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Research paper

Off-the grid solar-powered portable desalination system

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HIGHLIGHTS

- The process of optimizing the solar-powered distillation system is presented.
- Parametric analysis is conducted using a computer model validated by experiments.
- A range of optimum HTF flow rates is obtained from the computer model.
- The boiler water target temperature is achieved and observed experimentally.

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ABSTRACT

An economically sustainable model for water purification and desalination process is presented. This system is designed as a standalone, off-the-grid water purification system. It utilizes a parabolic trough as a heat concentrator, a tube collector filled with heat transfer fluid (HTF), and a boiler to distill sea/brackish water for the desalination process. The paper outlines the process of designing and optimizing the solar-powered distillation system and the process of fabricating the parabolic trough. The current troughs are designed and fabricated to facilitate the necessary energy required to raise the HTF temperature to the design temperature of 120 °C. A non-toxic, non-hazardous HTF is selected as the working fluid for the solar trough hot loop. System performance analysis is conducted through a set of experiments while parametric analysis is performed using a computer model custom built for this system. The computer model simulates the thermodynamic and heat transfer processes where a range of optimum flow rates are determined. An increase in the boiler water temperature is observed experimentally for the new range of HTF flow rates obtained from the computer model. The maximum temperature recorded experimentally is 124 °C exceeding the design temperature of 120 °C. This system is designed to fit into a standard shipping container for ease of transportation worldwide.

1. Introduction

Although over 75% of the earth's surface is covered with water, only 3% of the Earth's water is fresh water, and not all of that is suitable for drinking [1]. The growing stress on the ground water sources worldwide is increasing the need for alternative fresh water supply. The demand for fresh water is especially critical in rural and impoverish communities. With advanced and economical desalination techniques, the availability of fresh drinking water can be greatly increased to alleviate this need.

Desalination methods can be classified as either a membrane process or a phase-change (thermal) process [2]. In a typical membrane process, a pressure is applied to the salt water to overcome the osmotic pressure driven by the chemical potential across the membrane. The applied pressure forces the water through a semipermeable membrane, which has pores small enough to restrict transport of salt, microbiological organisms and other unwanted material. This process has a high rate of water production but requires regular system maintenance, chemical treatment and frequent replacement of the membrane, which can be costly. The current level of maintenance required is undesirable for systems located in remote or impoverished areas. In a phase-change process, commonly called thermal distillation, salt is removed by evaporating the water and condensing the vapor in a separate collection tank. In general, thermal distillation process requires a large amount of energy input however it is a low grade thermal energy that can be obtained directly from the sun using concentrated solar collectors unlike the membrane desalination

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Nomenclature

A	aperture area of troughs, m^2
C_p	specific heat of HTF, J/(kg-K)
h	convective heat transfer coefficient, W/(kg-m^2)
$\dot{m}$	mass flow rate of HTF, kg/s
$\mathbf{Q}$	rate of heat transfer, Watt (or Joule/s)
q	heat flux, Watt/m^2
T	temperature, °C
ε	emissivity rating
η	trough efficiency
σ	Stefan–Boltzmann constant, 5.67e-8 W/(m^2-K^4)

Subscripts

amb	ambient
avg	average
coil	heat exchanger tube inside the boiler
conv	convection
HEX	heat exchanger
irr	irradiation
nb	nucleate boiling
pipe	trough collector tube
rad	radiation
surf	surface
tr	trough

processes which require high grade (electric) energy input. This process has the added benefit of removing other impurities in addition to pasteurization of water which can occur if done at temperature above 71 °C and for longer than 15 s [3]. Thermal distillation, therefore, not only provides desalinated water, but also purified drinking water.

Various solar energy concentrators are available in the market today from which parabolic troughs and linear Fresnel reflectors are the most common. Parabolic troughs have recently reemerged as a low-cost yet effective solution [4,5]. This solution is based on an established technology and function by concentrating the solar energy into a pipe along the trough mirror's focal length. Linear Fresnel reflectors are an emerging technology consisting of an array of mirrors to focus solar thermal energy on a specific location. There are advantages to both of these two systems and for example parabolic troughs have high optical efficiency, while linear Fresnel reflectors are less susceptible to wind loading, occupy less space, and are easier to maintain. Fresnel reflectors experience large variation in optical efficiency with the largest decrease in efficiency is during the winter season [4,5]. Parabolic troughs are more appropriate for small scale applications due to their simplicity, ease of fabrication and higher energy collection efficiency per unit cost over other collectors' methods.

A parabolic trough operates by reflecting and concentrating the thermal energy it receives from the sun into a pipe carrying a heat transfer fluid (HTF) appropriately placed at the trough's focal length and consequently absorbed by the HTF. The HTF then flows through a heat exchanger (HEX) located in a boiler to transfer the heat into the seawater and bring it to a boil before returning back to the parabolic trough. The generated water vapor is then condensed in a condensing tube which is also used as a preheater for the incoming replenishing water.

In this paper, an economical and cost-effective approach to design and build a standalone solar-powered water desalination system is presented. The system utilizes thermal energy concentrators to provide the energy requirement for the thermal desalination process. This system includes a tracking mechanism, regenerative heat exchange, and a photovoltaic panel to generate the required power for the pump and tracking mechanism. The work on this paper is an extension of a previous work done on a similar system [6]. The recommendations and the issues faced in the previous system are addressed. The key design criteria for this system is to be completely energy independent when in operation and for the entire system to fit easily into a 20 foot (6.1 m) standard shipping container for shipping worldwide. The current results provide a proof of concept for such a system from the design and technical prospective. Additional water related treatments that may be required is not discussed in this paper.

2. System design approach

In this paper, a proof of concept of a solar-driven thermal desalination system is presented. The focus of this paper is on the design, construction and technical specifications for the proposed system. Modeling simulations are performed to estimate optimum design specifications and experimental tests are conducted to verify the results obtained from the system model. The selection and design criteria for the parabolic trough, HTF, boiler, drive components are outlined in details. The main components of the system are described in the following sections. A schematic depicting the current system layout is also shown in Fig. 1.

The thermal energy concentrators presented in this paper consist of two parabolic troughs with a length of 3.05 m (10 feet) and an aperture width of 1.0 m (39.5 inches). The two troughs are designed to focus the incoming solar radiation onto a copper receiver pipe which is circulating the HTF in a close-loop system. The parabolic troughs are constructed using a reflective mirror and a frame support structure. The reflective mirror selected for the current system is a ClearDome SolaReflex brand panels with a reflectivity index of 95.5%. This material is weather resistant, bendable, simple to machine, fabricate and maintain. The mirror sheet is bent into a parabolic shape using a laser-cut medium-density fiberboard (MDF) a frame support ribs. The focal point location is estimated based on the aperture area of the trough using the following relation (y and x are measured in cm):

$$y = 0.027x^2 - 5.3125 \quad (1)$$

The troughs are assembled based on the theoretical focal point obtained from equation (1). It is important to note that there is a tradeoff to consider when selecting the size of the receiver pipe. Larger receiver pipe diameters compensate for minor focus imperfections while smaller pipe diameter makes the focal length more difficult to locate. Other factors such as the HTF type and the system input energy requirement effect the pipe size selection. For the current experiments and based on all of these factors, a 2.54-cm (1.0 inch) copper receiver pipe is selected to provide the proper balance between the pipe external surface area and the optimum HTF flow rate. The current pipe selection is expected to maximize the parabolic trough solar energy concentration and to compensate for the trough expected inaccuracy. The consistency of the curvature of the trough reflective surface is examined using a laser pointer to simulate the incoming solar light and local deformities are found along the surface. The trough surface is adjusted and iteratively tested until the empirical focal length for the parabolic troughs is aligned with the receiver pipe. A proper alignment of the parabolic trough helps maintain an average trough efficiency of