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Hybrid solar-wind water distillation system

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HIGHLIGHTS

- Novel solar-wind hybrid system for solar distillers
- Direct use of wind energy to thermal energy convertors via frictional heating
- Increasing the productivity of solar distillers
- Increasing the operating hours of solar stills during nights and in winter

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ABSTRACT

In this study, a hybrid solar-wind water distillation system (HSWWDS) is proposed and studied. The system consists of a conventional single basin solar-still and a wind-water heater operating simultaneously. The advantage of the proposed system is its ability to operate day and night and, therefore, it produces larger quantities of distill water even in cloudy days with good winds. A simple model equations are constructed and simulated. Jordan's summer and winter climate conditions are considered to test the system and to estimate the monthly and annual yields. Results have shown a significant increase in the distillation output especially at times when the wind energy is significant at summer nights. Furthermore, the effect of the size of the wind turbine on the performance of the system has been studied and documented. The calculations showed that the yield can be three to four times more than conventional solar distillers.

1. Introduction

Renewable energy in the engineering sector has become very important and attractive. It is widely expected in the future that a large proportion of energy used by the human race will derive from a variety of renewable sources. Renewable energy is used in many processes where thermal solar energy, wind energy, and geothermal energy have been used in a large number of thermal systems such as air heating, heated water, and water desalination [1–3].

Jordan suffers from the lack of drinking water. On a per capita basis, the lowest levels of water availability in the world are recorded by Jordan [4]. Countries with per capita water production of less than 1000 m^3/year are considered to be water-poor countries by most experts [5]. According to the world bank data [6], the renewable internal freshwater resources per capita in Jordan is 108 m^3/year during the years 2011–2015. This lists Jordan at only 20% of the water poverty levels [7].

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Jordan is blessed with abundance of solar energy. The average daily solar irradiation in Jordan ranges between 5.5–6.5 kWh/m^2/day [8]. Wind Atlas in Jordan indicates that large areas have average annual wind speed between 6–6.5 m/s, and in some areas may exceed the average wind speed above 7 m/s at 10 m heights [8].

Several works have been carried out to use solar energy to produce distill water. Conventional or passive solar stills depend only on the heat from the sun to produce water, they include different types such as single effect, multi-effect, basin, double slope, and wick [9]. Solar stills are very simple systems for water distillation, which are driven by the thermal energy collected from the sun. Brackish water is fed into a basin, then it evaporates due to this thermal energy, finally, water vapor is condensed on the surface of the glass to be collected inside a container [10]. The maximum efficiency of solar stills has reached 50%. Stills with bad insulation caused a reduction of 14.5% in the still efficiency. The increase in wind speed from 0–3.6 mph causes a 2% efficiency loss in the still performance [11]. Even though, solar stills can provide an effective solution in places that suffer from poor water quality while having high solar intensities. Solar stills are cheap to manufacture and need less maintenance, but the main problem is the low water production rates [12]. Solar stills can be used in places with smaller needs

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Nomenclature

A_b	basin area (m^2)
A_g	glass cover area (m^2)
A_s	sidewall area (m^2)
A_t	swept area of the wind turbine (m^2)
C_w	specific heat of water (J/kg °C)
h_1	total heat transfer coefficient from water to the glass cover (W/m^2 °C)
h_2	convective heat transfer coefficient from glass to ambient (W/m^2 °C)
h_3	convective heat transfer coefficient from base liner to water (W/m^2 °C)
h_{cw}	convective heat transfer from water to glass (W/m^2 °C)
h_{ew}	evaporative heat transfer coefficient from water to glass (W/m^2 °C)
h_{rw}	radiative heat transfer coefficient from water to glass (W/m^2 °C)
I	solar irradiance (W/m^2)
K_g	thermal conductivity of the glass (W/m °C)
K_v	thermal conductivity of the vapor (W/m °C)
L_g	glass cover thickness (m)
$\dot{m}$	mass flow rate (kg/day)
M_w	mass of water (kg)
P_c	partial pressure at the inner surface of the glass cover (Pa)
P_w	partial pressure at the water surface (Pa)
P_{in}	power generated by wind turbine (W)
R_g	reflectivity of glass (−)
R_w	reflectivity of water (−)
t	time (s)
T_a	ambient temperature (°C)
T_c	glass cover temperature (°C)
T_w	water temperature (°C)
T_b	basin liner temperature (°C)
U_b	overall heat transfer coefficient from basin to ambient through bottom and sides (W/m^2 °C) insulation
V	ambient air velocity (m/s)
V_{in}	cut-in wind speed (m/s)
V_r	rated power wind speed (m/s)
V_{co}	cut-out wind speed (m/s)
α_b	absorptivity of the basin liner
α_b'	fraction by which solar radiation is absorbed by the basin liner
α_g	absorptivity of glass
α_g'	fraction by which solar radiation is absorbed by glass cover
α_w'	fraction by which solar radiation is absorbed by water mass
ε_g	emissivity of glass cover
ε_w	emissivity of water
ε_{eff}	effective emissivity
η	system efficiency (%)
ρ_a	ambient air density (kg/m^3)
σ	Stephan-Boltzman constant
$\dot{Q}_{cw}$	convective heat transfer within still from water to glass (W)
$\dot{Q}_{rw}$	radiative heat transfer within still from water to glass (W)
$\dot{Q}_{ew}$	evaporative heat transfer within still from water to glass (W)
$\dot{Q}_1$	total heat transfer within still from water to glass (W)
$\dot{Q}_u$	energy transferred from heat exchanger fluid to water (W)
F_c	convective energy fraction
F_e	evaporative energy fraction
F_r	radiative energy fraction

for water and passive water supplying systems which depend on solar energy [13].

In summary, conventional solar distillation systems have low productivity due to the following reasons: (1) the low evaporation rate in the still basin and (2) the low condensation rate at the glass cover. Numerous numbers of investigations have been conducted to overcome these two problems. The summary of the different implemented techniques will be presented in the next paragraph, while, the details of some of these techniques will be presented in the following paragraphs.

In general, modifications and/or hybridizations introduced to conventional solar desalination system included an element of sophistication to the base design but this alteration would make fresh water generation faster and of larger quantities. The evaporation rates is enhanced by using several techniques: concentrating solar radiation by using radiation concentrators or reflecting mirrors, or, enhancing the surface area of water evaporation by using porous domains and multistage (surfaces) of evaporations, or, enhance solar absorption, creating subvacuum conditions inside the still, or, using phase change materials to store heat and create a phase lag between evaporation and condensation processes, or, preheating the impure water before being used in the still. To enhance the condensations rates inside the still numerous numbers of techniques have been proposed and analyzed. These techniques included cooling the external side of the glass cover, or, using external condensers that condensate the extracted steam with the help of cooling sources such as cool water or geothermal cool resources.

Solar collectors are used to enhance the thermal processes by preheating water fed into the solar still [14,15]. Nakatake et al. [16] proposed a newly designed in a very small scale, maritime lifesaving which is a small distillery composed of a windmill and number of cylindrical partitions emerged in saline-soaked wicks. Eltawil and Zhao [17] proposed a hybrid desalination system that contains of wind turbine and inclined solar water still integrated with main solar still. The small mill turbine contribution was limited to operate a rotating shaft installed in the main solar still to break boundary layer of the basin water surface. Ninic et al. [18,19] have elaborated the idea of a solar distiller and an offshore wind power plant operating together. The system discussed is a single-stage solar distillation plant with vaporization, using adiabatic expansion in the gravitational field inside a wind power plant supporting column.

Another use of wind turbines is to supply electricity or mechanical power for desalination plants. Few applications have been installed using wind energy to drive a mechanical vapor compression (MVC) unit. In 1991, a pilot plant was installed in island in Germany, where a wind turbine with a nominal power of 45 kW was joined to a 48-m^3/day MVC evaporator, in addition to a 36-kW compressor. The experiment has been repeated in 1995 with a larger plant in the island of Rugen. A 50-m^3/day wind MVC plant was implemented in 1999 in Gran Canaria, Spain, within the Sea Desalination Autonomous Wind Energy System (SDAWES) project [20]. In addition to wind energy and RO combinations, few number of units have been designed and tested but all in a small scale [21,22].

Water preheating is the technique that has been followed in our work. Up to our knowledge this investigation is the first that utilizes the frictional thermal energy generated by a wind machine to preheat the impure water in order to enhance the solar still productivity. The positive features of the proposed solar/wind hybrid system may is that wind and solar resources complement each other. During winter and nights the still depends on the thermal energy generated by the wind machine to evaporate water. In summer and daylight time the still