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Performance study of the inverted absorber solar still with water depth and total dissolved solid

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ABSTRACT

In this communication, an experimental study of inverted absorber solar still (IASS) and single slope solar still (SS) at different water depth and total dissolved solid (TDS) is presented. Experiments are conducted for the climatic condition of Muscat, Oman. A thermal model is also developed for the IASS and validated with experimental results. A fair agreement is found for the daytime operation of the IASS. It is observed that higher water temperature can be achieved by using the IASS in comparison to the SS. The daily yield obtained from the IASS are 6.302, 5.576 and 4.299 kg/m^2-day at water depths (d_w) 0.01, 0.02 and 0.03 m respectively. At same respective water depths, the daily yield obtained from the SS are 2.152, 1.931, 0.826 kg/m^2-day respectively lower than that of the IASS. It is observed that for climatic condition of Muscat, Oman, the optimum water depth for the IASS is 0.03 m above which the addition of reflector under the basin does not affect its performance much more in comparison to that of the SS for sea water. The feed saline water and yielded distilled water are also compared for different TDS values, pH, and electrical conductance. On the basis of economic analysis of IASS, it is found that the annualized cost of distilled water in Indian rupees for Muscat climatic condition is Rs. 0.74, 0.66 and 0.62 (conversion factors: $ 1 = Rs. 50 and 1 OMR = Rs. 120) for the life time of 15, 20 and 25 years respectively.

1. Introduction

Water is a basic necessity for sustaining life on the earth. With the passage of time due to technological usage and their waste disposal along with ignorance of human being caused water pollution which led the world to water scarcity. Due to water pollution the surface and under ground water reservoirs are now highly contaminated. The demand of fresh water is increasing with growth in human population. To meet the demand of potable water, scientists have developed various technologies such as reverse osmosis (RO), vapour compression (VC) and electrodialysis (ED) [1]. These water purification methods are highly energy and cost intensive. It is well known that desalination plants use electrical energy which have both economical and environmental drawbacks and rely on conventional fuels [2]. Therefore a method is required to use renewable energy, low input cost and less efforts for the production of potable water.

To overcome the scarcity of fresh water in Gulf region, the availability of long sea shore and abundant solar energy is the boon for the application of solar distillation technology [3]. Several gulf countries, like in Kuwait and Oman, rely mainly on seawater desalination to get potable water. It is reported that reverse osmosis (RO) technology was utilized for the conditions of Arabian Gulf seawater in 1987 [4]. Gulf countries adopted most of dual-purpose multi-stage flash (MSF) desalination plants for producing both power and potable water as reported by Al-Mutaz [5]. Nairn [6] advocates for increasing the production of desalinated water to meet increasing water supply demand all over the world. According to Bremere et al. [7] the production of potable water in desalination market would need to reach 14.8 million m^3/day in water-scarce countries including Kuwait and Oman by year 2025.

A distillation method using solar energy can be economical, environment friendly and renewable energy based technology [8]. It is a method which can be applicable in rural, remote areas of developed and developing countries including gulf countries also where the availability of solar radiation is high. But it has certain limitations. According to Qiblawey and Banat [9], solar desalination requires large land areas in comparison to the other technologies. It has relatively low productivity but competitive to the other desalination methods for small-scale production of water due to its relatively low cost, simplicity in design and operation.

The conventional design of the solar still is a single slope solar still (SS). It is associated with few disadvantages like low amount

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Nomenclature

A_b	area of the basin plate (m^2)
A_g	area of the glass cover (m^2)
A_s	contact area of water with side wall (m^2)
d_w	water depth (m)
h_{kb}	heat transfer coefficient of basin (W/m^2 °C)
h_{kg}	heat transfer coefficient of glass cover (W/m^2 °C)
h_{ks}	heat transfer coefficient of side wall (W/m^2 °C)
h_1	total heat transfer coefficient from water to glass cover (W/m^2 °C)
h_2	convective-radiative heat transfer coefficient from outer surface of glass cover to ambient (W/m^2 °C)
h_3	heat transfer coefficient from basin plate to water (W/m^2 °C)
H_2	total heat transfer coefficient from basin plate to ambient (W/m^2 °C)
H_3	total heat transfer coefficient from water to ambient through side walls (W/m^2 °C)
$I_s(t)$	solar radiation on solar still (W/m^2)
$\dot{m}_{ew}$	hourly yield through solar still (kg/h)
$(MC)_w$	heat capacity of water (J/°C)
N	average no. of reflections
P_{gi}	partial vapour pressure at inner surface of condensing glass cover (N/m^2)
P_w	partial vapour pressure at water surface (N/m^2)
T_a	ambient temperature (°C)
T_b	basin liner temperature (°C)
T_{gi}	temperature of inner surface of condensing glass cover (°C)
T_{go}	temperature of outer surface of condensing glass cover (°C)
T_v	vapour temperature (°C)
T_w	water temperature (°C)
r_{inv}	reflectivity of reflector under the still.
v	wind velocity (m/s)

Greek letters

α_b	absorptivity of absorber basin liner
α_g	absorptivity of glass covers
α_w	absorptivity of water
ρ	density of the water (kg/m^3)
ε_c	emissivity of glass
ε_{eff}	effective emissivity of the system
ε_w	emissivity of water
τ_{g1}	transmissivity of glass used as condensing cover
τ_{g2}	transmissivity of glass on reflector
τ_w	transmissivity of water
σ	Stephan–Boltzman constant

of distilled water produced per unit area because of lower water temperature and low efficiency, etc. [10]. Researchers have proposed several methods to increase the water temperature, efficiency and yield of solar stills such as: by additional heat either through flat plate collector (FPC) or concentrating type devices such as reflector or parabolic dish to run the system in active mode of operation [11–13]; optimizing the water depth [14]; increasing the basin temperature by reflectors [15]; addition of dye in the feed water [16,17], etc. Sinha and Tiwari [18] presented a thermal evaluation of concentrator assisted solar distillation system and found that a passive system always has a higher thermal efficiency than that of the active system. Similarly, it is also seen that a concentrator-assisted still has higher thermal efficiency than that of the collector-assisted still [18].

An inverted absorber solar still (IASS) is a combined system of a single slope solar still and a curved reflector under its basin. It is an improved design of the SS with an advantage of double sided heating of basin i.e. from top as well as bottom which increases the temperature of basin as well as water also. Tiwari and Suneja [19–21] presented a thermal model and carried out theoretical analysis of the IASS with single, double and multiple basins and reported that an optimum water depth of 10 cm in the basin results 11% more yield when the water flows over the condensing surface to cool it [19]. Although, the 10 cm water depth is meant 100 l of water in the solar still having a basin area of 1 m^2 and is a very high amount of the water for passive distillation system over a day. The effect of water flow on the internal heat transfer of solar still has been analyzed and shown that convective and radiative heat transfer coefficients do not affected by water depth variation except the evaporative heat transfer coefficient [20].

Yadav and Yadav [22–26] have given the parametric study of compound parabolic concentrator (CPC) assisted inverted absorber asymmetric line-axis solar high temperature solar distillation system and derived mathematical expressions for temperature of water, glass cover, distillate output and efficiency. The effects of several parameters such as amount of water, absorptivity and concentration ratio is observed and reported an improved productivity over the conventional single basin solar still. It is observed by using simulation method that suppression of solar radiation decreases reflector and aperture cover temperature and an increment in concentration ratio from 1 to 3 increases water temperature and yield. Yadav et al. [27] reported yield up to 0.7 l, maximum solar radiation 800 W/m^2 between 12:00–13:00 h and similarly, maximum water temperature 64.8 °C between 12:00 and 13:00 h for an experiment on a double exposure single basin solar still with 3 l of water in basin (0.2 m × 1 m) for climatic condition of Darbhanga, Bihar in India. The maximum temperatures of basin, inner surface and outer surface of glass cover are found 69 °C, 61 °C and 53 °C respectively between 12:00 and 13:00 h in experimental period of 5 h (i.e. from 10:03 to 15:23 h) for a typical day in March'97 [28]. Tiwari et al. [28] presented modified designs of inverted absorber asymmetric line axis CPC. An experimental study of inverted absorber asymmetric line axis CPC conducted at Darbhanga, Bihar in India is reported with yield 3.04 l/m^2 for 6 h of testing period [29]. Abdul-Wahab et al. [30] reported that the productivity of an inverted absorber solar still can be more than 3.5 kg/m^2 for water depth 0.01 m in 12 h i.e. from 7:00 AM to 7:00 PM for the month of September 2008.

Apart from solar distillation, Norton [31] also introduced novel uses of asymmetric inverted absorber compound parabolic concentrators for air/water heating, and cooking. And in its application for distillation, it is reported that a significant temperature reduction may occur through the glass cover used in standard stills from the internal surface to the external surface, the elevated internal surface temperature results in low distillate output. Kumar and Tiwari [32] presented a life cycle cost analysis of single slope hybrid (PV-T) active solar still and estimated the lowest cost of the distilled water obtained from passive and hybrid active (PV-T) solar stills as Rs. 0.70 and Rs. 1.93 per kg respectively when life period is considered to be 30 years.

In the present study, the performance of an inverted absorber and single slope passive solar stills have been observed at different water depths and total dissolved solid (TDS) for the climatic condition of Muscat, Oman (one of the gulf countries where scarcity of