STEPPED AND EVACUATED TUBE COLLECTOR COUPLED SOLAR STILLS: A COMPREHENSIVE REVIEW

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Abstract

The demand of fresh water has been increased in modern world due to increased population and industrialisation. As per environment concerns, researchers are focussing towards renewable energy based desalination methods. Solar distillation is a promising method for the water desalination. Much research has been already done on different designs of solar still such as single basin, multi-basin, stepped type basin, wick type basin, inclined type basin etc. In this paper, recent advancements of stepped type solar stills and solar still coupled with evacuated tube collector have been made. In the stepped solar still, absorber surface of still is constructed in the steps to increase the surface area of basin. Productivity of weir type design of stepped solar still was observed nearly 7.4 kg/m^{2}day. Various techniques are developed to increase the productivity of stepped solar still such as sun tracking system, coupling it with solar air heater, using glass cover cooling, integrated flat plate collector, evacuated tube collector, use of internal reflectors and external condensers etc. Maximum increase in productivity of 380% was found over conventional solar still using internal mirrors on each step of stepped solar still with automatic sun tracking system. Solar still coupled with evacuated tube solar collectors provided highest daily yield (4.24 kg/m^2/day) among all active solar stills. Double layer wick solar still coupled with evacuated tube collector gave 114% higher distillate yield than simple solar still.

Keywords:- stepped solar still, evacuated tube collector, weir type design, active solar still

Introduction

More than two third part of the earth is covered with water. Among this, 97% is salty and only 2.6 % water is in fresh form. According to World Health Organisation (WHO), the permissible limit for salinity of water is around 500 ppm while most of water on the earth has salinity of nearly 10,000-30,000 ppm. Excess salinity may cause health problems to human being such as stomach problems, laxative effects etc. The demand of fresh water is increasing day by day due to increasing population and industrialisation in the world. But the availability of fresh water is fixed, so it becomes important to discover methods of converting brackish water into pure water. Several desalination methods for water purification employed are reverse osmosis, electro dialysis, vapour compression, multistage flash distillation, multiple- effect distillation and solar distillation etc. Among all above desalination methods, solar distillation is economical, requires low maintenance and easy to operate technique [1-3].

The solar still consists of number of components as shown in fig.1. The main components of solar still are transparent cover, absorber plate, collection trough. Solar radiations are transmitted to basin surface through a transparent cover which is provided at the top of solar still. After transmission, these are absorbed by a ceratin depth of water which is placed on the absorber surface. Absorber surface is generally made of galvanised iron, cement or concrete. The absorber plate is blackened to enhance its absorptivity. An inlet is provided for putting the impure water into the still. The water absorbs heat from sun rays and starts to evaporate. The evaporated water gets condensed on the condensing cover and is collected through a channel attached at the lower side of the still. Insulation is also provided at the back and sides to minimise heat loses [4,5].

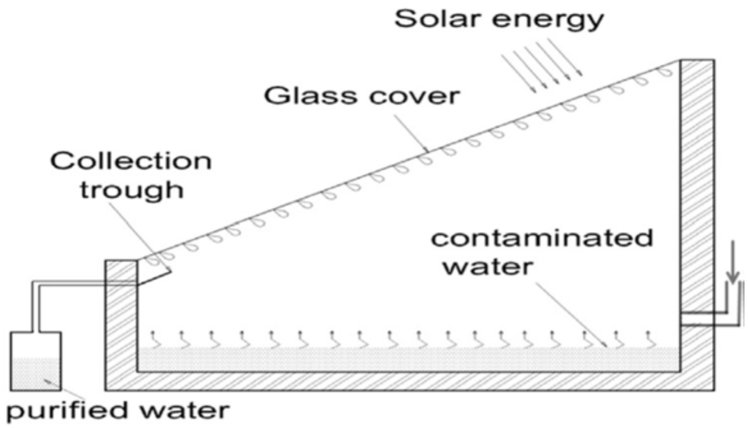

Fig. 1. Schematic diagram of the single basin solar still.

On the basis of source of heat, solar distillation can be classified into two categories. The major classification of solar distillation is shown in fig.2.

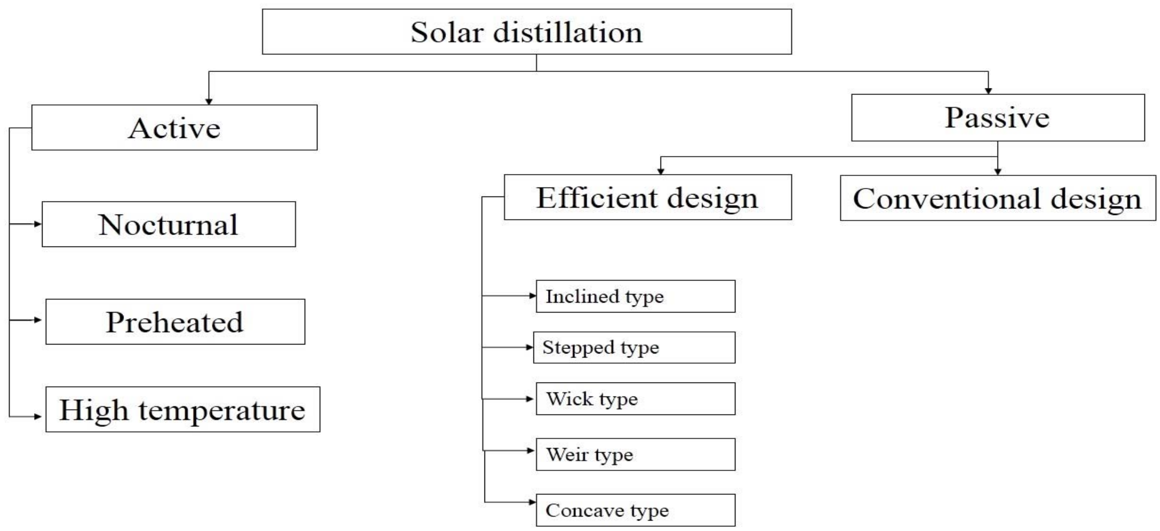

Fig. 2. Classification of solar distillation [6,7].

a). Passive solar distillation

In passive solar distillation method, direct solar energy is used to increase the temperature of basin water. The design of passive solar still are simple and economical but their distillate yield is low. The performance of passive solar still designs can be improved by using stepped, weir design and using wick on absorber surface [6].

The construction of stepped solar still is same as simple solar still except absorber plate is made in number of steps as shown in fig.3. Such type of construction is made to increase the evaporative surface and decrease water depth for same volume of water in comparison to simple basin solar still [8].

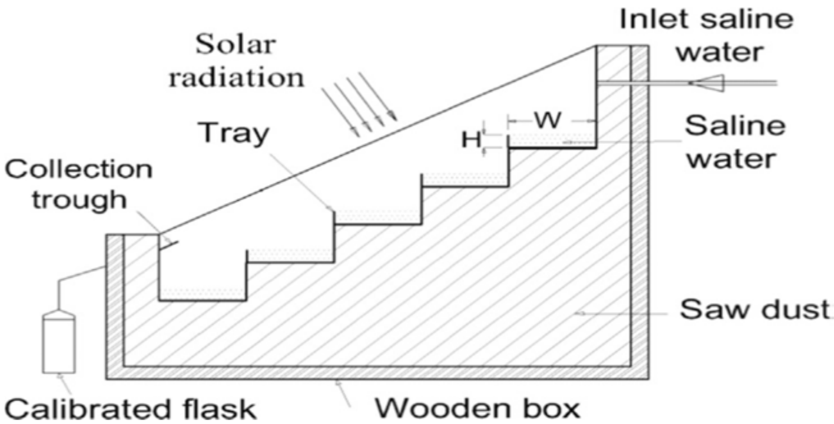

Fig. 3. Stepped solar still [8].

In weir type design of stepped solar still, barriers are placed to even distribution of water over evaporative surface. Flow of water over absorber plate with weirs is shown in fig.4. Other advantages of weir type solar stills are to increase residence time of water and make water film shallow [9,10].

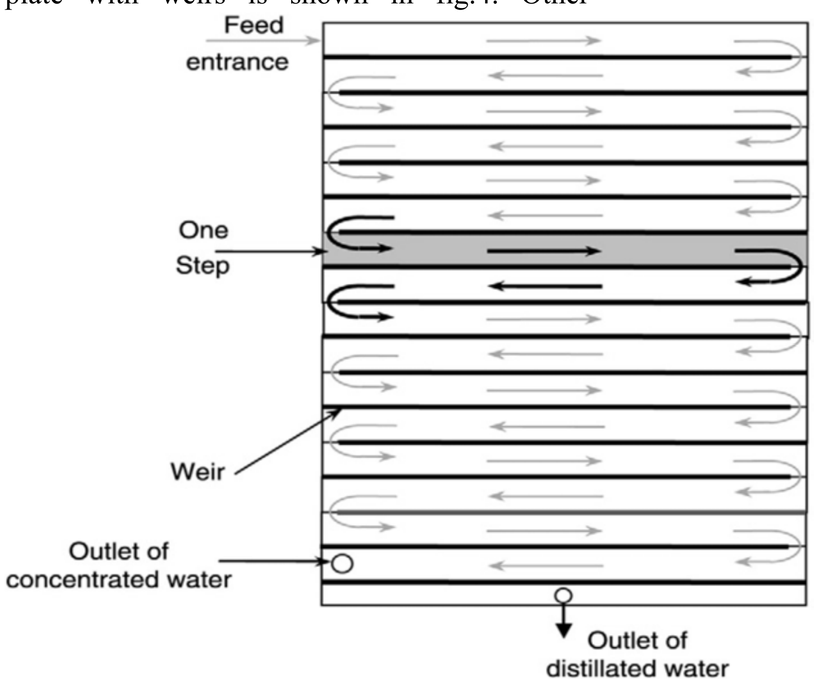

Fig. 4. A schematic top view of water flow path on the absorber plate [9]

b). Active solar distillation

In active solar still, external sources (solar heaters, concentrators and collectors) are used for heat input to water in addition to direct solar radiation. Different types of active solar distillation are: a). Nocturnal, b). Preheated water and c). High temperature. In nocturnal active solar distillation, the thermal energy is stored in the water mass which can be utilized during off sunshine hours for the distillation. In preheated water distillation system, pre heated water is supplied to the basin so as to increase the water temperature in the basin. The waste hot water available from various sources like paper industries, chemical industries, thermal power plants and food processing industries etc. can be utilized for preheating the water. In high temperature distillation, solar collectors and concentrators are used to supply additional heat to water. Evacuated tube solar collector is an efficient solar collector system to supply the heated water in solar still which increases the temperature of basin water and hence, can improve the distillate output [7] .

Evacuated tube solar collector consist of vaccum sealed glass tubes. Each glass tube consists of two concentric borosilicate glass tubes. Annular space between the tubes is evacuated to reduce heat losses. Absorber surface is placed in the inner glass tube. Evacuated tube solar collectors are of two types: Direct flow through and heat pipe type. In direct flow through type, a set of glass tubes are connected to a shell. The working fluid flows from tank to tube and it gets heated by absorbing solar radiations. After that heated water flows back to tank by natural circulation mechanism [11]. When the evacuated tube solar collector is coupled with solar still, the preheated water from evacuated tubes is supplied to the solar still. This preheated water further evaporates in the still and condenses on the glass cover. The condensed water is collected as a distillate in the distillate jar [12].

The direct flow through evacuated tube solar water heater coupled with simple solar still is as shown in fig.5.

Fig.5. Direct flow through type evacuated tube solar collector coupled with simple solar still

A heat pipe evacuated solar collector consists of number of tubes attached to a common tank. Each tube comprises of a finned copper pipe (heat pipe) surrounded by glass tube. Annular space between copper pipe and glass tube is evacuated. Heat pipe contains vaporizable fluid which evaporates using solar energy. The vapours condense at the condenser section and transfers its heat to the heat sink located at the top of tube [13].

In the next section, advancements in stepped and evacuated tube collector coupled solar stills have been discussed.

Researches carried out on stepped type solar still

Velmurugan et al. (2009) fabricated and tested a stepped solar still coupled with effluent settling tank. The textile effluent was purified in an effluent settling tank by removing large and fine solid particles and then supplied to stepped solar still as raw water. With the use of sponge, fin and pebbles in the basin of stepped solar still, productivity was increased by 98% [14]. Abdullah et al. (2013) studied experimental performance of stepped solar still by coupling it with solar air heater, sensible heat material (Al filling), glass cooling. When both solar air heating of basin and glass cooling was employed, productivity of stepped solar still was found 112% higher than conventional solar still [15]. Jagannath et al. (2013) studied effect of shape of absorber surface on the performance of stepped type solar still. Three types of absorber surfaces flat, convex and concave were investigated. Results showed that for stepped solar still, convex and concave type absorber surfaces provided 56.6% and 29.4% more output than flat shape surface [16]. Zoori et al. (2013) analyzed and modelled the energy and exergy efficiencies of weir-type cascade solar still. Effect of various parameters water thickness, solar radiation, inlet water temperature, inlet brine flow rate etc. on productivity of still was studied. The maximum energy and exergy efficiencies of 83.3% and 10.5% respectively were found at minimum inlet brine flow rate of 0.065 kg/min [17]. El-Agouz et al. (2014) designed a stepped solar still with continuous water circulation system. Effect of using storage tanks and cotton cloth cover over each step of still on the productivity of distilled water was investigated. The productivity of the modified stepped still with cotton absorber was found 53% and 47% higher than conventional still for sea and salt water respectively [18]. Alaudeen et al. (2015) studied the stepped type basin in a solar still attached with a flat plate solar collector. When coconut coir and wicks were used in the basin with flat plat collector, the maximum daily efficiency was found 16.36% [19]. El-samadony et al. (2015) studied effect of coupling external condensers and internal reflectors with stepped solar still. It was found that when external condenser and reflectors were coupled, productivity increase of stepped type solar still over conventional solar still was 165% [20]. Kumar et al. (2016) fabricated and tested the performance of stepped solar still with phase change materials (PCM). The performance of a stepped solar still was studied with different PCM materials (palmitic acid, bee wax and stearic acid). Maximum increase of 16.38% in efficiency was observed with the use of stearic acid as a PCM in stepped solar still [21]. Kumar et al. (2016) investigated thermal performance of a weir type cascade solar still with different phase change materials (PCM). The efficiency of weir type solar still was increased by 35% with the use of PCM [22]. Different designs of stepped solar still with low cost modifications are tabulated in Table 1.

Table 1.Different design and operational parameters researches on stepped solar stills

Authors	Research Technique	Optimal results
Sadineni et al. (2008) [23]	Weir type solar still with single pane glass cover and double pane glass cover	For weir type solar still with single pane and double pane glass covers, productivity was found 5.51 and 2.2 l/m^2/day respectively.
Abdallah et al. (2008) [24]	Performance of solar still by installing mirrors, by using stepped basin, using automatic sun tracking system	Productivity of solar still was increased by 380% with the use of stepped basin, mirrors on each step and automatic sun tracking system
Tabrizi et al. (2010) [25]	Cascade solar still with and without PCM storage and comparison of their performances	The total productivity was nearly the same for both stills in a typical sunny day. 3.4 kg/m^2 day productivity was observed for still with

	on sunny days and partially cloudy days	PCM and 2.1 kg/m ^{2} day was for still without PCM on partially cloudy day.
Dashtban et al. (2011) [26]	Weir type solar still integrated with PCM storage (Paraffin wax of 18 kg mass and 2 cm thickness)	Daily productivity of 6.7 and 5.1 kg/m^2 day for still with and without PCM was found.
Kabeel et al. (2012) [27]	Comparison of stepped solar still with conventional still by varying depth and width of trays, by employing evacuated tube collector and wicks on vertical sides	Maximum productivity of stepped solar still was achieved at a tray depth 5 mm and tray width of 120 mm and by using evacuated tube collector, productivity of stepped solar still was increased by 66.6%.
Omara et al. (2013) [28]	Performance of stepped and conventional solar still with and without internal reflectors	Productivity of stepped type solar still was higher than conventional solar still by 57% without mirrors and by 75% with mirrors.
El-Samadony et al. (2014) [29]	Theoretical estimation of optimum glass cover film thickness, water flow rate, film inlet temperature	The optimal film thickness was found from 2.5 x 10^{-4} to 5.5 x 10^{-4} m, cooling water volumetric flow rate was from 4 x 10^{-5} to 8.5 x 10^{-5} m^3/s, and glass cover length was from 2 to 2.8 m.
Gawande et al. (2015) [30]	Stepped solar still with varying water depth from 5 mm to 10 mm.	Distillate yield of stepped solar still at 5 mm water depth was found greater by 22.64% than stepped solar still at 10 mm water depth.
El-samadony et al. (2016) [31]	Influence of glass cover inclination angle on radiation heat transfer rate within stepped solar still	Influence of radiation shape factor on thermal performance predictions was found significant. At low solar insolation of 200 W/m^2 and glass cover inclination angle of 70^o, the percentage increase in productivity was 18.8%.

Review on solar still coupled with evacuated tube collector

Morrison et al. (2004) investigated the performance of water in glass evacuated tube heater. They determined factors affecting the operation of evacuated heater and made numerical study of water flow inside the single ended thermosiphon tubes. Numerical simulation results showed a stagnant region near the bottom of tube which can affect the performance of evacuated tube [32]. Tiwari et al. (2007) made thermal models of active solar still integrated with different types of solar collectors. Solar still integrated with evacuated tube collector provided highest daily total yield (4.24 kg/m^2/day) among all active solar stills [33]. Ma et al. (2010) did thermal analysis of glass evacuated collector with U-tube. They determined the effect of solar radiation insolation and air resistance on the thermal efficiency of evacuated solar collector. Results showed that because of air thermal resistance, coating temperature was increased and thermal efficiency was decreased [34]. Tang et al. (2011) studied effect of collector tilt angle on thermal performance of evacuated tube solar water heater. They constructed two solar water heaters, with 22° tilt angle (SWH-22) and with 46° tilt angle (SWH-46) respectively. They found that collector tilt angle have effect on solar heat gain but negligible effect of thermosyphonic circulation inside tubes [35]. Panchal et al. (2011) studied effect of coupling single slope solar still with evacuated heat pipe collector. Productivity of coupled solar still was found 30% higher than uncoupled solar still [12]. Patel et al. (2011) studied effect of coupling single slope double basin solar still with evacuated glass tubes. The productivity of double basin coupled solar still was found 9.47 % to 14.70 % higher than single basin coupled solar still [36]. Hayek et al. (2011) carried out investigation of performance of two kinds of evacuated tube solar collectors, water in glass and heat pipe designs. The results indicated that efficiency of heat pipe collectors was 15 to 20 % higher than efficiency of water in glass designs [13]. Dev et al. (2012) carried out comparative study of simple solar still and evacuated tube integrated solar still. Annual yield of coupled & uncoupled solar still was obtained 630 kg/m^2 and 327 kg/m^2 respectively [37]. Patel et al. (2012) studied the effect of dye on the productivity of single basin active solar still coupled with evacuated tube glass collector. When black dye was used, productivity was increased by 30.38 % [38]. Karuppusamy et al. (2012) studied the effect on productivity of solar still on coupling evacuated tubes. After coupling of evacuated tubes with solar still, productivity was increased by 49.7% [39]. Sampathkumar et al. (2012) studied experimentally and theoretically effect of coupling evacuated tube collector solar water heater with single basin solar still. They found that productivity of coupled basin solar still was double of simple basin solar still when operated for 24 hours [40]. Sakhrieh et al. (2013) investigated the efficiency and reliability of five types of solar collectors. These solar collectors used were selective blue and black coated copper, copper, aluminium, evacuated tube collectors. Maximum efficiency was found for evacuated tube collectors. Black coated selective copper was found most reliable among them because of its manufacturing quality and stable structure [41]. Omara et al. (2013) comapared the performances of wick solar still and conventional solar still coupled with evacuated tube collector. They found that productivity of double layer wick solar still was increased by 114 % over conventional solar still when both solar stills were coupled with evacuated tube solar collector [42]. Panchal et al. (2013) found that by coupling double basin solar still with evacuated tubes and by using black granite gravel stones in the basin, the productivity was increased by 67 % over conventional solar still [43]. Sampathkumar et al. (2013) compared the performances of active solar still (solar still coupled with an evacuated tube collector) and passive solar still. They found that at water depth of 0.04 m, maximum daily distillate yield was 7.03 and 3.225 kg for active and passive solar stills respectively. It was also observed that thermal efficiency of active solar still was lower than passive solar still [44]. Singh et al. (2013) carried out thermal analysis of solar still integrated with evacuated tube solar collector in natural mode. They optimized the system with number of evacuated tubes, water depth for keeping same maximum operation temperature 94°C in each combinations. The optimum system was found for 10 evacuated tubes with water depth of 0.03 m [45]. Kumar et al. (2014) investigated the performance of single basin active solar still coupled with evacuated tube solar collector. They found that at flow rate of 0.06 kg/sec and depth of 0.03 m, the maximum distillate yield was produced for active solar still coupled with evacuated tube collector operating in forced mode [46]. Gupta et al. (2015) investigated the performance of a solar still coupled with evacuated tube collector by varying the water depths from 0.01 to 0.03 m. When water depth was reduced from 0.03 to 0.01 m, the distillate yield was increased by 19.48% [47]. Mosleh et al. (2015) investigated the performance of a distillation system having basin attached with heat pipe inside evacuated glass tube collector. A parabolic trough concentrator was used to focus all the sun rays on the heat pipe. When oil was used as a medium of transferring heat between the heat pipe and evacuated tube, the production and efficiency was raised to 0.933 kg/(m^{2}h) and 65.2 % respectively [48]. Deshmukh et al. (2016) studied the effect of coupling double basin solar still with evacauted tubes and reflector. They found that this arrangement could increase productivity from 50.8% to 62.1 % as compared to single basin solar still coupled with evacuated tubes[49].

Summary

It has been concluded from above study that stepped solar still is an economical technique to get fresh water. Also, with some small modifications, distillate output of solar still can be improved. Coupling of solar still with evacuated tube gave a productivity much higher than simple solar still. Some of the important conclusions on stepped solar still and solar still coupled with evacuated tube collector are summarized below.

1). Maximum productivity for stepped solar still was achieved at minimum tray depth of 5 mm and tray width of 120 mm.

2). Productivity of stepped solar still was increased by 66.6% using preheated water from evacuated tube collector.
3). Stepped still without PCM was found to be economical for sunny days and stepped still with PCM should be preferred for partially cloudy days,.
4). Productivity of stepped solar still was increased by 112% with employing solar air heating of water below steps and glass cover cooling and by 18% with the use of internal reflectors on vertical side of each step.
5). Productivity was increased by 165% for stepped type solar still over conventional solar still with employing reflectors and condensers.
6). The productivity of double basin solar still coupled with evacuated tube collector was observed 9.47 % to 14.70 % higher than single basin solar still coupled with evacuated tube collector.
7). Efficiency of heat pipe evacuated tube collectors was found to be 15 to 20 % higher than efficiency of water in glass design evacuated tube collectors.
8). By coupling single basin solar still with evacuated tube collector and using black gravel stones, productivity of still was increased by 59.47%.

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