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ScienceDirect

Solar Energy 125 (2016) 360–372

SOLAR ENERGY

www.elsevier.com/locate/solener

Modeling of a modified solar still system with enhanced productivity

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Received 29 April 2015; received in revised form 15 December 2015; accepted 19 December 2015
Available online 8 January 2016

Communicated by: Associate Editor G.N. Tiwari

Abstract

The solar still is a sustainable device to produce potable water, especially in arid areas with abundant sunshine and low water demands. Its low productivity, however, hinders its wider application. A lightweight, black-finished, slowly rotating drum is introduced within the still to allow the formation of thin water films that evaporate rapidly. This modification notably increases productivity while maintaining the advantages of the still such as ease of handling, low-tech requirements, material availability, safe water quality, sustainability and space conservation. In this paper, the modified still with rotating drum is studied analytically to optimize performance. A theoretical model is developed based on governing heat and mass balance equations. The governing equations are solved numerically and the model is calibrated and validated using experimental data. The built model is used to study the effects of important variables. Three empirical correlations to determine heat transfer coefficients are employed and an error analysis is conducted for each case. Results reveal that the proposed modification significantly promotes the solar still desalination technology and gives insights for better optimization of the still. Design alterations thus offer a strong potential for this old device to serve impending challenges of severe water demands.

Keywords: Drum; Model; Productivity; Still

1. Introduction

The solar still emulates the natural hydrologic cycle to sustainably produce fresh water. Solar stills make use of a sustainable and pollution-free energy source, i.e. the sun, to produce high-quality water. The taste of the produced water is reported to be better than that produced by more sophisticated desalination techniques (Al-Hayek and Badran, 2004). Saline water in the basin evaporates due to solar heating, condenses as it hits the cooler cover, trickles down the inclined cover and is collected as distillate. This concept has been in use for many years, especially in ships and arid areas, to produce potable water using solar energy. The main drawback, however, is the low water productivity, compared to other desalination methods. Today, with the increased interest in renewable-energy desalination, attention to solar stills is revived. Researchers have employed different concepts to increase water productivity through the use of separate condensers for the still (Fatani et al., 1994; Fath and Hosny, 2002), reflectors to concentrate solar light (Zaki et al., 1992), double basins (Sodha et al., 1980), heat collectors (Rai and Tiwari, 1983; Yadav, 1991) and sun-tracking devices to optimize absorption of sunlight by following the movement of sunlight during the day (Abdallah and Badran, 2008; Tanaka and Nakatake, 2009a). Some researchers introduced modified geometries such as vertical stills (Boukar and Harmim, 2004), tubular stills (Ahsan et al., 2009),

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http://dx.doi.org/10.1016/j.solener.2015.12.025
0038-092X/

Nomenclature

A	evaporative surface area, m^2
a_c	contact angle
a_g	absorptance
a_i	measurement position at the rotating drum
C	coefficient in Dunkle's equation
C_p	specific heat, J/kg/K
C_{p_Al}	specific heat of Aluminum, J/kg/K
C_{p_w}	specific heat of water, J/kg/K
d	mean vertical height between evaporation and condensation surfaces, m
D	thermal diffusivity, m^2/s
Gr	Grashof number
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, $W/m^2/K$
h_c	convective heat transfer coefficient, h_c [$W/m^2/K$]
H_{cdai}	convective heat transfer coefficient between longitudinal drum element and the air inside the hollow drum, $W/m^2/K$
h_{fg}	latent heat of vaporization, J/kg
I	intensity of solar radiation, W/m^2
k	thermal conductivity, W/m/K
L	characteristic length scale of convection, m
m	mass, kg
m_{Al}	mass of Aluminum used in unit area of drum element, kg/m^2
m_{ew}	distillate output, kg
m_w	mass of water film along a longitudinal drum element, kg
n	coefficient in Dunkle's equation
N_d	rotational speed of the drum, rpm
p	partial vapor pressure, N/m^2
Pr	Prandtl number
q	heat transfer rate, W/m^2
R	radius of the drum, m
Ra	Rayleigh number
R_g	regression coefficient
S_d	peripheral speed of the drum, m/s
t	time, s
t_r	transmissivity
T	temperature, K
T_{ai}	temperature of air inside the drum
T_d	temperature of the drum element under consideration, K
t_f	film thickness, m
t_{f0}	limiting constant film thickness, m
t_{ft}	film thickness at top of the drum, m
tk_{Al}	thickness of the Aluminum used in the drum element, m
β	expansion factor
Δ	difference
ε	emissivity
σ	Stephan–Boltzmann constant
μ	dynamic viscosity, kg/m s
ρ	density; kg/m^3

Subscripts

d	drum
g	cover
w	water

transparent tubes to contain the water instead of basins (Reali and Modica, 2008), multiple-stage stills (El-Sebai, 2005; Al-Hinai et al., 2002; Suneja and Tiwari, 1998) and hemi-spherical stills (Ismail, 2009). Other researchers studied the effect of cover inclination (Singh and Tiwari, 2004), water depth in the basin of still (Tripathi and Tiwari, 2005) and other parameters and practices that affect the performance of solar stills (Tiwari and Tiwari, 2008). A complete review of these developments and their effects on performance was presented by Ayoub and Malaeb (2011). It could be concluded that the increase in water productivity of the solar still in most cases was offset by added cost and complexity of the introduced components. For example, the use of separate condensers, reflectors and sun-tracking devices entails additional cost as well as extra space to accommodate for these devices. In fact, a major concern while increasing productivity of the solar still is to maintain its basic advantages. These include its simplicity, ease of handling, safe water quality, sustainability, material availability, space conservation and low-tech requirements since it mainly targets rural or less developed areas where sunshine is abundant but water sources are scarce.

The improvement in productivity relative to conventional solar stills varies from one study to another depending on the modification introduced e.g. 22% for the use of reflectors (Zaki et al., 1992), 22–41% for sun-tracking devices (Abdallah and Badran, 2008; Tanaka and Nakatake, 2009a), 30–35% for heat collectors (Yadav, 1991), 35–77% for multiple-stage stills (Al-Hinai et al., 2002; Suneja and Tiwari, 1998) and 55% for condensers (Fath and Hosny, 2002) but is generally limited to less than 100%. A major cause for the low productivity of solar stills is the need to heat substantial amounts of water in the basin. A number of studies have used suction due to capillary action of sponges (Bassam et al., 2003) or wicks (Sodha et al., 1981; Minasian and Al-Karaghouli, 1995; Shukla and Sorayan, 2005; Janarthanan et al., 2005; Velmurugan et al., 2008; Tanaka and Nakatake, 2009a,b) to increase the surface area available for evaporation.