Energy Conversion and Management 166 (2018) 637–647

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Design and implementation of a robotic active solar distiller based on a Fresnel concentrator and a photovoltaic system

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ARTICLE INFO

Keywords:
Desalination
Robotic solar distiller
Solar energy
Fresnel lens
Photovoltaic system

ABSTRACT

In this article, an active solar distiller is designed and implemented. The distiller consists of a Fresnel lens concentrator with an auxiliary photovoltaic energy collector, which supplies an electrical water preheating process. The light concentrator and the photovoltaic system are oriented through a three-degree-of-freedom robotic system, achieving the sun tracking and focus tasks of the concentration process. The design uses concurrent engineering tools to improve the general behavior of the system for energy collection and water distillation. This approach demands some different analyses such as optical, structural, thermal, and dynamic, modeling, which yield to the main design. The system is validated through different tests concerning the energy collection process and the resulting water quality, leading to an energetically autonomous effective system that can provide an alternative distillation process.

1. Introduction

Nowadays, the use of renewable energies in almost any productive process is a basic necessity. Many countries and companies are moving their policies and processes toward sustainability in energy as well as supply security. One of the most important aims is to reduce the use of fossil fuels in energy production. Until the end of the last decade, 80% of the present worldwide energy used was based on fossil fuels [1].

A closely related challenge is the potable water supply, whose set of causes is wide, from population growing, inadequate drainage infrastructure, urban evapotranspiration, poor water management policies, to natural causes such as water pollution, among others [2,3]. The necessity of integral, inter-, and transdisciplinary efforts in research, policy, and practice to come up with alternatives to treatment, production, and consumption lead to imply the energy efforts of water production as well as collateral effects such as the carbon print of the transportation, treatment, and production processes.

As a water treatment and purification method, water desalination is a popular strategy owing to the amount of saltwater covering the planet (70%) as well as the variety of water resource uses in terms of the percentage of salinity [4]. This process can be developed on the small scale (homemade technologies [5]) for the research, development, and evaluation of pilot plants [6,7].

The commercial processes and technologies for desalination are reverse osmosis (RO), multistage flash (MSF), and multi-effect distillation (MED) [8]. The most popular and productive desalination technologies such as membrane processes are energy intensive, and even when there is an effort of including alternative energy supplies such as solar or wind [9], the carbon footprint of desalination plants is still a major issue [10].

The use of solar energy has been extensively developed in electric energy generation (photovoltaic or thermal) and in water desalination systems through the development of solar distillers (commonly known as solar stills). This class of desalination systems is considered among small-scale devices as an environmentally friendly and effective method for purifying water on the small scale for locations where an ample amount of solar irradiation is available [11,12]. In addition, this class of systems is considered a low-carbon technology that has significant potential as alternative-energy-based freshwater production [13]. In particular, thermal solar energy has attracted attention from both the academic and industrial communities. It is predicted that their participation in global electricity generation may be as high as 50% by 2050 [14].

Solar stills work using evaporation and condensation processes.

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https://doi.org/10.1016/j.enconman.2018.04.069
Received 19 January 2018; Received in revised form 6 April 2018; Accepted 18 April 2018
Available online 03 May 2018
0196-8904/

Solar energy is used to evaporate the brine inside the solar still. Then, the condensate is collected as distilled water output [15]. Solar stills can be divided in two main categories: active and passive [3]. Passive solar stills do not need any other external source to carry out the desalination task. These systems are cheaper and easy to construct. In addition, their repair and maintenance issues are minimal [16]. The usual design parameters are the inclination angle of the glass cover, the water depth of the basin, and the material used of the basin liner among other parameters related to the heat transfer, the internal form of the still, and the condensing cover (see [17–19]). Among the drawbacks of passive solar stills is their low productivity. In general, passive solar stills produce in a range of 3–6 kg/m^2 [20,21], which depends on the physical structure of the system and the weather operating conditions.

An alternative to improving the efficiency and performance of the classic passive still consists of increasing the condensation surface temperature by providing thermal energy to the basin in an indirect manner (from a solar collector, energy cogeneration system, etc). These systems are known as active solar stills [22–24]. Active solar stills are usually classified in terms of their application of hot water [25,26]: (1) high-temperature distillation (from a solar collector), (2) preheated water application (constant-flow-rate application), and (3) nocturnal production (one application per day). In this sense, the solar collectors can be flat plate [27], parabolic, and Fresnel concentrators [14,28,29] coupled with photovoltaic systems [30,31] using heatpipes [32], Peltier modules [33], etc. These systems feature higher water production by taking advantage of preheating and by including energy effects.

The use of solar concentrators in solar stills is usually indirect, that is, the parabolic/Fresnel concentrator reflects the sunlight on a receiver tube, where a heat transfer fluid is used to increase the radiation absorption [34]. This process is also used to generate electricity as well. Unfortunately, the fluids may be expensive, necessitating alternative schemes of energy concentration.

Even though Fresnel concentrators have lower steam cycle efficiency with respect to parabolic concentrators, they are lighter. In addition, their operating and maintenance costs are negligible [35,36]. The disadvantages owing to their optical efficiency can be overcome through the use of solar tracking technologies in a synergistic combination with the concentrator design. In this sense, the design can take advantage of the solar tracking system in order to be autonomous by means of a photovoltaic collector system, leading to feeding all of the tracking systems while providing some extra energy for general purposes. Although the combination of a Fresnel lens and sun tracking systems represents an improvement in energy collection, it is important to consider the final system design in an integral manner since the use of generic commercial tracking devices may result in a reduction of the efficiency of the final system [37]. Most of the literature analyses are focused on intermediate results, i.e, purely optical or purely thermal analyses. The problem arises when a final application implies an efficiency reduction or its modification in order to obtain a feasible system. The idea of a robotic system takes advantage of the energy concentration, but the sun tracking application cannot be the same as a purely photovoltaic system where the normal incidence admits a larger tracking error and the water heating needs a special design that needs to be protected from light deviations, which may cause accidents. In this sense, additional elements such as a focus control are necessary. Fresnel lens efficiency is very sensitive to sun tracking. Thus, the use of conventional trackers based on solar vector computing may not be useful. A light sensor is necessary. In addition, a specialized integral system needs to be developed for the water heating application. Thus, the task of improving the energy concentration with respect to classic active solar stills demands synergistic design techniques such as concurrent engineering [38] and mechatronic design [39].

In this article, an active solar desalination system is proposed. This system consists of a Fresnel-lens-based concentrator driven by a robotic system for sun tracking and automatic focus. The design includes a heat exchanger in which the water is directly exposed to thermal energy. If the weather conditions reduce the efficiency of the process, the design includes an additional preheating process to provide an additional heat source. This preheating scheme takes advantage of the solar tracking system by including a set of photovoltaic modules and an energy storage system that provides additional energy for both the instrumentation and tracking system as well as the preheating process. The system was tested by some analyses, including weather conditions and the efficiency of the process for water desalination and by extracting some other toxic elements.

The remainder of this document is as follows: Section 2 deals with the problem formulation and technical approach. Some technical analyses for each subsystem are detailed in Section 3. Then, the system features and the general aspects of the proposal are given in Section 4. The proposed tests for system validation are shown in Section 5, and the results are discussed in Section 6. Finally, some concluding remarks and future work aspects are addressed.

2. Problem statement

2.1. Main purpose of the proposal

The use of a Fresnel lens to concentrate thermal energy can be improved by means of auxiliary robotic manipulation systems, which simultaneously allow for the collection of photovoltaic energy to provide energetic autonomy and function as an additional source of heating energy in case of occlusions owing to clouds or other weather effects. To achieve this condition in an efficient manner, it is necessary to implement an integral system design strategy such as the concurrent engineering approach.

The main purpose of the proposed system is to develop an alternative solar distillation water process of the active class but to incorporate mechatronic design concepts in order to enhance the efficiency of the water production. The considered design parameters for the distillation process are the production capacity, system dimensions, portability, energy generation and conversion requirements, the simplicity of the system operation, and the parameters of solar distillation owing to the radiation input. The system aims are distillate water production, the system energy balance, and the system and proposed method profits.

2.2. Technical approach

The system was developed from a concurrent engineering approach [38] to develop a new alternative for the water distillation process with the use of solar energy as a thermal and electrical source. This approach considers life-cycle factors during the design process such as functionality, manufacturing, assembly, testing, maintenance, reliability, cost, and quality [40], and it allows for the integration of different disciplines and technologies in order to increase the system efficiency and the water distilled production. The general process consists of the use of solar radiation in two ways: for solar radiation concentration for the treatment of the brackish water, and for the generation of electric power through a photovoltaic (PV) array. For the brackish water treatment, the solar radiation is concentrated in a receiver that is inside a chamber for evaporation of the water. The design of the evaporation chamber requires an analysis of thermal and optical phenomena to increase the evaporation efficiency.

3. System analysis

The design of the proposal requires the following analyses: An optical analysis for the lens choice, and the radiation behavior. The energy obtained needs a thermal balance to set the thermal exchanger dimensions. The final calculations are complemented by the design of the robotic structure, which is approached from mathematical modeling, the trajectory tracking control, and the structural design.