Solar Energy 136 (2016) 659–667

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Solar dish concentrator for desalting water

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ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form 26 May 2016
Accepted 22 July 2016

Keywords:
Solar dish concentrator
Thermal desalination
Solar still
Renewable energy

ABSTRACT

The purpose of this study was to build, characterize and analyze the performance of a solar dish concentrator for desalinating water. To build this device, an equatorial mount was adapted to track the sun, a satellite dish was mirrored and the distillation system was assembled using a glass flask, a copper tube and a silicone tube. The system was characterized experimentally based on the main parameters that define a solar concentrator. However, to determine the potential energy of the device, dynamic heating was simulated by computer and validated experimentally. Finally, to analyze the performance of the solar dish concentrator in terms of water desalination, experiments were conducted with semi-continuous insertion of saline solution containing concentrations of 0–4% of sea salt. The yield of distilled water varied of 4.95 kg/m^{2}day (0%) to 4.11 kg/m^{2}day (4%), a consequence of colligative effects. Therefore, a solar dish concentrator was built with a simplified distillation system whose yield per square meter provided sufficient drinking water to meet the daily needs of at least two adults.

1. Introduction

Water is essential for human (Holdsworth, 2014), plant (Gutierrez and Whitford, 1987) and animal life (Rastogi, 2008), and is one of the most abundant sources of Earth, covering three quarters of the planet's surface. However, approximately 97.5% of that is salt water (Cech, 2010) unsuitable for drinking, since it can cause stomach upset, hypertension, strokes and laxative effects (Vineis et al., 2011). An alternative to render this water drinkable is to desalt it.

According to Daniels (1980), desalination can be performed by means of various techniques, including compressive steam, centrifugation, ion exchange, reverse osmosis, electrochemical treatments, electrodialysis, evaporation and solvent extraction. The desalting method used in this research was solar evaporation using a solar dish concentrator.

This type of concentrator has a reflective surface that directs sun's rays to an absorber installed on focus. The typical temperature range of this concentrator model ranges from 100 to 1500 °C (Born and Wolf, 1975). This device can be used in steam generators, solar cookers and other devices that require high temperatures. The solar trackings indicated for this model is dual axis (Duffie and Beckman, 2013).

However, desalination also requires an evaporation system. Thermal energy based processes usually involve the following systems: conventional solar still (Al-Hayeka and Badran, 2004; Singh et al., 2016; Tripathi and Tiwari, 2006), multi-stage flash (MSF) distillation (Ettouney, 2005; Farahbod et al., 2013), humidification/dehumidification (UD) (Kang et al., 2014; Summers et al., 2012; Hermosillo et al., 2012), freezing (Mandri et al., 2011) and multiple effect distillation (MED) (Frantz and Seifert, 2015; Zheng et al., 2006). There are several combinations of solar collectors and stills (Ibrahim and Dincer, 2015), which are described below.

Omara and Eltawil (2013) studied a hybrid solar dish concentrator (SDC) and a conventional solar still. Assuming 9 h of production per day, the preheated SDC produced 6.7 L/m^2. Arunkumar et al. (2013) investigated the possibility of increasing the yield of distillate by adding paraffin filled with black spheres, since paraffin is a phase change material (PCM) that can store large amounts of heat. Accordingly, a SDC was added to a conventional solar still. In 9 h of operation, the highest yields obtained from the systems with and without PCM were 4.46 L/m^2 and 3.52 L/m^2, respectively. A parabolic solar concentrator and an independent condenser were investigated by Elsafty and Abbas (2013), and their performance was compared considering two tracking directions, one oriented North-South and the other East-West. Considering two systems, one manual and the other automated, the East-West direction was 30.95% and 69.38% more efficient, respectively, than the North-South orientation.

The performance of three types of concentrators (flat mirror, CPC and V-shaped) was simulated by attaching them to a UD distiller (Riffat and Mayere, 2013). The V-shaped concentrator was found to be the most productive one when the working temperature was higher than 80 °C. At lower temperatures, the flat mirror concentrator proved to be more advantageous in terms of

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http://dx.doi.org/10.1016/j.solener.2016.07.039

Nomenclature

A_a	aperture area, m^2
A_{abs}	absorber area, m^2
A_f	geometrical factor, %
C	geometrical concentration ratio
c_{p_s}	specific heat of the specimen, J/(kg K)
c_p	specific heat of fluid, J/(kg K)
d	diameter of parabolic reflector, m
D	diameter of the cylinder, m
DEC	declination, °
f	focal length, m
$F_{C\to V}$	form factor between the test of the specimen and the neighborhood
g	acceleration due to Earth's gravity, m/s^2
Gr_L	Grashof number with characteristic length L
h	convective heat transfer coefficient, $W/(m^2\,K)$
I_b	direct normal insolation per unit of collector area, W/m^2
k	thermal conductivity, W/(m K)
L	height of cylinder or characteristic length, m
$\bar{Nu}_L$	Nusselt number with characteristic length L
Pr	Prandtl number
q_{conv}	convective heat loss rate of the specimen, W
q_e	heat loss from the specimen to the surroundings, W
q_r	heat loss from the specimen for reflection, W
q_{ri}	solar energy incident on the concentrator, W
q_u	useful thermal energy, W
r^2	coefficient of determination
Ra	Rayleigh number
RA	right ascension, °
t	time, h
T	temperature, K
T_1	temperature of the brackish water storage tank, K
T_2	fluid temperature in the absorber, K
T_3	condensate temperature after the copper tube, K
T_4	condensate temperature after the silicone tube, K
T_s	surface temperature, K
T_∞	ambient temperature, K
V	volume of the specimen, m^3

Greek symbols

α	thermal diffusivity, m^2/s
α_m	absorptivity of the absorber, %
β	volumetric thermal expansion coefficient, K^{-1}
ϵ_o	optical efficiency, %
φ_r	rim angle, °
γ	intercept factor, %
η	instantaneous thermal efficiency, %
η_{c1}	cooling efficiency (copper tube-1st section of the condenser), %
η_{c2}	cooling efficiency (silicone tube-2nd section of the condenser), %
η_{ct}	total cooling efficiency, %
μ	dynamic viscosity, $N\,s/m^2$
ν	kinematic viscosity, m^2/s
θ_{lim}	acceptance angle, °
ρ	density of fluid, kg/m^3
ρ_s	density of the specimen, kg/m^3
ρ_m	reflectivity of the reflector material, %
σ	Stefan-Boltzmann constant, $5.67 \times 10^{-8}\ W/m^2\,K^4$
τ_m	transmittivity of the cover glass, %

value for money. Liu et al. (2014) proposed a desalination system composed of a multi-stage evaporator attached to four CPC concentrator units, in series. The internal heat exchange system of the evacuated absorber was composed of concentric tubes. Its thermal efficiency was found to be 0.4 and its daily output was 7.87 kg/m^2, considering an average radiation of approximately 789 W/m^2.

A UD evaporator heated by a solar parabolic trough concentrator was studied in two configurations: one with hot air feed preceding the humidifier and the other with hot-air feed between the humidifier and dehumidifier, which were separated. The letter configuration was found to be about three times more efficient than the former (Al-Sulaiman et al., 2014). The SDC with a black chrome absorber was fed by preheated brackish water vapor leading to a heat exchanger. Operating 7 h a day produced a yield of 3.56 kg/m^2 (Gorjian et al., 2014).

The challenges for future inventions is to decrease the solar radiation catchment area, reduce costs and improve efficiency. Therefore, the purpose of this research was to plan, build and test a solar dish concentrator for desalting brackish and saline water, based on reuse and recyclable materials.

2. Material and methods

This section describes the geographic location of the solar concentrator, and the criteria for its design, construction and solar tracking. Also discussed are the methodology employed to obtain experimental data and the characterization parameters used here.

2.1. Geographic location

In this study, a solar dish concentrator plus an evaporator were considered a unit, and this unit was installed in the Department of Chemical Engineering, Federal University of Uberlândia (Brazil). The unit was positioned at 18.919216°S latitude, 48.257466°W longitude and 938 m altitude.

2.2. Design and building unit

The unit was designed to desalinate brackish and saline water in a solar dish concentrator made from reuse and recyclable materials. The unit consisted of two distinct parts: a tracking system and a solar concentrator.

The tracking system was adapted from an equatorial mount with astrophotography purposes. It consists of a steel tripod (1), shown in Fig. 1, to support a two-axis tracking system powered by two motors (2). Each of the motors, operation with a step of 1.8° and 64 steps per revolution, had a positioning accuracy of up to 1 arcmin. The direction of the Declination and Right Ascension axes was automated and programmed by means of a control (3).

The solar dish concentration (Fig. 2) was mounted on a mobile metallic base (4) with a counterweight (5), which was screwed onto crawler tracks. The galvanized steel parabolic dish (6) was 68 cm in height and 62 cm in width, and was recycled from a satellite dish antenna.

The reflective surface was mirrored in an electrostatic chroming process. The base structure supported a dual focal adjustment system, one to adjust the distance horizontally (7) from the absorber and the other to adjust it vertically (8). The borosilicate glass absorber (9), which was coated with a high-temperature matte black paint with absorptivity of 0.97 (Cengel and Ghajar, 2010), was installed in the focal region of the dish. The storage capacity of the absorber was 100 mL.

The counterweight mechanism (10), on the same axis as that of the absorber, held it vertically aligned to direct the evaporated liq-