Recent Advances in Stepped and Weir Type Solar Still

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Water is essential for all living creatures. It is abundantly available on earth surface but quantity of potable water is very less. The major fatal diseases and problems are caused by drinking of impure water. There are numerous techniques used for purification of water. In these, the most of techniques use the non-renewable source of energy. Solar distillation is a neat, economical and cheap way of collecting the distilled water from brackish water. There are various environmental, design and operational parameters which effect on the performance of solar still. The main drawback of solar distillation is its lower distillate of pure water. Hence, it is not fully commercialised yet. Stepped and weir-type solar still are simple and economical design of conventional solar still. Distillate output of these stills is 60-80% higher than simple basin type solar still. In this review a recent researches carried out on stepped and weir-type solar stills are discussed. Thermo-economic analysis of different solar stills is also discussed.

Keywords: Solar Distillation, Solar Still, Stepped and weir-type, Thermo-economic

I. INTRODUCTION

Water is among one of the natural gifted resources. Its abundance on earth surface is 96.54%. Among this only 2.53% water is drinkable and rest is salty [1]. The resources of fresh water are fixed i.e. pond, glaciers, sea and bore wall etc. These resources get distorted by much human activity. As a result, the availability of drinkable water decreased. Nearly 65-70% health problems occur mainly due to drinking of infected water in the world. Drinking of impure water causes many diseases such as cholera, guinea worm disease, water born diseases etc. [2]. The scarcity of pure water is present everywhere in the world. So purification of water is required for obtain potable water for living beings. Different type of techniques such as desalination/distillation, advance desalination is used for purification of water from brine [3]. Every process is governed by energy. There are two types of energy resources, i.e., renewable and non-renewable. The non-renewable source causes pollution and these are extinctable after a time period. Solar energy is a renewable resource. This is a low grade form of energy and it is freely available at every place. A nearly 10^{17}watts solar energy generated at sun surface and among 10^{16}watts energy is received on the earth surface. The worldwide we need nearly 10^{13}watts energy for civilization. Solar energy can be used for purification of saline/braine water with the help of solar still [4].

A Solar stills is a device used for distillation and desalination of saline, brackish water into pure form [5]. The brine flows inside the still basin and this is covered by a sloping cover of glass or plastic sheet. The solar radiations fall on glass surface. These incident solar radiations are partially absorbed by glass surface some reflected by glass surface and some radiation transmitted. Among transmitted radiations partially absorbed by water surface and major portion is absorbed by bottom of basin which is made of black colour for higher absorption of solar radiation. The radiated energy from basin in the infra-red region and these radiations are partially absorbed and re-radiated back into the still by the cover. These radiations transfer heat to the water and layers of water starts heated. As the temperature of water increases, the evaporation starts from upper layer of water. The temperature of successive layers also increased and convection current inside the still carry the warm vapour-air mixtures to the glass cover which is cooler as compare to water surface temperature. Condensation process takes place under the glass surface and heat of condensation transmitted to the surrounding. The condensed water flows down due to gravity and collected at outlet. In distillation process salt and other impurities such as water borne pathogens, heavy metals, microbiological organism etc. removes from the water [6]. Solar distillation is highly promising and safe for environment. The outlet water is in purist form as rain water [7].The maximum productivity of still is attained when the inclination angle of glass is equal to latitude angle of that place [8]. This process is also helpful in removing bacteria [9]. The main design consideration for solar still:

- The thickness of cover must be minimum and having excellent transparency for solar radiation
- The crystal of salt should not formed at the surface of water
- The distance between glass cover and the water surface should be minimum and having a constant value
- The basin of still must be insulated and its surface is blackened

The major extensive research had been done for improvement of design of solar still [10]. The basin still is also called the roof, greenhouse, simple or conventional still. As shown in Fig. 1. The productivity of still depends on various factors ambient temperature, solar intensity, surface area of water etc [11].

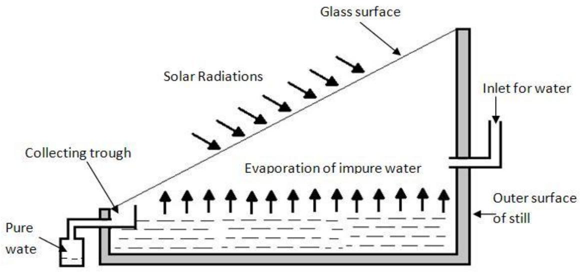

Fig. 1 Conventional Solar Still

Different design of solar still are shown in Fig.2

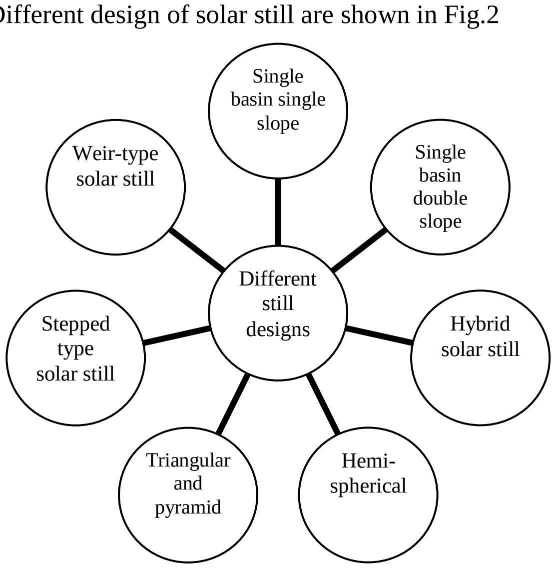

Fig. 2 Different designs of solar still

The design of stepped type solar still is same as conventional still in addition, the absorber plate is made of a number of steps for providing large surface area along with increase in stay time of water on each steps as shown in Fig. 3.

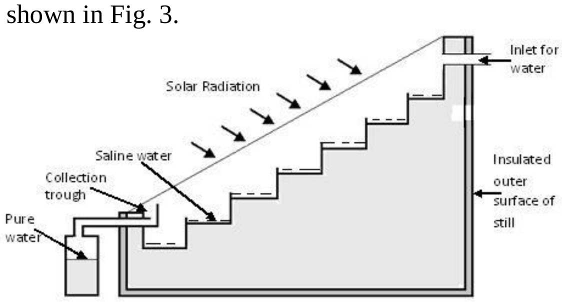

Fig. 3 Stepped type solar still

In weir-type still weirs are designed in each step of stepped solar still so that water get retarded and take a long time to reach at lower step. Hence it gets sufficient time for evaporation. The schematic diagram of weir-type solar still is shown in fig.4

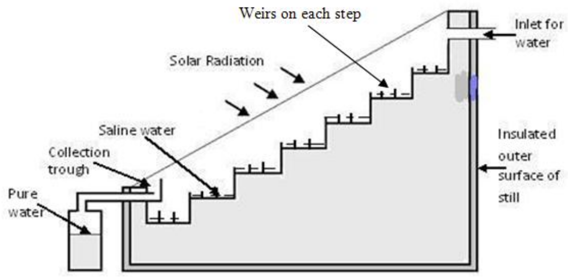

Fig. 4 Weir-type solar still

In this article, the various design and effecting parameters for stepped and weir-type solar still has been reviewed. This paper gives the details about parameters, performance of stepped and weir-type solar still and thermo-economic relations.

II. RESEARCH ON STEPPED TYPE SOLAR STILL

A Solar stills is a device used for purification of brackish/saline water into pure form. The stepped type solar still is most prompting way for solar distillation because of its higher productivity than conventional solar still. A lot of research work has been done by many researchers for increasing the efficiency and performance of stepped solar still.

Radhwan (2004) reviewed the design of stepped solar still. The basin of stepped solar still consisted of 10 steps which was made up of stainless steel. The basin of steeped solar still is black-coated and covered by sloped glass cover. The wind speed, ambient temperature and solar intensity considered as the environmental parameters. The insulation thickness, melting temperature of PCM (wax) considered as design parameters. The inlet air conditions, air flow rate and initial saline water mass was considered as operational parameters. Latent heat thermal energy storage used for enhancement the performance of stepped solar still. The paraffin wax was put inside the insulated basin with help of slab in 5 steps stepped solar still. The paraffin wax acts as latent heat thermal energy storage system (LHTESS). Hence, the performance of still was obtained as 4.6 L/m^2 [12].Abdallah et al., (2008) worked for design modification of solar still. They replaced the conventional still of flat basin by a step-wise basin and also use internal reflecting mirror on insulated wall of solar still. The internal reflecting mirror increased the performance of solar still up to the 30% and with the help of step-wise basin increased up to 180% but with the combination of both the performance of solar still increased up to 380% [13]. Velmurugan et al., (2008) worked for enhancement in distilled output of stepped solar still. They discussed various parameters i.e. design related, water depth, use of fin etc. for increasing the productivity. They used two different depth basin which were 10 mm and 5 mm with 25 number of trays inside the still [14].

Velmurugan et al., (2009) worked on solar still integrated with the solar pond, stepped solar still and a single basin solar still in series. Further, the single basin solar still was replaced by wick type solar still. They also examined the affect of this on performance of still [15]. Velmurugan et al., (2009) analyzed the performance of still for effluent desalination. For better productivity, sponge, fin, pebble and combination was used with two different depth 10 mm and 5 mm in 50 rays stepped solar still. They found that productivity increased by 98% [16]. El-Zahaby et al., (2010) design a new stepped solar still using flash evaporation chamber. They used the spray water system for increasing the performance of still [17].

Kabeel et al., (2012) used the reciprocating spray feeding system for increasing the performance of the still. A transverse reciprocating spraying system was used for feeding saline water on top surface of still in fine droplets. These fine droplets enhance the performance of the still as a result high efficiency nearly 77.35% gained [18]. Kabeel et al., (2015) worked on stepped type solar still having 5 mm depth and 120 mm width basin. They used the vacuum tube solar collector vary the temperature of feed water. They got performance of stepped still 57.3% higher than conventional still [19]. Abdullah (2013) designed a new stepped solar still coupled with a solar air heater for improving the performance of still. The hot air was passed beneath the base of stepped solar still with using aluminum filling as thermal storage material under the absorber plate for keeping the temperature of water high enough to produce distilled water in absence of sun shine. The performance of the still increased by 112% as compared to conventional solar still, when still is coupled with the glass cover cooling and solar air heater. When aluminum was used performance increased by 53% compared with conventional still [20].

Alaudeen et al., (2013) used the inclined flat plate collector in stepped solar still for increasing the performance of solar still. Rocks and pebbles were used as the sensible heat storage medium. The rate of evaporation improved with the help of packing material i.e. wicks and pebbles [21]. Omara et al., (2013) designed a new stepped solar still with the use of internal reflectors. These reflecting mirrors were placed on vertical side of still with trays (5 mm depth, 120 mm width). The performance was increased by 75% and 57% compared with and without internal reflector respectively [22]. El-Agouz (2014) worked on modified stepped solar still with cotton black absorber and a storage tank. The efficiency of still was 20% higher at 3L/m flow rate [23]. El-Samadony et al., (2014) optimized the water film cooling parameter of stepped solar still. The daily productivity of still depends on various factors such as flow rate, cooling film thickness, inlet temperature & air wind speed etc. [24]. Some parameters, result and conclusion which were concluded by researchers for stepped type solar still are summarized in Table 1.

Table 1 Research parameters of stepped solar still

S. No.	Researcher	Research parameters	Results and conclusion
1.	Radhwan et al. [12]	latent heat source (LHS) used	LHS - Paraffin wax Distilled output - 4.6 L/m^2
2.	Abdallah et al. [13]	Internal reflector mirror and combination with stepped type solar still	30% & 380% performance increased with internal reflector mirror and with combination
3.	Velmurugan et al. [14]	Depth of water and fins	80% efficiency increased w.r.t. conventional still
4.	Velmurugan et al. [15]	Solar pond, wick type solar still combination with stepped solar still & single solar still in series	The 100% productivity is achieved with fin type stepped solar still with pebble and sponge
5.	Velmurugan et al. [16]	Different water depth, sponge, fin, pebble & combination	98% productivity increased at depth of 10 mm & 5 mm of water
6.	El-Zahaby et al. [17]	Flash evaporation chamber used	77.35% efficiency achieved with productivity of 6.355 L/m^2
7.	Kabeel et al. [18]	Reciprocating spray feeding system used	77.35% efficiency increased
8.	Kabeel et al. [19]	Vacuum tube solar collector used	57.3% higher Performance than conventional still
9.	Abdullah [20]	Solar air heater, cooling glass cover and aluminum heat absorber used	Performance increased by 112% and 53% with used of glass cover, solar air heater and aluminum heat absorber compared with conventional still
10.	Alaudeen [21]	Different packing material used at different depth of water	Maximum productivity 1468 kg/cm^2 at 2cm depth,1745 kg/m^2 productivity combination of rock, sponge and wick material
11.	Omara [22]	Internal reflector are used	75 and 57% performance with and without internal reflector respectively
12.	El-Agouz [23]	Modified stepped solar still with cotton absorber	Daily efficiency is 61%
13.	El-Samadony [24]	Cooling film thickness parameter used	Best rang of film thickness 2.5×10^{-4} to 5.5×10^{-4}m & glass cover length 2 to 2.8 m

III. RESEARCH ON WEIR-TYPE SOLAR STILL

A solar still is highly promising method for distillation of water. It fulfills the requirements of potable water. The most of research work has been done on various parameters which enhance the performance of still. In this section research work and review on weir type solar still is highlighted.

Sadineni et al., (2008) designed a weir-type inclined solar still. The water flows from top basin to bottom basin and unevaporated water goes back to top basin with the help of small pump. The productivity of still is 20% higher than conventional still [25]. Tabrizi et al., (2010) examined the affect of flow rate and mass transfer rate on a weir-type cascade solar still. They concluded that productivity is influenced with flow rates. They got daily productivity was 7.4 and 4.3 kg/m^2 at minimum and maximum flow rates [26]. Tabrizi et al., (2010) designed a weir-type cascade solar still combined with latent heat storage system. They used the paraffin wax as phase change material. They compared the productivity of cascade solar still with weir-type solar still with and without phase change material [27]. Dashtban and Tabrizi (2011) used 18 kg mass of paraffin wax for increasing the temperature of water in the basin in the lack of sun shine. They also considered other parameters for increasing the productivity of still. The productivity of still was nearly 31% higher when the phase change material was used [28].

Zoori et al., (2013) analyzed the energy and exergy efficiencies of weir-type cascade solar still. They considered the various parameters, i.e., water thickness, solar radiation, inlet water temperature, inlet brine flow rate etc. for enhancing the productivity of still. The maximum energy and exergy efficiencies were found to be 83.3% and 10.5% respectively when flow rate was considered minimum at 0.065 kg/min [29]. Al-Hamadani and Shukla (2011) used the lauric acid as a heat storage medium for distillation of water. They concluded that productivity of still is higher when mass of water in basin is lower as compare to mass of PCM [30]. The conclusion and results of some researcher on weir-type solar still are assembled in Table 2.

Table 2 Research parameters of a weir-type solar still

S.No.	Researcher	Research parameters	Conclusion & result
1.	Sadineni [25]	Double and single-pane glass covers used	Productivity approximately 2.2 and 5.5 L/m^2/day
2.	Tabrizi et al. [26]	Mass transfer rate and water flow rate	7.4 & 4.3 kg/m^2 productivity at minimum and maximum flow rate
3.	Tabrizi et al. [27]	Paraffin wax used as phase change material	Total productivity changed 2.1 to 3.4 kg/m^2 without and with latent heat thermal energy storage system respectively
4.	Dashtban & Tabrizi [28]	Phase change material with various water level	Daily productivity nearly 6.7 and 5.1 kg/m^2 with and without phase change material
5.	Zoori et al. [29]	Parameters: Flow rate, solar radiation	Maximum efficiency at minimum flow rate 0.065 kg/min and minimum efficiency at maximum flow rate of 0.2 kg/min

IV. THERMO-ECONOMIC ANALYSIS

A. Thermal analysis

The energy equations are solved for glass cover, absorber plate and brackish water for solar still. The main assumptions are considered for thermal analysis for still [28]

- The still is air tight for stopping the saturated air flow out.
- The still is completely insulated for inhabitation of heat flow from sides.
- Considering a constant thickness of water and water layer is immobile.
- The immobile layer of water having a uniform temperature on the absorber surface.

The thermal balance equation for glass cover is considered as

$$I(t)\alpha_g+h_2(T_w-T_g)=h_{3,g-a}(T_g-T_a)+(m_g c_g/A_g)(dT_g/dt) \quad (1)$$

where the equivalent heat transfer coefficient $h_2 = h_{rwg} + h_{ewg} + h_{cwg}$ from water surface to the glass cover. The Dunkle's relation is used for calculation of evaporative (h_{ewg}) and the radioactive (h_{rwg}) heat transfer coefficients [31]. The solar radiation intensity I(t) and heat transfer coefficients from the glass to the surrounding air $h_{3,g-a}$. The convective heat transfer coefficient (h_{cwg}) is between water surface and glass cover. Tiwari (2006) [32] gives the Dunkle's correlation as

$$h_{cwg} = 0.884\left[T_w - T_g + \frac{(P_w-P_g)(T_w+273)}{268.9\times10^3 - P_w}\right]^{1/3} \quad (2)$$

Kumar and Tiwari (1985) modified the convective heat transfer coefficient [33].

$$h_{cwg} = C'(k_v / d)(Gr'.Pr)^n \quad (3)$$

Tabrizi et al ., (2010) [26] determined the values of C' and n equal to 1.22 and 0.22 respectively. Then convective heat transfer coefficient presented as

$$h_{cwg} = 1.22(k_v / d)(Gr'.Pr)^{0.22} \quad (4)$$

where Pr is prandtl and Gŕ is grash of number. Gr' is given by expression

$$Gŕ = \frac{\beta' d^3 \rho^2 g \Delta T'}{\mu^2} \quad (5)$$

where d = distance between glass surface and water and $\Delta T' = (T_w - T_g) + (P_w - P_g)(T_w + 273) / (268.9\times10^3 - P_w)$ [34]. All the variable (β,d,g,Δt) of above equation are temperature dependent [29].

Thermal balance equation for saline water is sum of evaporative, radiative and convective heat transfer between glass and water and energy sorted by saline water.

$$I(t)\, T_g\, \alpha_w + h_1 (T_p - T_w) = h_2 (T_w - T_g) + (m_w c_w / A_w)(dT_w / dt) \quad (6)$$

Convective heat transfer coefficient (h_1) between saline water and absorber plate is expressed as

$$h_1 = 0.54\, (k_w / x')\, (Gr\, Pr)^{0.25} \quad (7)$$

where Gr and x' represent the grashof number and characteristic dimension respectively.

Thermal balanced equation for absorber plate

$$I(t) \propto_p T_g T_w = h_1(T_p - T_w) + U_b(T_p - T_a) + (m_p c_p / A_p)(dT_p / dt) \quad (8)$$

where U_b is back loss coefficient and its value is 14 W/ $m^{2o}C$.

The productivity of distilled water form still is calculated as

$$m'_{ew} = \frac{q_{ewg}.A_w.3600}{L_w} = h_{ewg}.A_w.(T_w - T_g).3600/L_w \quad (9)$$

The efficiency of still is ratio of evaporation to the incident solar energy given as

$$\eta_{passive} = \frac{\sum m'_{ew}.L_w}{A_p \int I(t)dt} \times 100 \quad (10)$$

where dt is small interval for measuring the solar radiation.

B. Economic analysis

The solar still is designed for providing potable water at minimum cost. The main objective is to minimize the cost of solar still which can fulfill our daily requirement. The total cost© is sum of variable cost (V) and fixed cost (F) [35].

C = F + V, where variable cost (V) = 0.2 -0.3F per year and assumed still life (n) is 5 to 10 year. The overall cost of solar still for payback period depends on designing, operating cost, cost of maintenance and feed water [36].

Consider total designing cost = C

Cost of distilled water per liter = C_w

Assume still productivity (L/m^2/day) = m

Cost of distillated water generated per day = $C_w \times m$

Maintenance cost of still per day = M

Total economy profit = Cost of pure water obtained – cost of maintenance

Payback time period of still = Total investment/ Total profit

The cost of water per liter is calculated on annual productivity of still [37]. It is obtained by following formulae.

Daily average productivity is m.

Total annual productivity is m × total working day.

Cost of water per liter is ratio of the total cost © to the total annual production.

The productivity of different type of still and annual cost of different still is given in Table 3.

Table 3 productivity of various still with annual cost [11]

Sr. No.	Researcher	Type of still	Productivity of still (L/m^2/ day)	Annual cost of water/liter	Per unit system cost in US $
1.	Omara et al. [38]	Single slope	4.1	0.065	79.95
2.	Ali et al. [39]	Single slope	1.7	0.196	100
3.	Rajamanickam et al. [36]	Double slope	3.070	0.217	200
4.	Singh et al. [40]	Hybrid	7.54	0.388	879.56
5.	Omara et al.[37]	Hybrid	12.48	0.027	550
6.	Kumar et al. [41]	Hemispherical	4.2	0.017	233
7.	Basel [42]	Hemispherical	5.7	0.560	958
8.	Kabeel [35]	Pyramidal	4.1	0.065	582.3
9.	Ahsan et al. [43]	Domestic design	1.6	0.072	35.03
10.	Sadineni et al. [25]	Weir-type	3.85	0.017	54

V. CONCLUSION

Distilled water is necessary for every living creature. Distillation of water has been done by numerous methods. The solar distillation is one among them. The productivity of solar still is low. Stepped and weir-type still are designed for increasing the surface area with in same volume of still. The stepped solar still having greater productivity as compared to the conventional still and weir-type still having greater productivity than stepped solar still. The productivity of still is also increased by different method i.e. thermal storage system etc. but optimization is also necessary for obtaining an economic still. The conclusions are listing below

- The productivity of still depend upon various parameters i.e. angle of still, depth of water, ambient parameters, flow of brine and heat absorbers etc.
- The surface area of stepped solar still is larger than conventional still.
- The latent heat thermal storage system is used for enhancing the efficiency and the productivity of stepped solar still is 4.6 L/m^2 with use of phase change material (PCM)
- The surface area and stay time of water on absorber plate is larger for weir-type still as compare to stepped type with similar dimensions.
- The daily productivity is nearly 6.7 and 5.1 kg/m^2 with and without phase change material.

Nomenclature

A area (m^2)

c heat capacity (J/kg^{o}C)

C' constant

d distance between water and glass surface (m)

g acceleration due to gravity (m/s^2)

Gr Grashof number

h convective heat transfer coefficient (W/m^{2o}C)

h_1 convective heat transfer coefficient from absorber plate to water (W/m^{2o}C)

h_2 equivalent transfer coefficient from water surface to glass cover (W/m^{2o}C)

h_3 convective heat transfer coefficient from glass cover to ambient (W/m^{2o}C)

I(t) solar intensity (W/m^2)

k thermal conductivity (W/m^{2o}C)

Gr' modified Grashof number

L latent heat (J/kg)

m mass (kg)

m′ hourly productivity (kg/h)

n constant

p partial vapor pressure (N/m^2)

Pr Prandtl number

q rate of heat transfer (W/m^2)

t passed time from starting

T temperature (^{o}C)

U heat loss coefficient (W/m^{2o}C)

V average wind velocity (m/s)

x thickness (m)

x' characteristic dimension of a rectangular surface (m)

g glass

e evaporation

equ equivalent

l liquid

m melting

r radiation

p absorber plate

s solid

w water

v vapor

α absorptivity

β′ coefficient of volumetric thermal expansion (K^{-1})

δ′ incremental rise

ρ density (kg/m^3)

μ viscosity of fluid (Ns/m^2)

ε_{eff} effective emissivity, dimensionless

ε_g emissivity of glass cover, dimensionless

ε_w emissivity of water, dimensionless

σ Stefan–Boltzmann's constant (5.6697×10^{-8} W/m^2 K^4)

ΔT temperature difference (^{o}C)

ΔT′ effective temperature difference (^{o}C)

η overall thermal efficiency %

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