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A solar still augmented with an evacuated tube collector in forced mode

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HIGHLIGHTS

- Modified design of solar still integrated with an evacuated tube collector in forced mode is proposed.
- Thermal analysis of the system has been carried out.
- System has been optimized for mass flow rate.

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ABSTRACT

A single slope solar still has been integrated with an evacuated tube collector (ETC) and operates in forced mode. Thermal model of integrated system has been developed to predict performance of solar still under New Delhi (India) climatic conditions. The daily yield has been obtained as 3.47 kg for basin water depth 0.01 m and at mass flow rate of 0.006 kg/s. However, the optimum performance has been found to be at mass flow rate of 0.06 kg/s for basin water depth 0.03 m. The optimum daily yield has been obtained as 3.9 kg with energy and exergy efficiencies as 33.8% and 2.6% respectively during typical summer day. The average annual yield per unit of solar collector area has been estimated higher than the natural mode.

1. Introduction

The availability of clean drinking water to everyone remains a challenge in many parts of the world. Solar energy plays an important role for sustainable development in coming years as an alternative energy source. Solar stills are one of the most famous desalination technologies which use the solar energy in producing potable water. In recent years, various studies (i.e. experimental and theoretical) have been conducted on different configurations of solar stills to enhance the performance and productivity. Sampathkumar et al. [1] presented the detailed review of various designs of active solar stills. In active mode, water in the basin is heated directly as well as indirectly (hot water available from solar collector or industries), and research work reported by various authors in this field. Tiwari et al. [2] experimentally predicted the comparative performance on three single basin solar stills. The better yield obtained using single-slope solar still made of fiber reinforcement plastic (FRP) than the double slope in winter, but in summer, the reverse results appeared. Al-Hayek and Badran [3] showed that using mirrors in asymmetric greenhouse type solar still, yields 20% higher than that of the symmetric greenhouse types. Mutasher et al. [4] reported the enhancement in clean water productivity by using a combination of sun-tracking system with solar still. Esfahani and Rahbar [5,6] used thermoelectric technology to improve the productivity of solar stills. In addition to experimental researches, there are many studies which use mathematical modeling to estimate the productivity of solar stills. Al-Hinai et al. [7] used the mathematical model to predict the effect of climatic and design parameters on the performance of solar still. They concluded that the climatic conditions such as solar radiation, wind velocity and ambient temperature have a direct effect on productivity. They have also concluded that although the initial water temperature and insulation thickness have direct effects but, the cover angle has inverse effect in summer and direct effect in winter. Better efficiency was obtained at maximum temperature difference between water and glass cover [8].

Many active designs of solar still (i.e. solar still integrated with parabolic concentrator, evacuated tube collector (ETC) and flat plate collectors (FPC), hybrid photovoltaic (PV-T) solar still) have been studied by various scientists to enhance the daily yield. The effects of shape and size by using plastic condensing cover for passive solar still have been proposed and used by various scientists [9–11]. They concluded that the daily yield decreases due to reduction in top loss and large surface tension between condensed water and condensing cover for the same

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design. However, in solar stills integrated with parabolic concentrator, evacuated tube collector (ETC) and FPCs, the daily yield increases. Voropoulos et al. [12] reported that by coupling of the solar still with thermal storage, heated by flat plat collectors, the yield increases by two times than that of the solar still alone. Zaki et al. [13] carried out experimental investigation on an active system under thermosyphon mode of operation and reported that the maximum increase of yield by 33%, when the water in the single slope solar still was preheated in the flat plate collector. Tiwari et al. [14] developed a thermal model for integrated active solar still coupled with different types of the solar collectors and validated with experimental values for 0.05 m water depth. They concluded that active solar still integrated with evacuated tube collector with heat pipe gives yield 4.24 kg/m^2 day, maximum among all other types of solar still.

The current research in renewable energy indicates a growing interest for solar collectors with evacuated tubes. The evacuated tube solar collector has more advantageous than the flat plate collectors for water heating purposes. In flat plate collectors, sun rays are perpendicular to the collector only at noon and thus a proportion of the sunlight striking the surface of the collector is always likely to be reflected. But in evacuated tube collector, due to its cylindrical shape, the sun rays are perpendicular to the surface of the glass for most of the day [15]. However, Kim et al. [16] have found a significant increase in the outlet temperature of water and thermal efficiency (about 16.7%) of ETC by using tracking mechanism in comparison to that of stationary ETC. In high temperature operation, evacuated tube collector has higher efficiency and better performance than the flat plate collector, due to minimize convective heat loss. El-Nashar [17] predicted a decrement in the performance of ETC by 60% when the transmittance of glass tubes decreases from 0.98 to 0.6. Budihardjo and Morrison [18] studied heat transfer and flow patterns on all-glass vacuum tube water heaters with the diffuse reflection plate through experiments and numerical simulations. Simulation results show that when the tube aspect ratio is too large, there is a dead zone (no flow region) at the bottom. Further they predicted that performance of evacuated tube system with 30 tubes has slightly lower energy savings than a two panel (3.7 m^2) flat plate system. However, the performance of evacuated tube collector system was shown to be less sensitive to tank size than flat plate collector systems [19]. Li et al. [20] establish the heat transfer model of all-glass vacuum tube collector used in forced-circulation solar water heater. Recently, theoretical performance evaluation of solar still integrated with ETC in natural mode has been carried out by Singh et al. [21] for summer climatic condition.

The objective of this work is to complement the studies cited earlier on ETC integrated solar still in natural mode, with modified geometry in forced mode. Force mode operation of evacuated tube collector allows better heat removal from the tube and avoid effects such as internal recirculation and stagnation of cold water in reservoir. In conventional model of ETC operating in natural mode, two water streams move in opposite directions inside the tube and therefore disfavors the extraction of thermal energy. This adverse effect becomes visible when checking the presence of a recirculation region near the inlet where the heated water mixes with the cold water coming from the reservoir and creates a turbulence region [22]. Another unfavorable characteristic is the presence of a stagnation region in the storage tank when it is subjected to small inclinations. Glembin et al. [23] predicted that collector efficiency is highly depending on the flow rate. They predicted an efficiency reduction of 10% with a decrease in flow rate from 78 kg/m^2 h to 31 kg/m^2 h for a collector group with 60 parallel vacuum tubes with a coaxial flow conduit at one-sided connection. Also water flow rate through tubes in forced mode is in controlled manner, unlike in natural circulation. Numerical simulation has been performed to investigate the yield, water temperature, and energy and exergy efficiencies of the solar still with variable mass flow rate through the collector tubes. Further, the system has been optimized for water flow rate at optimum water depth (0.03 m), in order to predict comparative performance with natural combination and hybrid (PV-T) active solar still.

2. System description

A photograph and schematic of proposed design of water-in-glass evacuated tube integrated solar still is shown in Fig. 1a–b respectively. It consists of a solar still connected with number of evacuated tubes, insulated pipes and a water pump. FRP made solar still of 0.005 m thick having thermal conductivity of 0.351 W/mK is considered for analysis. Transparent glass cover (thermal conductivity of 0.76 W/mK) of thickness 0.004 m with an inclination of 15° to the horizontal is fixed to the top with proper sealing to prevent vapor leakage. Glass cover allows 95% the solar radiation (short wave) to transmit inside, which mostly is being absorb by the blackened absorber liner and water in it. The water pump withdraws the water from the solar still and sends it back after passing through evacuated tubes.

An evacuated tube collector (ETC) consists of a number of concentric borosilicate tubes inclined at an angle of 45° from horizontal, with vacuum in their annular space. Evacuated tubes of 1.4 m long and absorber diameter of 0.044 m are mounted over a diffuse reflector with center-line spacing of 0.07 m. The inner glass tubes are blacked at its outside surface with a selective coating to absorb maximum solar radiation. Solar radiation incident on these tubes is being absorbed and the heat is being transferred to the water inside through its contact peripheral surface.

To prevent the reverse flow during nighttime, a check valve is provided in the pipe line. The orientation of the complete system is assumed to be kept due south in order to receive maximum solar radiation throughout the year. Specification of the complete system and the design parameters of different components of the solar still under study is given in Table 1.

3. Thermal analysis

The energy balance for each component of the integrated system in forced mode has been carried out with the following assumptions for simplification.

(a) Solar distillation unit is vapor leakage proof,
(b) Heat capacities of glass and basin material are negligible,
(c) Temperature dependent heat transfer coefficients have been considered,
(d) Side heat loss from the solar still is neglected,
(e) Water temperature of ETC is an average of inlet and outlet water temperatures,
(f) Initial values of water and condensing cover temperatures have been used to determine the value of internal heat transfer coefficients,
(g) System operates in quasi-steady state regime during the day,
(h) Water level in the basin of solar still is constant.

3.1. Inner surface of glass cover

Energy balance at inner surface of glass cover is given as;

$$\alpha'_g \cdot I_s(t) \cdot A_g + h_{1w} \cdot A_b \cdot \left(T_{sw} - T_{gi}\right) = h_{kg} \cdot A_g \cdot \left(T_{gi} - T_{go}\right). \tag{1}$$

3.2. Outer surface of glass cover

Energy balance at outer surface of glass cover is given as;

$$h_{kg} \cdot A_g \cdot \left(T_{gi} - T_{go}\right) = h_o \cdot A_g \cdot \left(T_{go} - T_a\right). \tag{2}$$

3.3. Basin liner

The heat loss from the side wall of the solar still can be neglected because of small surface area in contact with water. The energy balance for the basin liner is written as;

$$\alpha'_b \cdot I_s(t) \cdot A_b = h_{bw} \cdot A_b \cdot (T_b - T_{sw}) + h_{ba} \cdot A_b \cdot (T_b - T_a). \tag{3}$$