



The exergetic efficiency as a performance evaluation tool in reverse osmosis desalination plants in operation

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ABSTRACT

Exergetic efficiency characterizes the performance of a system or a system component from the second-law of Thermodynamics viewpoint. Although this parameter can be used in the comparison of the operation of similar components working under similar conditions, there are not many articles in the literature dealing with this purpose. In this paper, a desalination plant located in Gran Canaria (Canary Islands, Spain) is considered. Different configurations are possible in the ten reverse osmosis production lines of the plant, depending on the procedure used for the energy recovery, the number of reverse osmosis stages, the technologies applied to the intake and filtration processes, or the components involved in feed water pressurization. Using real data, the exergetic efficiency is assessed as a performance evaluation tool. Through the comparison of the exergetic efficiency of similar devices, though different production lines, the components with operation defects that should be repaired are identified: the most inefficient pelton turbines, intake pumps, high pressure pumps, booster pumps, reverse osmosis membrane modules, and pressure exchanger modules. This way, exergetic efficiency can be successfully used to control and to improve the operation of the plant.

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1. Introduction

Freshwater is not evenly distributed across the globe, and it is not available in sufficient quantity, where and when needed. Therefore, desalination of sea water and brackish water, are essential to provide freshwater to a large number of populations and communities around the world. There are countries like Qatar and Kuwait which are 100% supplied with desalinated water [1]. Also, some islands of the Caribbean or the Mediterranean rely heavily on desalination for drinking water, for agriculture or for industrial processes [2]. In the Canary Islands (Spain), the uneven distribution of rainfall and the population increase have made necessary the development of desalination systems since the 60s.

Water and energy are closely linked. According to Olsson [3], water and energy should take a parallel planning. The production and treatment of water require energy, and the conversion of primary energy requires water. With regard to desalination, energy needs vary considerably depending on the process and technology. In general, thermal processes require more energy than membrane-based processes, such as reverse osmosis (RO) or nanofiltration.

The first desalination plants in the Canary Island were distillation plants, and this was the predominant technology well into the 80s [4].

Then, distillation plants gave way to reverse osmosis systems, which is a more efficient technology from a productive and economic point of view. Reverse osmosis is the current technology in almost all of the plants located in the Canary Islands.

Energy optimization of desalination processes has led to significant reductions in energy consumption. Related to reverse osmosis processes, energy consumption has dropped from 20 kWh/m³ in the 70s to <2 kWh/m³ nowadays [5]. Several factors can be given for these significant achievements: membrane developments, pump efficiency improvements, the use of variable-frequency drives, or the implementation of energy recovery devices, such as hydraulic turbines or pressure exchangers, in order to recover the energy of the brine.

Exergy analysis is a widely accepted methodology for the characterization and optimization of energy systems. This second law analysis identifies thermodynamic inefficiencies in a process and their locations. One interesting parameter that characterizes the performance of an energy system from the thermodynamic viewpoint is the exergetic efficiency. The difference between the actual value of the exergetic efficiency –as percentage– and 100% represents the exergy provided to a system that has been wasted in this system as exergy destruction and exergy losses.

The application of exergy analysis to desalination plants date back to the 1960s: In 1963 Tribus and Evans [6] presented a wide report with the thermoeconomics of sea-water conversion. Later on, in 1970, El

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Nomenclature

BP	Booster pump
DWEER	Dual Work Exchanger Energy Recovery
ERI	Pressure exchanger from Energy Recovery Inc.
HPP	High pressure pump
PES	Pressure exchanger
RO	Reverse osmosis
e	Specific exergy, kJ/kg
$\dot{E}$	Exergy flow rate, kW
ε	Exergetic efficiency
h	Specific enthalpy, kJ/kg
in	Inlet
$\dot{m}$	Mass flow rate, kg/s
out	Outlet
p	Pressure
s	Specific entropy, kJ/kg·K
T	Temperature, K
$\dot{V}$	Volumetric flow, m ³ /s
$\dot{W}$	Electric power, kW
y^*	Exergy ratio

Subscripts and superscripts

O	Dead state
CH	Chemical
D	Destruction
F	Fuel
i	i -th material stream
k	k -th component
L	Loss
P	Product
PH	Physical
RO	Reverse osmosis
tot	Total

Sayed and Aplenc [7] analyzed and optimized a vapor-compression desalination process by the application of a thermoeconomic approach. Since then, many related papers have been published.

Just concerning reverse osmosis desalination plants in operation, first exergy analysis was performed by Cerci [8] on a brackish water plant, which had a production of 7250 m³/d. The process had just one RO stage, and the brine flowed through throttling valves directly into the ocean. In their results, the membrane modules were responsible for the greater exergy destruction of the system. The exergetic efficiency of the whole plant was reported as 4.3%. The introduction of a pressure exchanger on the brine stream increased this value to 4.9%. Kahraman et al. [9] presented also an exergy analysis of a brackish water RO desalination plant in operation. They calculated the exergy destruction within all the components. The largest exergy destruction occurred in separation units and in the pumps. The total RO unit presented an exergetic efficiency of 8.0%. They proposed that the cost of desalination could be significantly reduced with the use of variable frequency drives and high-efficiency pumps. Romero-Tenero et al. [10] applied an exergy analysis to a seawater RO desalination plant in operation with a production capacity of 21,000 m³/d placed in Tenerife (Canary Islands). The RO process had just one stage, but it operated already with Pelton turbines. They found that 80% of the exergy destruction occurred in main components (high-pressure pumps, regulation valves, RO modules, and energy recovery devices); 48% of this amount corresponded to the high-pressure pump and the Pelton turbine. Mabrouk et al. [11] presented an exergoeconomic analysis of several desalination plants in operation located in the Suez Gulf region, including a RO plant. Aljundi [12] analyzed thermodynamically the brackish water RO plant of Al-Hussein using

actual plant data. In their calculations, the throttle valves were responsible for the highest exergy destruction followed by the two-stage RO units. The exergetic efficiency of the plant was only 4.1%. They proposed the use of high-efficiency pump/motor set-up with a variable frequency drive, and the replacement of the traditional throttling valves with energy recovery devices. Gasmi et al. [13] optimized the energy consumption of a RO desalination plant in operation using exergy analysis and exergetic efficiency. The plant had a capacity of 30,00 m³/d and four double stage RO lines, but they did not performed a comparison between similar devices in the different lines. They just indicated the percentage of exergy destroyed in each device with and without several design improvements, like the use of booster interstage pumps, Pelton turbines or pressure exchangers. Peñate and García-Rodríguez [14] analyzed the reduction of specific energy consumption in seawater reverse osmosis desalination plants in operation using energy recovery devices instead of Pelton turbines. Their study was technically and thermoeconomically justified. Also related with energy recovery devices is the work of Al-Zahrani et al. [15]. They showed the variation of some indicators (specific energy consumption and recovery ratio) with salinity, temperature, and pressure. They summed up the relevance of energy recovery devices when salinity of feed water is high. Sharqawy et al. [16] proposed a new formulation for the calculation of seawater thermodynamic properties, exergy among others. They demonstrated the deficiencies of previous ideal mixture models in calculation of the flow exergy and the exergetic efficiency. Nevertheless, they still obtained a very low second law efficiency for a reverse osmosis desalination plant (<2%), even when energy recovery devices were used. Therefore, they suggested the pressure retarded osmotic method as energy recovery technology. With it, an exergetic efficiency of 20% and an input power reduction of 38% were obtained. Mistry et al. [17] calculated the total entropy generation in various desalination systems, including RO. They concluded that the definition of the useful exergy output of the system is crucial to set out the Second Law efficiency. For desalination systems, this is the minimum least work of separation required to extract a unit of water from a feed stream of a given salinity. El-Emam and Dincer [18] used Thermoeconomic analysis to obtain the performance of a RO plant as a function of salinity. The exergy analysis showed that the largest irreversibilities occurred in the RO module and the high-pressure pump. A second law efficiency of 5.82% was obtained for the base case. An actual 127 ton/h two pass RO desalination plant was studied by Eshoul et al. [19] with the seawater solution treated as a real mixture and not an ideal mixture. The exergy efficiency of the RO desalination was improved by 49% using an energy recovery turbine, and by 77% with a pressure exchanger. Qureshi and Zubair [20] discussed the correct definition of exergetic efficiency for RO desalination systems. They saw a clear connection between specific energy consumption and the chosen efficiency definition. They studied the effect of salinity, mass ratio, and turbine and pump efficiency. In all case, the reverse osmosis unit had the best efficiency when a pressure exchanger was used as an energy recovery device. Later on, the same authors [21] utilized operational data to perform an exergy analysis of a brackish water desalination plant located in California. The reverse osmosis unit of the plant presented a second law efficiency of 0.066%. In order to justify this low value, they compared it with the value obtained by Cerci [8] (4.3%). Qureshi and Zubair concluded that their low value of the exergetic efficiency was not completely unexpected taking into account that: a) the use of accurate seawater properties resulted in an exergetic efficiency that was 2.85 times lower than the originally reported by Cerci [8]; and that b) Cerci considered the brine in the definition of exergetic efficiency of the total plant, but they considered it as a lost. In a recent work, Evelyn et al. [22] evaluated the exergetic efficiency of a complex system (including a reverse osmosis unit) for the production of electricity and freshwater. They obtained a second law efficiency of 29% in the RO unit.

This article presents an exergetic analysis of a large reverse osmosis desalination plant in operation. The plant is located on the Atlantic

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