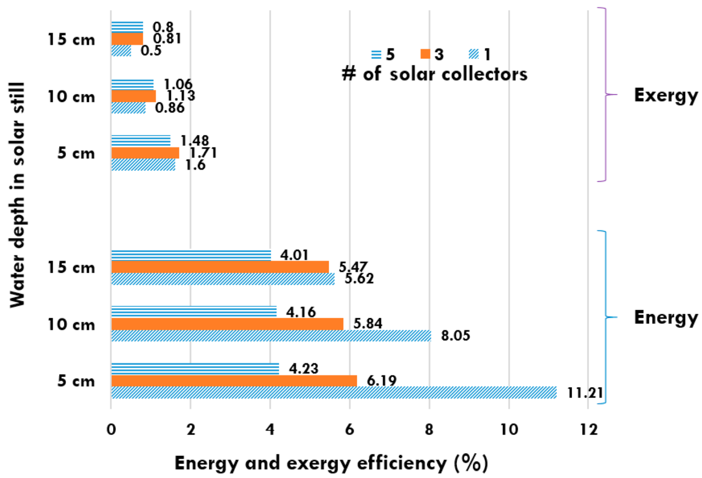

Figure 3. Energy and exergy efficiencies of an active solar still.

Higher number of solar collectors resulted in lower energy and exergy efficiencies while the optimum number of solar collectors was determined as 3. The depth of the saline water in the solar still also showed a negative effect on the energy and exergy efficiencies of the active solar still. Lower depth of saline water at about 5 cm was favorable in view of both the first law and second law efficiencies. Solar stills and similar configurations can be driven by low grade waste heat sources such as the heat rejected from domestic air-conditioning unit and other industrial process waste heat sources [9,10].

3.4. Entropy Generation in Desalination Systems

Exergy destruction can also be shown as entropy generation in desalination processes [11]. Physical models can be developed to estimate the magnitude of entropy generation by component and individual processes. Table 1 shows the total entropy generation in multiple effect distillation (MED), multistage flash (MSF), and, reverse osmosis (RO) desalination systems.

Table 1. Entropy generation in MED, MSF, RO desalination systems.

Process components	MED!	MSF*	Process components	RO≠
Thermal disequilibrium	2.5%	0.2%	-	-
Chemical disequilibrium	6.2%	10%	Chemical disequilibrium	15.9%
Evaporators	-	-	Feed through PX	3.2%
Condenser	21.8%	-	Brine through PX	3.3%
Flash boxes	0.6%	-	Feed pump	0.7%
Feed heaters	12.3%	73.9%	Booster pump	2.1%
Brine heaters	-	12.5%	High pressure pump	20%
Effects	56.5%	-	RO module	54.8%

! forward feed MED system; * once-through MSF system; ≠ single stage RO system

4. Conclusions

Exergy analysis provides insight into the thermodynamic losses in desalination systems. This information can be used to modify process configurations to optimize the exergy performance. For thermal desalination systems the exergy losses occur in the condenser where the latent heat is lost to the environment or rejected to the cooling water. For membrane systems, the membrane barrier itself is the major exergy destructor indicating opportunities for development of high permeability and low energy consuming membranes. In renewable powered desalination systems, the exergy losses are the highest for the solar energy based systems. This is because the solar exergy is very high. It is also advisable to utilize high exergy sources for higher quality product development. For desalination purposes, considering the unavoidable destruction in both membrane and thermal systems, low exergy sources should be utilized as driving forces where possible. This may lead to efficient utilization of available energy resources and sustainable environment and process development.

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