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Multi-objective optimization of MED-TVC-RO hybrid desalination system based on the irreversibility concept

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HIGHLIGHTS

- The mathematical model for MED-TVC desalination system considering the Boiling Point Elevation and various thermodynamic losses, has been presented.
- The computational model based on the diffusion and convection transport mechanisms and concentration polarization concept has been developed for the RO system.
- Hybrid MED-RO desalination system has been studied with the maximum permeate flow production.
- Sensitivity analysis is presented to study the effects of the various parameters on the system performance.
- Irreversibility analysis was performed and the exergy destruction and exergetic efficiency were assessed considering the chemical and physical exergies.
- Multi-objective optimization based on the irreversibility concept has been presented.

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ABSTRACT

The mathematical model for the performance prediction of a multi-effect desalination system with thermal vapor compression (MED-TVC) and a reverse osmosis (RO), was presented. To develop the mathematical model, the energy and concentration conservation laws were applied by considering the Boiling Point Elevation and various thermodynamic losses. This analysis led to the determination of the thermodynamic properties at different points and the Gain Output Ratio value. The exergy analysis of a sea water RO desalination plant was performed and its performance was investigated. A computational model based on the diffusion and convection transport mechanisms as well as the concentration polarization concept, was developed to predict the performance of the RO membrane. Then, the hybrid MED-RO desalination system was studied, the irreversibility analysis was performed and the exergy destruction (considering chemical and physical exergy), exergetic efficiency and system performance were assessed. To obtain the optimum point of the system, the multi-objective optimization with the genetic algorithm tool was used. The determination of the best tradeoff between the exergetic efficiencies of MED and RO, was the final goal of this optimization. The optimum design led to the selection of a MED-RO hybrid system with the highest exergetic efficiency.

1. Introduction

Nowadays, the fresh water shortage is one of the major problems in human societies. Increasing environmental pollution and excessive consumption of limited available resources will create a major challenge for the people that live in warm and dry regions. Saline water desalination technologies are the most important methods for overcoming this problem. Desalination methods are divided into thermal and membrane desalination systems. Multi-effect distillation and reverse osmosis are the most common methods. Johansen et al. [1] as well as Kamel and Sims [2] studied the combination of the different states of power plants and water desalination systems (RO, MED and MSF) for single-purpose, dual-purpose and hybrid desalination. They presented a financial model based on a classical method of cost allocation in dual-purpose facilities for the cost estimation of the integrated plant as well as the power and water costs calculation. Vlachos and Kaldellis studied the use of exhaust heat of gas turbine by a technical-economical approach to produce fresh water [3]. They concluded that it could provide fresh water needed by local residents and decrease about 15,000 tons of annual oil import. Wang and Loir investigated two separate research cases of gas turbines with steam injection and humid air by coupling to the MED-TVC desalination system. Using a heat recovery boiler, the steam was produced for injection into the combustion chamber as well as starting the desalination process [4–5]. They concluded that when 3 bar steam pressure is available, instead of using MED-TVC desalination, MED is preferred. The injected steam flow to the combustion chamber had a major influence on the power and the water production.

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Nomenclature

A	heat transfer area (m^2)
A_m	active surface of the membrane (m^2)
B	brine water flow rate (kg/s)
C	Concentration (ppm)
C_m	membrane (excess) concentration (ppm)
Cp	specific heat (kJ/kg K)
D	distillated water flow rate (kg/s)
e	Exergy (kW)
F	feed seawater flow rate (kg/s)
h	Enthalpy (kJ/kg)
H	height of channel (m)
L_p	membrane hydraulic permeability (m^2/s)
M	flow rate (kg/s)
P	pressure (kPa)
q	specific heat consumption (kJ/kg)
Q	flow rate (m^3/s)
S	Entropy (kJ/K kg)
T	Temperature (K)
U_i	overall heat transfer coefficient (kW/m^2 K)
W	width of channel (m)
X	Salinity (ppm)

Greek letters

α	friction pressure drop
β	nonlinearity of osmotic pressure
Λ	latent heat
μ	viscosity
μ_0	chemical potential
π_0	feed water osmotic pressure
ρ	density
Σ	reflection coefficient

Abbreviations

BPE	boiling point elevation (K)
CR	compression ratio
Ev	entrained vapor
ER	expansion ration
GOR	Gain Output Ratio
LMTD	logarithmic mean temperature difference (K)
NEA	Non-Equilibrium Allowance (K)
ppm	part per million

Subscripts

0	raw water
c	condensing vapor
cw	cooling seawater
f	feed water
p	permeate water
m	motive steam
n	number of effects
s	steam
t	total
v	vapor

Increasing the steam flow rate, would increase the power capacity and reduce the water production. Moreover, the turbine inlet temperature increase would enhance the power and water production. They showed that the application of the hybrid systems would result in the fuel utilization saving as well as the design and operation flexibility. Those studies were limited to the thermodynamic simulation without any economic assessment and optimization studies. Fiorini and Sciubba performed a thermo-economic analysis on a MED desalination plant [6]. They provided a model for simulation of thermodynamic and thermo-economic analysis of a MED desalination with parallel flow. The MED desalination units was connected to a combined cycle power plant and they received steam from the steam turbine. The produced water price in that system was largely influenced by the investment cost even more than the operating costs. Chacartegui et al. studied a modified combined power plant cycle [7]. They evaluated various systems for heat recovery from the steam turbine condensate. They used combined cycle power plant condenser to increase the salt water temperature and then modified the heat recovery from the chimney flue gasses to increase the temperature of the salt water. They analyzed a co-generation power plant cycle and a desalination unit. Finally, they evaluated the parameter effects such as the condenser pressure, the chimney flue gas temperature and the condenser cooling water inlet temperature. They concluded that for all suggested cogeneration schemes, a decrease in power generation was expected due to the increase in the condenser pressure. Zhao et al. used the MED desalination for a saline wastewater refinery in China. The thermodynamic model which was based on the mass and energy balances, was developed in various stages of the desalination process [8]. They showed that in the MED system, the number of effects is an important parameter to keep the balance between lower costs and more permeate water production. Therefore, higher effect numbers led to higher capital costs and permeate water costs. On the other hand, they found that the total heat transfer areas of system reduced with the increase of the feed steam temperature. They also found that increasing the evaporator temperature in the last effect led to the GOR value increase. Kamali et al. [9], Kamali and Mohebinia [10], Kamali et al. [11] and Kouhikamali et al. [12] developed a model to simulate and optimize the thermodynamic MED-TVC desalination system. The developed model was compared with the experimental data from Kish island desalination plant and validated. The model was developed based on the shell-tube exchanger's principles, whereas the study did not include the economic aspects. The results of the last study showed that the optimum value of the compression ratio of thermo-compressor was between 2 and 2.5. Ameri et al. also provided a thermodynamic model for a MED desalination system to produce 2000 cubic meters per day and analyzed the impact of the number of effects on the desalination performance [13]. They found a relation between optimum values of the number of effects for a system with constant production capacity and operational parameters such as the seawater salinity, effects temperature difference and feed water temperature. They showed that the increase in the inlet steam pressure led to the performance ratio and the system required heat transfer surface area enhancement. Sayyaadi and Saffari and Sayyaadi et al. also developed and optimized a model of MED-TVC desalination using the thermo-economic analysis. The developed model was related to Kish Island's desalination plant [14–15]. They tried to reduce the cost of the system product (fresh water) with the optimization procedure. Al-Mutaz and Wazeer reviewed the current status of MED-TVC and modeled it [16–17]. Kashi investigated the effects of some input parameters such as motive steam temperature, concentration, and input water temperature on the energy efficiency and produced water in a MED Plant [18]. He found that the input feed water increase led to the produced distilled water (or GOR), with the explanation that the rate of the increase in different MED models were different. Hanafia et al. studied a thermo-economic model of a combined cogeneration power plant. The MED-TVC plant optimum design point for the maximum production of water was obtained [19]. Amer developed a method for ME-TVC desalination system analysis [20]. He proposed that the maximum gain ratio for 4 and 12 effects varied between 8.5 and 18.5. He used the optimal top brine temperature ranging between 55.8 and 67.5 °C. Paula et al. focused on the mathematical modeling and optimization of Multi-Effect Evaporation plants (MEE). A detailed model to predict accurately the MEE system performance, was presented [21]. Iman et al. proposed a systematic approach for the analysis and optimization of the multi-effect distillation thermal vapor compression (MED-TVC) desalination