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Performance analysis of hybrid system of multi effect distillation and reverse osmosis for seawater desalination via modelling and simulation

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ABSTRACT

The coupling of thermal (multi stage flash, MSF) and membrane processes (reverse osmosis, RO) in desalination systems has been widely presented in the literature to achieve an improvement of performance compared to an individual process. However, very little study has been made to the combined multi effect distillation (MED) and reverse osmosis (RO) processes. Therefore, this research investigates several design options of MED with thermal vapor compression (MED_TVC) coupled with RO system. To achieve this aim, detailed mathematical models for the two processes are developed, which are independently validated against the literature. Then, the integrated model is used to investigate the performance of several configurations of the MED_TVC and RO processes in the hybrid system. The performance indicators include the fresh water productivity, energy consumption, fresh water purity, and recovery ratio. Basically, the sensitivity analysis for each configuration is conducted with respect to seawater conditions and steam supply variation. Most importantly, placing the RO membrane process upstream in the hybrid system generates the overall best configuration in terms of the quantity and quality of fresh water produced. This is attributed to acquiring the best recovery ratio and lower energy consumption over a wide range of seawater salinity.

1. Introduction

In the recent past, the demand for fresh water increased in many regions, especially in the developing countries, which in turn pushed the researchers toward more energy-efficient ways for seawater desalination. Coupling a power plant with a thermal desalination process allows reaching a greater thermal efficiency. This is attributed to the thermal energy produced from the power plant that would be used in the desalination process aside from wasting it. In this respect, the MSF was considered as the preferred technology to couple with a power plant. However, the low-temperature MED process proved to be more appropriate to couple with a power plant steam generator. This is due to employing low temperature steam in the MED process [1].

Over the last decades, the use of RO process as a complementary option with MED process is progressively increased. Interestingly, this technique acts in accordance with lower energy consumption with attaining the regulated limits of potable water issued by the World Health Organization [2]. For instance, the Fujairah 2 desalination plant in the United Arab Emirates is one of the biggest desalination facilities in the world, with a capacity of 591,000 m^3/day. Quantitatively, this facility consists of a 2000 MW power plant coupled with a 450,000 m^3/day MED plant and a 136,000 m^3/day RO plant [3].

The desalination industry was growing very rapidly in the 2000s, and many researchers focused on the development of more efficient desalination processes, including hybrid systems. The next section illustrates several examples of the published research in the open literature regarding the hybrid systems of MED, with or without the thermal vapor compression (TVC) section, coupled with RO process.

Hamed [4] reviewed the major features of commercially available hybrid desalination plants. The study confirmed that Nanofiltration (NF) membranes can be the best technology to couple with a thermal process, regarding fresh water productivity. Also, the full integration of membrane and thermal desalination processes provided a higher thermal performance than the simple integration. An economical evaluation of a small 2000 m^3/day MED + RO system powered by natural gas and includes heat recovery is carried out by Cardona et al. [5]. This in turn affirmed that the hybrid process can be more economical, producing fresh water with a lower specific cost per cubic meter.

In the same context, Rensonnet et al. [6] showed that the full hybridization of MED and RO is the most economical option if the

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electricity cost is high, otherwise the standalone RO process can be more convenient. Mahbub et al. [1] proposed a detailed thermodynamic analysis of a combined cycle power (CCP) plant with MSF, MED and RO (standalone), or with hybrid MSF + RO and MED + RO. It is concluded that the specific energy consumption can be reduced by 17% with the CCP + MED + RO system, compared to CCP + MSF + RO system. Furthermore, the lowest cost of fresh water produced with the CCP + MED + RO option of about 1.09 $/m^3.

The techno-economic performance of an integrated system of concentrating solar plant (CSP) with MED and Ultrafiltration (UF) is investigated by Olwig et al. [7]. The results showed the necessity of the RO process to improve the economics of the integrated process compared to a simple CSP + MED configuration. Specifically, a cost of fresh water of 1 $/m^3 was estimated based on 0.24 $/kWh as the electricity cost of CSP. Manesh et al. [8] studied the optimal integration of site utility and MED + RO desalination plant based on a simultaneous exergetic and economic optimisation. Also, Weiner et al. [9] modelled and optimised a hybrid MED + RO system. This confirmed that the MED + RO hybrid system can be more energy efficient than a standalone MED process and with a recovery ratio superior to a standalone RO process. Recently, a comprehensive mathematical model is developed by Sadri et al. [10] to describe the MED_TVC + RO integrated system. Moreover, the performance of integrated process is maximised by using a Genetic Algorithm (GA) technique.

The net outcome of the above literature review already showed that much attention been paid on the integration of power and desalination technologies and consequent energetic and/or economic assessment of the process. However, up to the authors' knowledge, the implementation of an integrated hybrid system of MED_TVC process coupled with RO process, has not yet been fully investigated. Also, it has been noticed that a parametric sensitivity analysis of several operating conditions using a hybrid system of MED_TVC + RO processes has not yet been explored. Therefore, the aim of this paper was to propose and evaluate different configurations in the context of simple and full hybridization of MED_TVC + RO processes. Also, the integrated process performance and sensitivity analysis to be explored via modelling and simulation. To systematically conduct this aim, detailed mathematical models of both MED_TVC and RO processes are initially developed. The mathematical models have been used to predict the performance of both MED_TVC and RO processes with a minimum amount of assumptions and limitations, which is rarely in other literature studies. This results in accurate models also the one developed for the hybrid process. Occasionally, most studies neglected the TVC section, which can be important to increase the performance ratio of the thermal process. The models developed of MED_TVC and RO process are individually validated against the predictions of several previous models of MED and the projected data collected from Toray Design System 2.0 (TDS2) for RO, respectively. Then, five different configurations have been designed to explore the best one in terms of productivity, fresh water quality, energy efficiency and recovery ratio of the whole hybrid process. A parametric sensitivity analysis with respect to seawater conditions and steam available from the power plant has been carried out in four of the proposed configurations. The output variables under investigation are the fresh water productivity, fresh water purity, energy consumption, and recovery ratio of the hybrid plant.

2. Description of the process

The description of both MED_TVC and RO processes is provided in Sections S.F.1 and S.F.2 in the Supplementary file, respectively. In this respect, the schematic diagrams of forward feed multiple effect desalination process with thermal vapor compression and an industrial full-scale seawater RO desalination plant are given in Figs. S.F.1 and S.F.2 in the Supplementary file, respectively.

Table 1 presents the technical specification and operating conditions of the MED and RO membrane processes. This also includes the permissible bounds of operating conditions of the membrane. The next section illustrates the description of the hybrid system of MED_TVC + RO.

Table 1
Specification and operating conditions of the MED and RO membrane processes.

	Value	Unit
Operative parameter		
Number of effects	10	–
External steam flowrate	5.67	kg/s
Steam temperature	70	°C
Rejected brine temperature	40	°C
Rejected brine salinity	60	kg/m^3
Seawater temperature	25	°C
Seawater salinity	39	kg/m^3
External steam pressure	1300	kPa
Effective operating pressure in RO	50	atm
Membrane properties		
Membrane	TM820M-400/SWRO	–
Supplier	Toray membrane	–
Membrane material and module configuration	Polyamide thin-film composite Spiral wound element	–
Maximum operating pressure	81.91	atm
Maximum operating feed flow rate	0.00536	m^3/s
Minimum operating feed flow rate	0.001	m^3/s
Maximum pressure drop per element	0.987	atm
Maximum operating temperature	45	°C
Effective membrane area (A_m)	37.2	m^2
Module width (W)	37.2	m
Module length (L)	1	m
$A_{w(T_o)}$ (m/atm s) at 25 °C[a]	3.1591 × 10^{-7}	m/s atm
$B_{s(T_o)}$ NaCl (m/s) at 25 °C[a]	1.74934 × 10^{-8}	m/s
Spacer type	Naltex-129	–
Feed spacer thickness (t_f)	8.6 × 10^{-4} (34 mil)	m
Hydraulic diameter of the feed spacer channel d_h	8.126 × 10^{-4}	m
Length of filament in the spacer mesh	2.77 × 10^{-3}	m
A'	7.38	–
n	0.34	–
ε	0.9058	–

[a] Estimated using parameter estimation in Section 4.2.2.

3. Description of the hybrid MED_TVC + RO process

Figs. 1 to 4 show the proposed configurations of the hybrid MED_TVC + RO process under investigation. In each configuration, the permeate of the RO membrane process is blended with the product of the thermal process, which is a distillate with a salinity close to zero. However, a value of 10 ppm is assumed for the salinity of the distillate to account a few seawater droplets that can be entrained in the vapor phase beyond the demisters. According to the World Health Organization (WHO), the salinity of a good quality drinking water should be below 300 ppm, and precisely below 200 ppm for the most tap water [2]. Therefore, the MED_TVC process has been designed to have a capacity approximately 4 times bigger than the RO process to produce enough distillate for the blending and commensurate with a salinity of the final product below 200 ppm.

Fig. 1 shows the so-called simple hybridization of the thermal and pressure driven desalination processes. The seawater feed is split between the two processes, which operates unconnectedly. In other words, the operating conditions of one process have no effect on the other one, since the connection is only at the level of final products (fresh water) and rejected brine streams.

Fig. 2 shows the full hybridization when the membrane process is