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Conceptual design and optimization of a small-scale dual power-desalination system based on the Stirling prime-mover

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HIGHLIGHTS

- A systematic approach for the design of Stirling-desalinations was presented.
- The problem was classified as a multi-objective and multi-criteria problem.
- Various configurations of humidification-dehumidification were examined.
- The foremost system was found for higher productions and lower costs.
- The system was a reliable option for the small-scale power-water production.

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ABSTRACT

Producing the electric power using discrete systems as well as providing fresh water is essential for rural areas near to seawater that have no access to electricity and sweet water. In this regards, a small-scale production of fresh water and electricity was considered here. Due to the capability to be fueled with different sources of energy, Stirling engines are a suitable alternative for the discrete production of the electricity for rural areas. Accordingly, a conceptual design of a small-scale dual power-desalination system was presented here. Three configurations of small-scale desalination systems using a humidification-dehumidification system, HDH, was examined to be coupled to the GPU-3 Stirling engine and the waste thermal energy of this engine was delivered into the HDH system. The best operating parameters of the combined systems were found in a multi-objective optimization with the goal of maximization of the generated electricity and fresh water as well as minimizing the product cost, simultaneously. Among three optimized configurations, the best one was introduced using analytical hierarchy process, AHP. The proposed system could deliver 2.58 kW of the electric power as well as 23.3 m^3 of the fresh water per day with a production cost of 0.25 \$ kWh^{-1} and 0.66 \$ m^{-3}, respectively.

1. Introduction

There is increasing demand for fresh water due to drastically grow in population nowadays. On the other hand, the resources of fresh water are limited, especially in countries with dry weather condition like Persian Gulf region. In these areas that have access to seawater, desalination is an alternative for the production of the fresh water through the use of thermal or electrical energies. In this regard, various types of the desalination system have been invented and employed. Dual productions of fresh water and electrical power through thermal power plants are an attractive alternative; because these desalination systems employ the wasted thermal energy of the power plant. The large-scale production of water and electricity through the thermal power plant needs piping networks and electricity grid to transfer water and electricity to consumers. The large-scale production of water and electricity is not a recommended alternative for regions with scattered populations and rural areas. In this condition, the small-scale production of water and electricity through the use of discrete power generation methods and inexpensive type of desalination is an optimistic alternative. The small-scale electricity in discrete systems is mostly produced by internal combustion, IC, engines. Stirling engine, SE, is another alternative for small-scale power production. This type of engine has a higher efficiency than the IC engine. On the other hand, as SE is an external combustion engine that can be heated up using various types of thermal energy from natural gas to biomasses or animal wastes; therefore, SE is a more desirable option in rural areas compared to IC engines.

The main objective of this paper is to provide a conceptual design

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Nomenclature

Symbols

A	heat transfer area (m^2)
BBY_j	balance at the beginning of the jth year ($)
$\dot{C}_F$	cost rates of the fuel ($)
$\dot{C}_L$	cost rates of exergy losses ($ s^{-1})
$\dot{C}_P$	cost rates of products ($ s^{-1})
C_p	specific heat at a constant pressure (kJ kg^{-1} K^{-1})
C_V	specific heat at a constant volume (kJ kg^{-1} K^{-1})
CC_L	levelized values of the carrying charge ($)
CRF	capital recovery factor
ex	specific exergy (kJ kg^{-1})
$\dot{E}x$	the rate of exergy (kW)
$\dot{E}x_L$	the rate of the exergy loss (kW)
f	frequency (Hz)
FC_L	levelized values of the fuel cost ($)
h	enthalpy (kJ kg^{-1} K^{-1})
i_{eff}	effective interest rate (%)
$\dot{m}$	mass flow rate (kg s^{-1})
OMC_L	levelized values of the operating-maintenance cost ($)
P	pressure (kPa)
PEC	purchased equipment cost ($)
Q	heat transfer (kW)
R	gas constant (kJ kg^{-1} K^{-1})
ROI	return on investment ($)
r_{FC}	inflation rates of the fuel cost (%)
r_{OM}	inflation rates of the operating-maintenance cost (%)
T	temperature (K or °C)
TCR	total capital recovery (S)
TRR_L	levelized values of the total revenue requirement ($)
V	volume (m^3)
$\dot{W}$	power (kW)
$\dot{Z}$	cost of capital investment and operating-maintenance ($)

Greek symbols

γ	specific heat ratio
ω	absolute humidity
φ	relative humidity
τ	annual operating time of the system (h)
λ	percentage of the excess air
η	efficiency

Subscripts

a	air
ave	average
b	the salinity of the water at the outlet from desalination
c	compression
ck	the boundary of the compression and cooler chambers
d	distilled water
da	dry air
e	expansion
f	flame
HDH	humidification-dehumidification desalination
HX	heat exchanger
h	heater
he	the boundary of the heater and expansion chambers
in	inlet
k	cooler
kr	the boundary of the cooler and regenerative chambers
out	outlet
r	regenerative
rh	the boundary of the regenerative and heater chambers
sat	saturated
w	water

Abbreviation

GOR	gain output ration
HDH	humidification-dehumidification
CAOW-AH	close air-open water-air heated
CAOW-WH	close air-open water-water heated
CRF	capital recovery factor
MECAOW-WH	multi-effect close air-open water-water heated
MED	multi-effect desalination
PWR	pressurized water reactor
SE	Stirling engine
TRR	total revenue requirement

for a small-scale production of water and electricity via a dual power-desalination system that works based on an SE prime mover and a humidification-dehumidification, HDH, system.

Regarding the combination of power systems and thermal desalination, several studies have been conducted for large-scale and small-scale production of water and electricity. As an example of a large-scale system, Ansari et al. performed thermoeconomic optimization of the combination of a 1000 MW pressurized nuclear reactor, PWR, power plant and a multi-effect desalination, MED, with thermos-vapor compressor, TVC [1]. In another paper, they performed multi-objective optimization of the same PWR-MED plant with objectives of thermoeconomics as well as the exergetic efficiency [2]. As the bypassing the steam for desalination, reduces the capacity of power generation of the power plant, in a most-recent research, Lee et al. [3] evaluated a large PWR-desalination power plant by using the supercritical S-CO2 Brayton technology with two configurations of the S-CO2 cycle. Numerical analysis of the combination of the desalination system and a solar chimney power plant was studied by Ming et al. [4]. A thermodynamic analysis of a combined power, refrigeration, and desalination system was performed by Sadeghi et al.[5], and a new triple-production system with a number of advantages was suggested. In another work, the coupling between a desalination system and a thermal vapor compression refrigeration plant as well as a Rankine power plant was studied by Ortega-Delgado et al. [6]. Moreover, utilizing the waste heat of a refinery for power and fresh water generation was studied by Sharaf Eldean et al. [7]. In an innovative method, simultaneous production of power and fresh water was introduced through the usage of super-capacitive microbial cells [8]. Finally, a pathway for the synchronize generation of water and energy for a long-term resource planning was introduced by Khan et al. [9]. Various aspects of desalination systems and also their hybrid forms were reviewed in a number of review articles. In this regard, economic feasibility and standardization of cost determinants were reviewed in [10]. In addition, solar desalinations were reviewed in [11–15]. In addition, combined power desalination systems using the combination of reverse osmosis desalination powered by photovoltaic and solar Rankine cycle were reviewed in [16]. Employment of general forms of renewable energy, including solar, wind, geothermal, and ocean energies in desalination technology were reviewed in [17–19]. Due to the strong theoretical background for the combined power-desalination plant; nowadays, a number of practical plants such as Fujairah power and desalination plant [20] and Ras Laffan 1025 MW Combined-Cycle Plant [21].

Small-scale cogeneration of the freshwater and electricity is usually performed by employing engines, i.e. internal combustion, IC, engine or