Applied Energy 154 (2015) 480–490

Contents lists available at ScienceDirect

Applied Energy

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

Maximized production of water by increasing area of condensation surface for solar distillation

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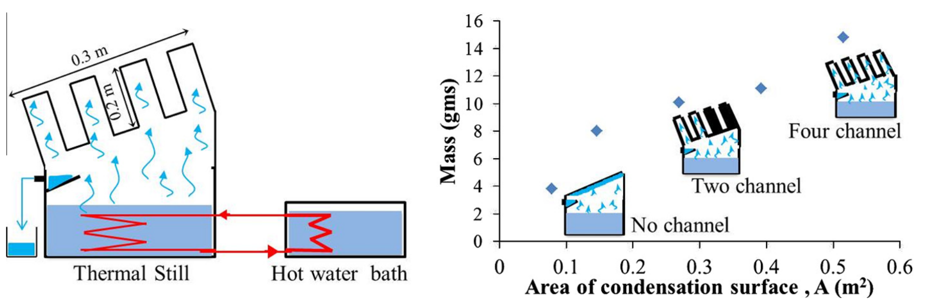
HIGHLIGHTS

- Achieved enhanced production of water by increasing the condensation area.
- Developed a model for estimation of water produced for increased condensation area.
- Enhanced cooling on condensation surface increased water production by eight times.
- Demonstrated simple cooling methods for achieving higher production of water.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form 16 April 2015
Accepted 18 May 2015

Keywords:
Cooling
Solar still
Cheap
Drinking water

ABSTRACT

Cooling of the condensation surface increases the production of purified water in solar distillation devices, also known as solar stills. However, most cooling methods are costly, complex and involve regular monitoring. Simple, easily operable and cheap cooling in solar stills can make it attractive for commercial adaptation at a large number of rural locations across the world. Here we demonstrate the increase in the area of the condensation surface as an effective way of increasing the production of purified water from the stills. Experiments were conducted inside the lab and under the sun. In the lab experiments, performed at a constant energy input of 625 W/m^2, the production of water increased by more than 65% with an increase in the area of the condensation surface by 7.5 times. In the experiments conducted under the sun, the production of water increased by more than 50% by using an additional area for condensation which is 7.5 times larger when compared with a reference still without an additional area of condensation. Further, by using a higher heat input, we show that the effect of increase in the area of the condensation surface by 6.5 times can increase the production of water by more than five times. We further demonstrate the effect of external cooling by decreasing the temperature of the condensation surface to almost 0 °C. The amount of water produced from the still was increased by more than eight times by maximizing cooling of the condensation surface. The results suggest that a solar still device with an increased area of condensation surface can be adapted as a cheap, easy to manufacture and easily operable device for a large number of people who are in need of drinking water.

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http://dx.doi.org/10.1016/j.apenergy.2015.05.060
0306-2619/

Nomenclature

A	area (m^2)
h	heat transfer coefficient ($W/m^2\,°C$)
k	mass transfer coefficient (m/s)
$\dot{m}$	mass transfer (kg/s)
m	mass (kg)
M''	normalized mass ($kg/m^2\,h$)
P	vapor pressure (N/m^2)
$\dot{Q}$	heat transfer (J/s)
Q	heat (J)
R	gas constant (J/mol K)
T	temperature (K)
t	time (s)
ΔH_{vap}	enthalpy of vaporization of water (J/kg)

Greek letters and symbols

σ	Stefan Boltzmann constant ($W/m^2\,K^4$)
ϵ	emissivity
η	efficiency

Subscripts

amb	ambient
conv-wat	convection from water
conv-sur	convection from surface
e	external
evap-wat	evaporation from water
i	internal
in	input
rad-wat	radiation from water
rad-sur	radiation from surface
sur	surface
top	top condensation surface
wat	water

1. Introduction

Desalination is an effective way to satisfy the increasing demand of fresh drinking water [1]. In underdeveloped and developing countries, more than 768 million people drink water from unreliable sources [2]. Many remote and coastal areas do not have resources of electric power for producing potable water using conventional desalination techniques such as multi-stage flash, reverse osmosis and vapor compression [3–6]. The cost of installation, operation and maintenance of these techniques are high and are far beyond the financial resources of the local population in most areas. In addition, a water pipe line distribution system is not available in these regions, and the road network and transportation system are insufficient to carry a large amount of potable water regularly from desalination plant areas to the consumers.

Amongst various desalination technologies, solar distillation has been found to be most suitable for application in villages and small islands [3–6]. It represents the best technical solution to supply remote villages or settlements with fresh water without depending on high technology and expertise [3]. They further offer several other advantages [6]. Solar stills work on cheap and renewable solar energy, hardly use any electricity and hence do not produce carbon dioxide. There is often plenty of solar energy available in regions of scarce drinking water resources. Moreover, solar stills are easy to build and operate. Finally, solar stills can be more economical than other desalination technologies for providing water to households and small communities. Kumar and Tiwari [5] suggested that a solar distillation plant with a capacity less than 200 kg/day was more economical than other types of desalination plants.

However, solar stills have not been widely applied because of their lower productivity of drinking water [4,7–17]. Arunkumar et al. [17] have concluded two reasons for low productivity of solar stills. Firstly, the difficulty in rejection of the latent heat of condensation to the atmosphere and secondly, the difficulty of raising the evaporation temperature and decreasing the condensation temperature. Several other authors [4,7–17] have evaluated the reasons for the low productivity of water and suggested various solutions. These are (i) achieving a higher basin temperature (lower water level, use of wick, adding black dyes, additional external heating-collector, concentrator, and waste heat recovery), (ii) lowering the cover temperature by using condensation cover cooling, overnight cooling with basin energy storage and use of additional condensers, (iii) large evaporation and condensation surface areas, re-utilization of the latent heat of condensation (multi-effect) and (iv) minimizing heat losses (good side and bottom insulation). Ahsan et al. [16] has studied the factors affecting the productivity of water from a low cost solar still and suggested a triangular solar still as a preferable design. Furthermore, Xiao et al. [6] have categorized several improvements in design which are done in order to increase the productivity of the solar still into six sections. These are installing reflectors, coupled with solar collectors, enhancing condensation, increasing free surface area, recovering latent heat and coupling with heat storage. Xiao et al. [6] further present two conclusions. Installing reflectors and solar collectors are more practical in places where solar radiation is weak and the ambient temperature is relatively low. Increasing free surface area, recovering vapor latent heat, installing a heat storage system and enhancing condensation are more suitable for places where solar radiation is relatively strong.

Enhancing condensation is one of the central ways of improving the production of water from the solar still [6]. Depending on the methods used to enhance the production of water in the stills, they are categorized into active and passive type of solar stills [11,14,15,18]. In active type of stills, additional condensers or collectors are used [19]. In passive type of stills, either modifications will be done inside the still or some materials are used in the basin along with the saline water. An active system is, however, generally costly and may require regular monitoring [20–22]. The current study focuses on passive type of stills. The use of enhanced condensation for increasing the production of water in passive solar stills has been evaluated by several authors [23–27]. Madhlopa and Johnstone [23] reported that the theoretical productivity of a passive solar still with a separate condenser was 62% higher than that of a conventional still. Fath and Elsherbiny [25] added an external condenser to a single slope simple still. They reported an increase in production of water of up to 50% by addition of a passive condenser inside a solar still. The condenser acts as a heat and mass sink which continuously sucks water vapor from the still, condenses it and maintains the still at low pressure and temperature. The uses of condenser limits vapor leaks and losses of energy from the solar still [25]. Furthermore, [25] reported an increase of up to 75% in the production of water with an increase in the temperature difference between the still and the condenser from 4 °C to 6 °C. Fath and Hosny [24] used one of the cover sides tilted to be parallel to the sun rays and, therefore, be