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Energy metrics analysis of N identical evacuated tubular collectors integrated double slope solar still

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ABSTRACT

This paper deals with the theoretical analysis of double slope solar still (DS) integrated with N identical evacuated tubular collectors (N-ETC-DS) on the basis of energy metrics. The analysis has been done considering four types of weather condition for each month of year for New Delhi climatic condition. Results of the proposed N-ETC-DS has been compared with DS integrated with N identical photovoltaic thermal (PVT) flat plate collectors (N-PVT-FPC-DS), DS integrated with N identical PVT compound parabolic concentrator collectors (N-PVT-CPC-DS) and conventional DS (CDS). It has been concluded that N-ETC-DS performs best on the basis of exergy based energy payback time, energy production factor and life cycle conversion efficiency followed by N-PVT-FPC-DS, CDS and N-PVT-CPC-DS.

1. Introduction

The potable water is one of the basic needs for the survival of life on the planet earth. The proposed active solar still can mitigate the contemporary issue of scarcity of potable water in remote areas where sunlight and brackish water are available in abundance. Zaki et al. [1] and Rai and Tiwari [2] introduced active solar stills under natural and forced circulation modes of operation respectively for the first time. The forced mode operation accelerates the heat transfer rate resulting in higher evaporation. Rai and Tiwari [2] reported that the daily yield of active solar still in forced mode, having only one collector, was 24% higher than that of conventional solar still. A pump was provided between the basin and the inlet of first collector in active solar stills having a number of series connected flat plate collectors (FPCs).

In the case of active solar still, external source is provided to supply thermal energy to the basin either with the help of flat plate collector/concentrator collector/evacuated tubular collector or by heat exchanger placed in basin. The fluid in the heat exchanger loop may be either water or some other suitable liquid depending on the requirement. Abdel-Rehim and Lasheen [3] studied basin type single slope solar still (SS) by integrating solar parabolic trough collector and a heat exchanger. The amount of distillate output obtained from such a system was 18% higher than the one obtained from conventional solar still. This improvement was basically due to increase in temperature of water in the basin caused by impinging solar radiation and heat transferred by heat exchanger placed in the basin. A considerable enhancement in yield is also obtained if thermal energy is supplied to solar still by circulating heat transfer fluid at its bottom. It was reported that doubling the heat transfer fluid rate effected a 9% enhancement in the production of potable water [4]. The relation between production of potable water and the heat transfer fluid rate is thus non-linear. Badran et al. [5] explored basin type double slope active solar still in forced mode operation. They reported that an improvement of about 52% in the production of potable water could be achieved when compared with the output of conventional solar still. Taghvaei et al. [6] carried out an experimental study, lasting 10 days, of an FPC coupled SS for assessing the long term performance. They recommended selection of higher depths of water for practical applications as the potable water yield and thermal and exergy efficiencies were found to be higher at higher depths due to heat storage effect. A novel tri-generation system employing PVT collectors was designed by Calise et al. [7] for seawater desalination in European Mediterranean countries, known to have abundant renewable sources but deprived of fossil fuels and water resources. Ibrahim et al. [8] carried out experimental investigation of the performance of a modified solar still fitted with an external air cooled condenser and reported an enhancement of 16.2% and 29.7% in the production of potable water and thermal efficiency respectively in comparison to conventional solar still.

Active solar distillation system can be made self-sustainable by including a photovoltaic (PV) panel with FPC coupled to the basin so that it can operate even in remote areas having abundant sunlight but no grid power. The surplus energy generated, if any, by the system can be

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put to use for other domestic applications. The integration of PV panel to collector was proposed by Kern and Russell [9] and it was reported that higher electrical efficiency could be achieved if the fluid was made to pass below the panel. A theoretical study of such system was done by Hendrie [10]. In continuation of this approach, an experimental study of SS by incorporating two series connected FPCs, one covered partially with PV, was undertaken by Kumar and Tiwari [11–14]. Such a system could produce 3.5 times more potable water than conventional solar distillation system. They developed empirical relation for heat transfer coefficient and also reported that the payback period of the FPC coupled solar still lied in the range of 3.9 to 23.9 years. It was extended for double slope active solar still by Singh et al. [15]. Further, Tiwari et al. [16] and Singh et al. [17] extended their work by covering both the series connected FPCs partially with PV panels. Further, Saeedi et al. [18] used simulation technique to obtain 0.044 kg/s and 7 as the optimum values of mass flow rate and number of collectors respectively for PVT active solar still. Singh and Tiwari [19–22] performed theoretical study on basin type solar stills included with N identical PVT-CPC collectors for New Delhi climatic condition and reported that the performance of double slope was better than the similar single slope set up at 0.14 m water depth under optimized condition due to higher energy, exergy and lower embodied energy for double slope set up. They also reported that the performance in terms of average daily productivity, thermal and overall thermal efficiencies of single slope was better than double slope PVT-CPC active solar still when the depth of water in basin is chosen higher than 0.31 m. In a study, the optimum number of collectors on the basis of exergy efficiency was found to be 4 for 50 kg water mass in the basin of active solar still coupled with multiple PVT-FPCs [23].

Etawil and Omara [24] studied experimentally a single slope solar still incorporated with collector, spraying unit and external condenser. They concluded that the yield of developed solar still was 51–148% higher than conventional solar still depending on type of modification. Rabhi et al. [25] studied experimentally a modified single slope solar still which consisted of pin fins absorber and condenser. They concluded that the yield of modified solar still was higher by 41.98% as compared with conventional solar still because of increased temperature of water in the basin. The increased temperature of water was obtained due to surface geometry of absorber. Sharshir et al. [26] studied hybrid solar still which consisted of humidification-dehumidification and evacuated solar water heater and concluded that the yield of hybrid solar still was 200% higher as compared with conventional solar still. It happened due to reutilization of drain water from humidification-dehumidification as this water was fed to solar still. Singh et al. [27] investigated the performance of SS augmented with evacuated tubes in natural mode, with one end of all the tubes being inserted into the basin, and concluded that the overall energy and exergy efficiencies lied in the range of 5.1–54.4% and 0.15–8.25% respectively during the sunshine hours at 0.03 m water depth for a typical day in summer. Further, Kumar et al. [28] investigated SS augmented with evacuated tubes in forced mode in which one end of all tubes were inserted into the basin and concluded that the daily yield and mass flow rate were 3.47 kg and 0.006 kg/s at 0.01 m water depth for climatic condition of New Delhi. Singh and Tiwari [29] have presented the development of analytical characteristic equation for double slope solar still incorporated with N identical evacuated tubular collectors.

The current literature survey shows that not much research efforts have been devoted to analyze the performance of basin type solar stills integrated with N identical evacuated tubular collectors (ETCs). Recently, Mishra et al. [30] developed a set of characteristic equations for N identical ETCs connected in series. This paper presents the energy metrics analysis for double slope basin type solar still integrated with N identical evacuated tubular collectors. In the proposed system, the first evacuated tubular collector (ETC) is fed with water from basin through pump and the water is discharged to the basin from the outlet of last ETC forming a closed loop. The proposed system is different from the systems considered by earlier researcher primarily in two ways. Firstly, FPCs/CPCs have been replaced by ETCs. Secondly, ETCs have been connected in series rather than just inserting one end of all the collectors to the basin of the solar still as done by Singh et al. [27] and Kumar et al. [28]. The objective of the proposed investigation can be stated as follows:

(i) To find optimum number of collectors and mass flow rate for double slope basin type solar still incorporated with N identical ETCs.
(ii) To compute energy metrics for proposed system for optimum number of collectors, mass flow rate and 0.14 m water depth under New Delhi climatic conditions.
(iii) To compare proposed system with double slope solar still (DS) integrated with N identical partially covered photovoltaic thermal (PVT) flat plate collectors (N-PVT-FPC-DS), DS integrated with N identical partially covered PVT compound parabolic concentrator collector (N-PVT-CPC-DS) and conventional DS (CDS) on the basis of energy metrics.

2. System description

Fig. 1 shows the schematic diagram of N identical evacuated tubular collectors integrated double slope solar still (N-ETC-DS). Fig. 2 shows the cross sectional view of evacuated tubular collector (ETC). The exhaustive specifications of the proposed systems are provided in Table 1. The collectors connected in parallel give higher discharge at lower temperatures; whereas the collectors connected in series provide lower discharge at higher temperature. In this work, we have opted for series connection in order to get higher temperature of water in the basin.

Each of the ETC in the proposed system consists of an inner copper tube and outer evacuated co-axial glass tube. Water is allowed to flow through the inner tube. The evacuated coaxial glass tube consists of two tubes and an evacuated space is provided between two glass tubes to minimize the heat loss by convection. The inner surface of evacuated coaxial glass tube is coated. The diameter of inner copper tube is 0.0125 m. The inner radius of inner glass tube and the outer radius of outer glass tube of evacuated coaxial glass tube are 0.0165 m and 0.024 m respectively. The thickness of inner/outer glass tube of evacuated coaxial glass tube is 0.002 m.

In series connection, outlet of each ETC is connected to the inlet of its succeeding ETC. The inlet of first ETC is fed with water from basin with the help of a pump and hot water available at the outlet of N^{th} ETC is discharged into the basin thus forming a closed loop. An inclination of 30° is provided to all series connected ETCs to obtain highest yearly solar radiation. The power source for DC motor pump can be grid supply or photovoltaic module. The function of pump is to prevail over the pressure drop to ensure smooth circulation of water throughout the system.

The double slope active solar still in this study is made of glass reinforced plastic and has an effective basin area of 2 m × 1 m. The still is oriented east-west to get maximum annual solar intensity. A transparent glass inclined at an angle of 15° with the horizontal has been used as condensing cover of the solar still. The inner surfaces of bottom and side walls of solar still are painted black so that the major portion of the solar flux is absorbed. The glass surface is sealed with window-putty. An opening at the wall facing east/west is provided to feed saline/brackish water into the basin. Provision of another opening at the bottom is made to facilitate the cleaning of the basin when necessitated. The entire unit is mounted on an iron stand.

The outer surface of transparent glass reflects and absorbs the solar flux impinging on it partially and transmits the rest to water. Then, the water mass too reflects and absorbs some portion of the received solar flux and transmits the remaining part to the basin liner. Basin liner absorbs almost all the radiation falling on its surface and transfers the heat to water causing the temperature to increase further. Evaporation