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Performance investigation and enviro-economic analysis of active vertical solar distillation units

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ABSTRACT

In this work, performance enhancement of vertical still by active mode operation was carried out using mathematical modeling. The reported model is validated with the mass transfer model that is usually employed for prediction of mass transfer in vertical stills. The two configurations considered for active mode operation are CVDS (cascaded vertical-double slope) still and CVSS (cascaded vertical-single slope) still. The optimum absorber area and gap between condensing and evaporating surface is 4 m^2 and 0.20 m, respectively. Effect of shade on system performance has also been reported. CVDS and CVSS unit produces nearly 25.63% and 13.33% higher distillate than the passive vertical still of similar dimensions. The yield is found to decrease by 10% for every 5% increase in salinity of feed. Maximum yield of 24.06 kg/d is recorded for CVDS unit during the month of April. CVDS unit has maximum energy payback period of 2.25 years and can mitigate at least 69.85 tons of CO_2 emission during its life time of 20 years and can provide distilled water at 34.3 USD/kL or less. High yield, low water production cost and less ground area occupancy make the unit more feasible and competitive for rural and urban applications.

1. Introduction

The rising demand for high quality potable water for domestic and industrial applications can be met by desalination of saline water which is available in plenty [1]. Desalination is an energy intensive process which requires large quantity of fossil fuel to be burned to produce distilled water. Pollution and environmental impacts due to conventional desalination plants can be minimized if desalination units are powered by renewable energy sources. The initial cost associated with renewable energy based desalination units are higher than the conventional methods of desalination but on the other hand, the cost of water produced using renewable energy for remote and arid locations are cheaper because of the elimination of large pipelines and transport of fresh water from the decentralized desalination units [2].

In remote and arid regions, desalination units must be designed in such a way with minimal or no maintenance, running cost and less operational difficulties. This has lead to the development of basin type solar stills which has been widely studied by many researchers around the globe. Distillate output of basin type stills has been increased by reducing the water mass and its depth in the basin [3,4]. Floating absorbers has also been studied for their feasibility in improving the yield of basin type stills [5,6], Solar concentrators like cylindrical parabolic concentrator [7], parabolic trough collector [8] and thermosyphon heat pipes [9] has also been coupled with basin type stills to enhance their productivity. Cooling of glass cover by water film to reduce the condensing surface temperature has also shown to enhance the productivity of basin type stills by 8.2% [10]. Utilization of latent heat of condensation by increasing number of stages in single slope still [11,12] and double slope still [13] and usage of waste heat from other processes [14] were also found to be effective in enhancing the yield of basin type solar stills.

Other types of solar stills considered for rural areas are mainly hemispherical stills [15] and concave type stills [16]. One of the interesting types of solar still is the vertical solar still and it is of two types namely, double sided vertical still and single sided vertical still. This type of still occupies less ground area and they receive solar radiation depending on their orientation (either East-West or North-South). Generally, for vertical stills feed water is allowed to flow as a thin film over the absorber plate instead of allowing the water mass to accumulate as a bulk as in case of basin type distillation units. The studies associated with these types of units are found to be scarce in literature. Kiatsiriroat et al. [17], has carried

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out experimental and numerical investigation on double sided vertical solar still and has confirmed that the still can produce 1.0 $kg/m^2/d$ of potable water under the climatic conditions of Bangkok. Analytical solution for the equations associated with double sided vertical solar still and its optimum dimension has been given by El-Sebaii [18] and the vertical still considered in the study has produced a distillate yield of 3.99 kg/m^2-d under the climatic conditions of Egypt. Boukar and Harmim [19,20] carried out experiments with one sided vertical solar still in deserts of Algeria and found that the still productivity depends mainly on still orientation and climatic conditions. The maximum yield reported in their study is around 2.3 kg/m^2-d [19].

It could be seen from the literature, that the distillate yield from vertical solar still is comparable to basin type solar stills and these kinds of vertical stills has not been studied widely. In the present study, interest has been directed towards enhancing the yield of the double sided vertical still by making it to operate in active mode. Active mode operation of vertical still is done by modifying the feed water tank of the vertical still into a basin type solar still. Two types of stills namely single SS (slope still) and DS (double slope still) has been considered as feed water tank for the vertical still. Optimum configuration of these two active vertical distillation units and its performance based on climatic condition, feed water salinity has been reported. Economic and environmental benefit analysis of the best active vertical distillation unit has been discussed and the results were found to be encouraging.

2. Active vertical solar distillation unit

The active vertical solar distillation unit consists of a double sided vertical still incorporated with a basin type solar still overhead which acts as a feed water storage and preheating unit. The length and breadth of the incorporated basin type unit is similar to the breadth and width of the double sided vertical still. The incorporated basin type solar still receives solar radiation from either south direction (single slope still) or east-west direction (double slope still) and the double sided vertical still receives solar radiation from both east and west direction. Feed water preheated in the basin type unit, placed overhead is allowed to flow as a thin film over the blackened absorber plate of vertical still using feed water distributor. Preheated feed water receives additional thermal energy from the absorber plate of vertical still which is exposed to east-west solar radiation and hence enhanced evaporation begins. Movement of water vapor from the evaporating surface (i.e., absorber plate) towards the condensing surface (i.e. glass cover) takes place because of partial pressure difference [21]. The condensed vapors are collected using suitable provisions and the brine is discarded. In this unit additional distillate can also be collected from the modified feed water tank (i.e. the basin type still) kept overhead. Double sided vertical still incorporated with single slope still is termed as CVSS (cascaded vertical-single slope) still and Double sided vertical still incorporated with double slope still is termed as CVDS (cascaded vertical-double slope) still. The schematic representation of the two types of active vertical distillation units is shown in Fig. 1a and Fig. 1b.

3. Mathematical modeling of the CVSS and CVDS solar distillation units

The assumptions that were considered for the development of mathematical model are listed below:

a) The distillation unit is vapor tight and free from leakage [14].
b) The heat capacity of the absorber plate, glass covers and water mass in basin are considered.
c) There is no temperature gradient across the water mass in the basin and across the thickness of the glass covers [3,9,11].
d) The thickness of the feed water flowing over the absorber plate of double sided vertical still is assumed to be very thin and the brine leaves the distillation unit at the absorber plate temperature [17].
e) Heat transfer from the evaporating surface to the condensing surface is by convection, radiation and evaporation.
f) Heat losses to the ambient is by convection and radiation from the glass covers and by conduction through the insulation [17].

The schematic of energy transport process in CVSS and CVDS solar distillation units considered in shown in Fig. 2 and Fig. 3.

The energy balance of each component of the CVSS and CVDS solar distillation units under consideration is given below.

Basin liner of basin type still (3),

[Rate of change of temperature of basin liner of basin type still]
= [Solar radtion absorbed by the basin liner]
− [Convective heat transfer from basin liner to water mass]
− [Heat loss from basin liner to ambient through insulation]

$$(MC)_b\frac{dT_b}{dt} = I_tA_b\tau_g\tau_w\alpha_b - Q_{c(b-w)} - Q_{l(b-a)} \quad (1)$$

Water mass of basin type (4),

[Rate of change of temperature of water mass of basin type still]
= [Solar radiation absorbed by the water mass]
+ [Convective heat transfer from basin liner to water mass]
− [Convective, radiative and evaporative heat transfer from water mass to glass cover]
− [Net heat carried by the feed water]

$$(MC)_w\frac{dT_w}{dt} = I_tA_b\tau_g\alpha_w + Q_{c(b-w)} - (Q_c + Q_r + Q_{ew})_{w-g} - m_fc_f(T_w - T_a) \quad (2)$$

Glass cover of basin type still (1 or 2),

[Rate of change of temperature of glass cover of basin type still]
= [Solar radiation absorbed by the glass cover]
+ [Convective, radiative and evaporative heat transfer from water mass to glass cover]
− [Convective and radiative heat transfer from glass cover to ambient]

$$(MC)_g\frac{dT_g}{dt} = I_tA_g\alpha_g + (Q_c + Q_r + Q_{ew})_{w-g} - (Q_c + Q_r)_{g-a} \quad (3)$$

Where, $I_t = I_e + I_w$ for Double slope still east west orientation; $A_g = A_e (or) A_w$

$I_t = I_s$ for Single slope still facing south

Mass balance in basin type still (4),