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Augmentation of saline streams in solar stills integrating with a mini solar pond

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ABSTRACT

Industrial effluent was evaporated in a fin type single basin solar still and a stepped solar still separately. To preheat the saline water, a mini solar pond was integrated with these stills. Both the stills were operated with mini solar pond and tested individually. In fin type single basin solar still, maximum productivity is obtained, when it is modified with black rubber, sponge and sand. The stepped solar still was modified with fin, pebble and sponge to enhance their productivities. When mini solar pond, pebble, sponge and fin are used in stepped solar still, maximum productivity was obtained To settle the industrial effluent, a settling tank was also fabricated with five layers namely: tray for raw effluent, pebble layer, coal layer, sand layer and collection tray for settled effluent. Physical and chemical analyses were made for raw effluent, settled effluent and distilled water. Economic analysis was made.

1. Introduction

Freshwater is one of the Earth's most valuable renewable resources. Along with the supply of energy, access to freshwater is a fundamental need of all societies. Although water covers approximately 70% of the earth's surface, supplies of potable water are rapidly disappearing. This is because only 0.62% of the available water is in a form that can be traditionally treated for human consumption [1]. During the last century, these potable water sources from both surface and ground water resources have been increasingly depleted due to increases in worldwide population.

One study [1] of water scarcity trends estimates that of the approximately 6.3 billion people living on earth (US Census, 2003), 400 million people now live in water scarce areas, and the number living in water stressed areas could grow to four billion by mid-century. The demand for potable water increased by six-fold while the world's population increased into three-fold. At the same time, pollution and overuse of potable water sources reduced the ability of developed potable water sources to meet demand.

Solar desalination is used to produce potable water from water sources containing dissolved chemicals, and is most often used when water sources are salty. To enhance the yield of the single basin solar still, continuously research works are carrying out. Badran et al. [2] integrated a conventional flat plate collector with a solar still to augment the production rate. They found that, the mass of distilled water production was increased by 52%, when the still was coupled with flat plate collector. Tiris et al. [3] integrated two flat plate collectors and a storage tank with single basin still for enhancing productivity of the still. They proved that, the average daily production of distilled water was 100% higher than a single basin solar still. A flat plate collector coupled with solar still [4], and flat plate collector with solar stills and hot water storage tank [5,6] was designed by Voropoulos et al. Also they designed a hybrid solar desalination and water heating system [7]. When the free surface water area increases in solar stills, the productivity increases. To increase the free surface area, and in turn evaporation rate, Hijileh et al. [8] used sponge cubes in the saline water. The volumetric ratio between sponge and water was maintained as 20%. They proved that distillate productivity increased by 18% when sponge cubes were used in the still. For the same reason, a wick basin type solar still [9] was designed by Minasian and Al-Karaghouli. The wick basin type produce 85% more than the basin type and 43% more than the wick type solar still. Multiwick single slope solar still [10] was designed by Shukla and Sorayan. Also they derived an expression for water and glass temperatures, yield and efficiency of both single and double slope multi wick solar systems. Mathioulakis and Belessiotis [11] investigated the possibility to exploit energy from geothermal and industrial waste chiller condenser. Tiwari et al. [12] used a multi wick solar still with electrical blower. Nafey et al. used black rubber [13], floating perforated plate and black gravel [14] for augmenting the productivity of the solar still. They proved that black rubber improves the productivity by 20% and floating perforated plate improves the productivity by 15%. A baffle suspended absorber was designed by El-Sebaii et al. [15] and a stepped solar still [16] with trays was designed by Ward. Zurigat and Arabi used double glass [17] in the solar still. Hermann [18] developed a corrosion free solar collector for sea water desalination. The efficiency is increased in this setup, by adding a specially shaped reflector. Hayek and Badran [19] used mirrors on the inside walls of solar still

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to enhance the production. Hussaini and Smith [20] studied the effect of applying vacuum in the solar stills. They found that, the water productivity increases by 100%, when vacuum was created. Kalogirou [21] designed a parabolic trough solar collector. El-Sebaii [22] found that the daily total productivity of the still was 12.3 kg/m^2/d, when a triple basin solar still was used.

Tanaka and Nakatake [23] presented a theoretical analysis of a titled-wick solar still with an inclined flat plate external reflector and proved that the daily amount of distillate of a still with an inclined reflector would be about 15% to 27% greater than the conventional still. The daily efficiency of the solar still was increased by 85.3%, when phase change material [24] was used as storage medium by El-Sebaii et al. Thermal characteristics and economic analysis of a solar pond coupled with multi stage desalination plant was presented by Agha [25]. Thermal performance of a single basin solar still integrated with a shallow solar pond was studied by El-Sebaii et al. [26]. Kumar and Bai [27] presented a performance study on solar still with enhanced condensation. Performance study on an acrylic mirror boosted solar distillation unit utilizing seawater was presented by Shanmugan et al. [28]. Kumar et al. [29] presented a performance analysis of a “V” type solar still using a charcoal absorber and a boosting mirror. Performance assessment of a solar still using blackened surface and thermocol insulation was presented by Sahoo et al. [30]. Concentrating solar power for sea water desalination was presented by Trieb and Steinhagen [31]. A maximum percentage increase in productivity of 7% was obtained when surfactant additives [32] are added in the solar stills.

Velmurugan et al. used fins [33] in the single basin solar still to enhance its productivity. Industrial effluents [34] are used as feed in single basin solar still for effectively disposing the effluent as well as to produce potable water by Velmurugan et al. A modified stepped solar still [35] was designed for enhancing its productivity by Velmurugan et al. For augmenting the evaporation rate of industrial effluents, Srithar and Mani developed a pilot plant with an open fibre reinforced plastic (FRP) flat plate collector (FPC) and spray network systems [36] and their performances were analyzed. Theoretical simulation and experimental performance of an open solar flat plate collector for treating tannery effluent was compared by Srithar and Mani [37]. They [38,39] analyzed a single cover FRP flat plate collector for treating the same. Also they [40] compared a conventional and open flat plate collector for evaporation of tannery effluent. Based on these papers, it is planned to use industrial effluent as feed in this work.

The following research works show the thermal applications of solar pond. Lu et al. [41] tested a small multi effect, multi stage flash distillation unit, a membrane distillation unit, a brine concentration and recovery system with salinity-gradient solar ponds over a broad range of operating conditions. Sreenivas et al. [42] proposed a new model, explains the equilibrium condition, which accounts both for turbulent entrainment and the effects of molecular diffusion. El-Sebaii [43] used black painted baffle plate made up of stainless steel, with and without vents in the plate, for different masses of water in the upper and lower layer in the solar pond. Ibrahim and Reidy [44] made a shallow covered mobile salt less solar pond with boosting reflector. The thermal performance tests proved that the pond was trouble-free and suitable for practical water heating use and cheaper than a flat plate collector. Tahat [45] et al. produced a portable mini solar pond and analyzed the performance. Also they determined the effect of depth in various zones of solar pond and its water's salinity on store's temperature distribution both by experimentally and theoretically.

Velmurugan et al. [46] conducted an experimental study in a single basin solar still integrating with a mini solar pond for enhancing the productivity of the still. An experimental and theoretical analysis for the same was done by Velmurugan and Srithar [47]. Also they [48] had reviewed the various applications of solar pond.

The objective of this work is to effectively make use of solar stills for desalinating the industrial effluents. An ordinary basin type solar still and stepped type solar still were tried individually. In the single basin stills, longitudinal fins were integrated in the basin plate and in the stepped solar stills, basin plates are in the form of trays with two different depths. Also fins were integrated with those trays. To get clarified pure saline water, first the raw effluent was passed through a settling tank. A solar pond was integrated individually with each still and the performances were compared. To enhance the productivity, in both stills, sand, pebbles and sponges were tried and their performances were also compared.

2. Experimental set up

The schematic diagram of the experimental set up is shown in the Fig.1. It consist of a settling tank, a storage tank, a mini solar pond, a single basin solar still and a stepped solar still. The settling tank had five layers; tray for raw effluent, pebble layer, coal layer, sand layer and collection tray for settled effluent. Each tray was separated by wire meshes. A storage tank was placed in between mini solar pond and settling tank. The settled effluent was stored in the storage tank. From the storage tank the settled effluent was allowed to flow through the mini solar pond by using the flow control valve V_1. The single basin solar still and stepped solar still were coupled to outlet of the mini solar pond. For controlling flow, from mini solar pond to single basin solar still, control valve, V_2 was used. The valve V_3 was used to control the settled effluent from the mini solar pond to the stepped solar still. To preheat the settled effluent in the mini solar pond, a swirled copped tube was used. Heat can be extracted from solar pond through two modes namely, batch mode [49] and continuous mode [50]. In this work, water is not sent through the mini solar pond continuously. For every half an hour, the hot water is taken from the mini solar pond and send to solar still. The same quantity of the water will supply to the solar pond. So, in this work batch mode of heat extraction was used. The solar pond was fabricated as truncated conical shape. The diameter at the top layer was 900 mm and the diameter at the bottom layer was 300 mm. The upper convective zone was at a height of 80 mm from the top surface. The total height of the pond is 300 m. Prasad et al. [51] estimated the thickness of lower convective layer of solar pond. Using the estimation, it was taken as 100 m. The intermediate zone or the non-convective zone was 120 mm from the top. The copper tube of 7 mm diameter was swirled as a coil structure in order to have more contact area with the hot salty water. The inlet of the copper coil was connected to the collecting tank, which was placed beneath the settling tank. The outlet of the solar pond was connected to the basin type still and stepped still. The flow rate of effluent through the copper coil was being regulated by means of the valve V_1. Thermocouples were placed in each zone to measure the temperature. An optimum salinity of 80 g/kg [47] was maintained in the solar still.

A single sloped solar still consist of a wooden box having dimensions as 1.2×1.2 m^2. Holes were provided for the distilled water output and for the effluent water input. The outer side of the wooden box was covered by the sheet metal, in order to protect it from solar radiation and rain. The basin of the still was made up of Galvanized Iron (GI) sheets, for its good conductivity and cheaper cost. The surface of the basin was coated with a matte black paint in order to absorb more incident energy from the sun. The dimensions of the basin were 1000×1000 mm^2. The sides and the bottom of the basin were insulated by using sawdust. The condensing surface in the still was simply a glass cover. The glass of size 1100×1100 mm^2 was used as the roof for the still. The distilled water was collected in the collection trough. The water condensed on the glass surface was collected into the trough by a piece of glass attached in the glass, right above the collection trough. The glass cover of still box was tilted with an angle of 10°. Leather sheet was used to prevent leakage from any gap between the glass covers and the still box. Poly Vinyl Chloride (PVC) tubes were used to discharge the distilled water from each unit to the bottles. The inlet water was fed into the still using flexible hoses.