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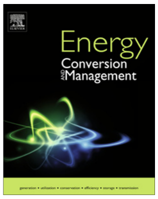

Theoretical investigation of the performance of integrated seawater desalination plant utilizing renewable energy

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ABSTRACT

In the present work, theoretical investigation of the performance of two sequential desalination systems, multi-effect distillation and mechanical vapor compression, is carried out. A mathematical model is developed and implemented in MATLAB and validated by results available in the literature. Then the parametric analysis is carried out to produce distillate water and salt utilizing renewable energy. A parametric analysis has been conducted to understand the important factors that affect the performance of the plant. Furthermore, three sites are selected in Egypt (Marsa Matrouh, Ras Benas, and Taba) and economic feasibility of the proposed desalination system is carried out and compared with plant economy of conventional fossil fuels. The results show that site location, solar intensity, wind speed, ambient temperature, and water salinity are the most dominant factors in the performance.

1. Introduction

The process of seawater desalination is intended to reduce the deficits in potable water both in the present and future. The total world-wide capacity of desalted water is about 23×10^6 m^3/d [1]. “Seawater desalination processes offer various environmental benefits; however, they may have adverse environmental impacts, the most serious of which is the intensified use of energy, particularly when this energy is provided with conventional fossil fuel” [2]. Desalination systems driven by renewable energy are rare, only representing about 0.02% of total desalination capacity [1]. But renewable energy is appropriate for seawater desalination for several reasons, such as, energy diversification. Also, the renewable energy systems are normally easier to operate and maintain than ones which use conventional energy, making them suitable for remote areas. Furthermore, plants are usually located in coastal areas where renewable energy sources are available. Conventional energy supply is not always possible in remote areas or small islands, due to the difficulties of fossil fuel supply, or because the grid does not exist or the available power is not enough to drive a desalination plant. In all cases, renewable energy encourages sustainable socioeconomic development through utilizing local resources.

The cost reduction of renewable energy systems has been significantly in recent decades. Therefore, future reductions as well as the rise of fossil fuel prices could make seawater desalination driven by renewable energy a more competitive alternative [1]. Solar energy is utilized as the necessary source of thermal energy for heating saline water. Meanwhile, wind energy supplies the electric power required to drive the auxiliary equipment.

There are many research works available in the literature that deal with the general method of desalination and the application of renewable energy in the desalination process with sustainable desalination [3] and more efficient desalination process, like the role of thermal and electrical storages in renewable energy source driven desalination process [4], thermo economic optimization [5], optimization of flow patterns [6], use of low-grade heat source for powering the desalination unit [7] or modeling of energy systems with close integration of renewable and desalination [8–11].

Abbreviations: BBT, brine boiling temperature; BWRO, brackish water reverse osmosis; BPE, boiling point elevation; DNI, direct normal irradiance; GCC, Gulf Cooperation Council; GDP, gross domestic product; HF, hollow fiber; HTE’s, heat transfer elements; H.V., heating value of fuel; IAEA, International Atomic Energy Agency; MGD, million gallon per day; MENA, Middle East and North Africa; MED, multi effect distillation; MVC, mechanical vapor compression; RE, renewable energy; RES, renewable energy systems; SW, sea water; VTE, vertical tube evaporator; VVC, vacuum vapor compression; WEC, wind energy conversion.

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Nomenclature

A_c	heat transfer area of condenser, m^2
A_{col}	solar collector area, m^2
A_E	evaporator heat transfer area, m^2
A_i	heat transfer area of each effect of MED unit, m^2
A_m	mean heat transfer area of effect of MED unit, m^2
A_P	preheater heat transfer area, m^2
A_s	swept area of wind turbine, m^2
a	axial induction factor
C_p	specific heat at constant pressure, kJ/kg K
C_{psw}	specific heat of brine entering the preheater, kJ/kg K
C_{pdw}	specific heat of distillate water entering the preheater, kJ/kg K
C_{pv}	specific heat of distillate steam entering the evaporator, kJ/kg K
CR	circulation coefficient of brine entering the crystallizer
Cp	turbine power coefficient
CT	thrust coefficient of a wind turbine
d	wind turbine diameter, m
FR	heat removal factor
h_i	latent heat of exit vapor from effect i at temperature Ti, kJ/kg
h_n	latent heat of vapor exit from last effect at temperature Tn, kJ/kg
h_o	latent heat of distillate water exit from the evaporator, kJ/kg
h_s	latent heat of steam at temperature Ts, kJ/kg
h_{16}	latent heat of brine entering the evaporator, kJ/kg
h_{19}	latent heat of steam entering the evaporator, kJ/kg
I	global solar intensity, W/m^2
I_b	beam solar irradiation, W/m^2
I_d	diffuser solar irradiation, W/m^2
$LMTD_C$	logarithmic mean temperature difference of the condenser, K
$LMTD_P$	logarithmic mean temperature difference of the preheater, K
$\dot{m}_a$	mass flow rate of air through wind turbine, kg/s
$\dot{m}_{b1}$	mass flow rate of brine exit from first effect, kg/s
$\dot{m}_{cw}$	mass flow rate of cooling water entering MED unit, kg/s
$\dot{m}_d$	total mass flow rate of distillate water exit from integrated plant, kg/s
$\dot{m}_{d1}$	mass flow rate of distillate water exit from MED unit, kg/s
$\dot{m}_{d2}$	mass flow rate of distillate water exit from MVC unit, kg/s
$\dot{m}_f$	feed water mass flow rate, kg/s
$\dot{m}_i$	mass flow rate of vapor (exit from effect number i), kg/s
$\dot{m}_n$	mass flow rate of vapor (exit from the last effect), kg/s
$\dot{m}_s$	mass flow rate of steam entering the first effect, kg/s
$\dot{m}_{salt}$	mass flow rate of salt exit from the crystallizer, kg/s
$\dot{m}_{sw}$	mass flow rate of sea water entering the plant, kg/s
$\dot{m}_1$	mass flow rate of the (vapor exit from the first effect), kg/s
$\dot{m}_{15}$	mass flow rate of brine (entering the MVC unit), kg/s
$\dot{m}_{16}$	total mass flow rate of feed brine (entering the evaporator), kg/s
$\dot{m}_{17}$	mass flow rate of vapor exit from the crystallizer (entering the compressor), kg/s
$\dot{m}_{18}$	mass flow rate of recirculate brine exit from the crystallizer, kg/s
n	number of effects
P	wind turbine power, kW
P_{av}	average wind turbine power, kW
PMED	required thermal power for MED unit, kW h/m^3
P_{pump}	required electrical power for pumps, kW h/m^3
P_{MVC}	required electrical power for MVC unit, kW h/m^3
PR	performance ratio of MED unit
P_i	pressure of the vapor entering the compressor at T17, kPa
P_o	pressure of the vapor exit from the compressor at Te, kPa
P_w	wind power, kW
Q_c	condenser thermal load, kW
Q_E	evaporator thermal load, kW
Q_P	preheater thermal load, kW
Q_1	thermal load in the first effect, kW
r	the compression ratio
R	vapor constant = 0.4615, kJ/kg K
sA	specific heat transfer area of MED unit, $m^2/(m^3/h)$
sA_E	specific heat transfer area of evaporator, $m^2/(m^3/h)$
t_a	ambient temperature, K
t_{Pm}	mean absorber plate temperature, K
t_i	temperature of the fluid entering the solar collector, K
T_{cw}	cooling water temperature, K
T_{cond}	the condensation temperature, K
T_{d2}	temperature of distillate water exit from the preheater, K
T_e	temperature of exit vapor from compressor in MVC, K
T_f	feed water temperature, K
T_n	exit vapor temperature from last effect, K
T_o	temperature of condensate distillate water exit from the evaporator, K
T_s	steam temperature, K
T_{sw}	intake temperature of sea water, K
T_1	exit vapor temperature from first effect, K
T_{14}	temperature of brine entering the preheater, K
T_{15}	temperature of brine exit from the preheater, K
T_{16}	temperature of brine entering the evaporator, K
T_{17}	temperature of water vapor mixture exit from the evaporator to the crystallizer, K
T_{19}	temperature of vapor inlet to the evaporator, K
U_c	over all heat transfer coefficient of condenser, kW/m^2 K
U_E	overall heat transfer coefficient of the evaporator, kW/m^2 K
U_i	overall heat transfer coefficient in effect i (for i = 1:n), kW/m^2 K
U_L	heat transfer coefficient, W/m^2 K
U_p	overall heat transfer coefficient of the preheater, kW/m^2 K
V	wind velocity, m/s
V_1	wind velocity through the rotor disk, m/s
V_2	wind velocity at the exit of wind turbine, m/s
W	work of the compressor, kW
X_f	feed water salinity
X_n	salinity of brine exit from last effect
X_1	salinity of brine exit from first effect
X_{15}	salinity of brine entering the MVC unit, ppm
X_{16}	salinity of total brine entering the evaporator, ppm
X_{18}	salinity of brine exit from the crystallizer, ppm
ΔT_{cond}	temperature difference between feed water temperature and cooling water temperature, K
ΔT_i	temperature difference between inlet and exit vapor temperature of effect i (for i = 1:n), K
ΔT_{loss}	temperature drop in all effect, K
ΔT_{Th}	thermodynamic loss (temperature drop) in all effect, K
ΔT	total temperature drop a cross the effects, K
ΔT_E	temperature difference between the feed brine to the evaporator and the boiling temperature of water exit from the evaporator, K