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Different designs and parametric study of solar water distillation system

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Abstract

Solar desalination is one of the promising methods of harnessing the solar renewable energy for fulfilling potable water requirement for small communities where the natural fresh water supply is inadequate. This paper presents the literature review to categorize solar stills into six sorts based on the design guidelines and their parametric study. It presents designs and the studies carried out by various researchers to find out the effect of various design and operating parameter on the efficiency (out put) of distillation units suggested. Basin type solar still with simple symmetrical still, vertical basin with improved condensation, increased surface area and basin still with a built in sandy heat reservoir, weir type solar still with cascade and concave type have been enlisted as per studied by various researchers.

Keywords: Solar still, basin type solar still, vertical basin, weir type, stepped solar still, evacuated tubes.

Contents

1 Introduction

Clean and safe drinking water is essential to humans and other life forms. Approximately one billion population still lack access to safe fresh water and over 2.5 billion lack accesses to adequate sanitation. The fresh water is utilized 70 percent for irrigation, 20 percent for industry and 10 percent for domestic use [1]. The world's population is growing year by year, implying increased freshwater demand.

Supply of portable water is a major problem in underdeveloped as well as in some developing countries. Simultaneously fresh water demand is increasing continuously, because of the industrial development, intensified agriculture, improvement of standard of life and increase of the world population. Only about 3 % of the world water is potable and this amount is not evenly distributed on the earth [2].On deserts and islands where underground water is not readily obtainable and the cost of shipping the places is high it is worthwhile to take into consideration of producing potable water from saline water, using solar energy that is in abundance in every part of the Earth's surface and solar energy, a renewable source of energy delivered by the Sun in plenty amount at zero cost. We require harnessing the solar energy in effective ways.

1.1 Solar Distillation

Solar distillation is a technology for producing potable water from brackish and underground water of low-quality at low cost. It can reduce water scarcity problems together with other water purification technologies. It uses an apparatus called a solar still in which water is evaporated using solar energy and collected as distillate after condensation of the vapor. It effectively produces distilled water after removal of impurities. The major advantage of this is the use of solar energy instead of electrical energy generated from conventional fuels. This helps in producing potable water without degrading our environment. Over time, researchers have studied several designs of solar stills to evaluate its performance for different climatic, operational, and design parameters.

1.2 Basic Principle

A solar still is a device used in which impure/saline water is fed to obtain distilled water by solar distillation. Figure 1 shows the schematic diagram of the conventional single slope passive solar still. It is a box type structure that can be made of materials such as fiber reinforced plastic (FRP), wood, concrete, or galvanized iron (GI) sheet covered with some insulation. The box is covered with a glass cover. The solar radiation passes through the glass cover. A major portion of this solar radiation is absorbed by the black painted surface of the basin, generally known as the basin liner. However, a small amount of reflection loss takes place at the glass cover, the water, and the basin liner surfaces. A small amount of solar radiation is also absorbed by the glass cover and water because of their absorptivity.

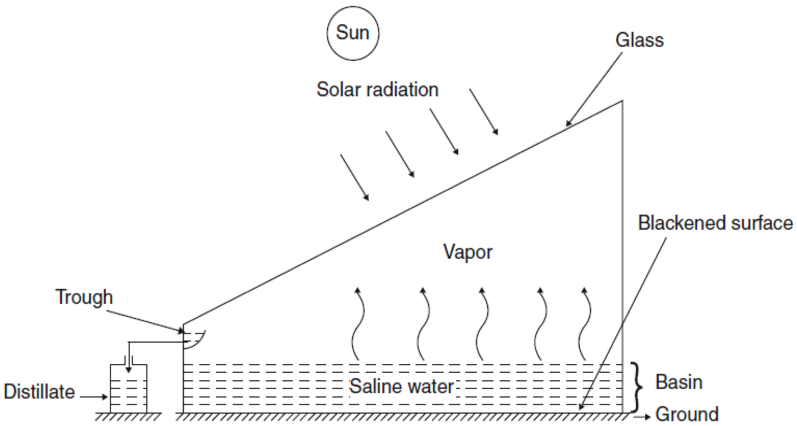

Fig. 1 Schematic diagram of a conventional single slope passive solar still [3].

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Heat absorbed by the basin liner is transferred to the saline water. The remaining amount of absorbed heat is lost by conduction as bottom heat loss. Heat transfer from the water surface to the glass cover takes place by three mechanisms: evaporation, convection, and radiation. An evaporative heat transfer is a dominant effect, which is responsible for the production of the distillate.

Evaporated water leaves most of the contaminants and microbes on the basin liner. Further, this evaporated water with some volatile material undergoes film type condensation at the inner surface of the glass cover. A film type condensation occurs because of inclination of the glass cover, cohesion between condensed water molecules, and gravity effect. The condensed water trickles down to a trough, which guides it into a container. The yield from a single slope passive solar still may vary from 0.5 to 1.2 l/m^2/day (in winter) and 1.0 to 2.5l/m^2/day (in summer). The overall thermal efficiency (the ratio of energy output to the energy input for a system) of the system can vary from 5 to 40% throughout the year. It is also seen that the salinity of the water is reduced to 8–15 ppm [3].

2 Various Still Designs

The performance of a solar still based on the various designed is studies. Figure 2 shows different designs of still.

2.1 Basin Type

2.1.1 Simple basin type still

Tarawneh [4] worked with a small-scale solar powered desalination system and evaluated the effect of water depth and productivity in the basin type solar still. He investigated the effect of the design and operational parameters on the solar desalination process. Their setup was constructed of two symmetrical greenhouse-type solar stills as shown in Fig. 3. Different depths of brackish water (0.5cm, 2cm, 3cm, and 4cm) with TDS of 5000ppm were tested. He showed that the decreased water depth has a significant effect on the increased water productivity, while the performance characteristics showed that the water productivity from the lower depth was 6.699 Lit/Day and closely related to the incident solar radiation intensity, the efficient percentage efficiency of solar utilization comes to be about 75%.

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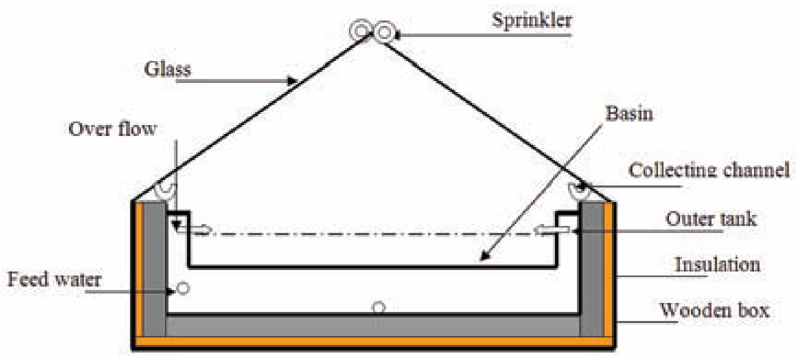

Fig. 3 Schematic sketch of the basin type solar still [4].

2.1.2 Vertical basin solar still with improved condensation technique

A vertical basin solar still with improved condensation technique provides additional condensation surface on the sidewalls of the still to enhance the distillate yield and the efficiencies of the still. The rise in the efficiency was for pre-heated sample (65ºC) compared to that of the other. And the highest efficiency of 30.41% was reached in tap water for both sample temperature conditions (25ºC and 65ºC). The maximum daily production of the solar still is reported to be about 1.4 L/m^2.d, and its efficiency was about 30% with corresponding average solar insolation of 28 MJ/day. [5]

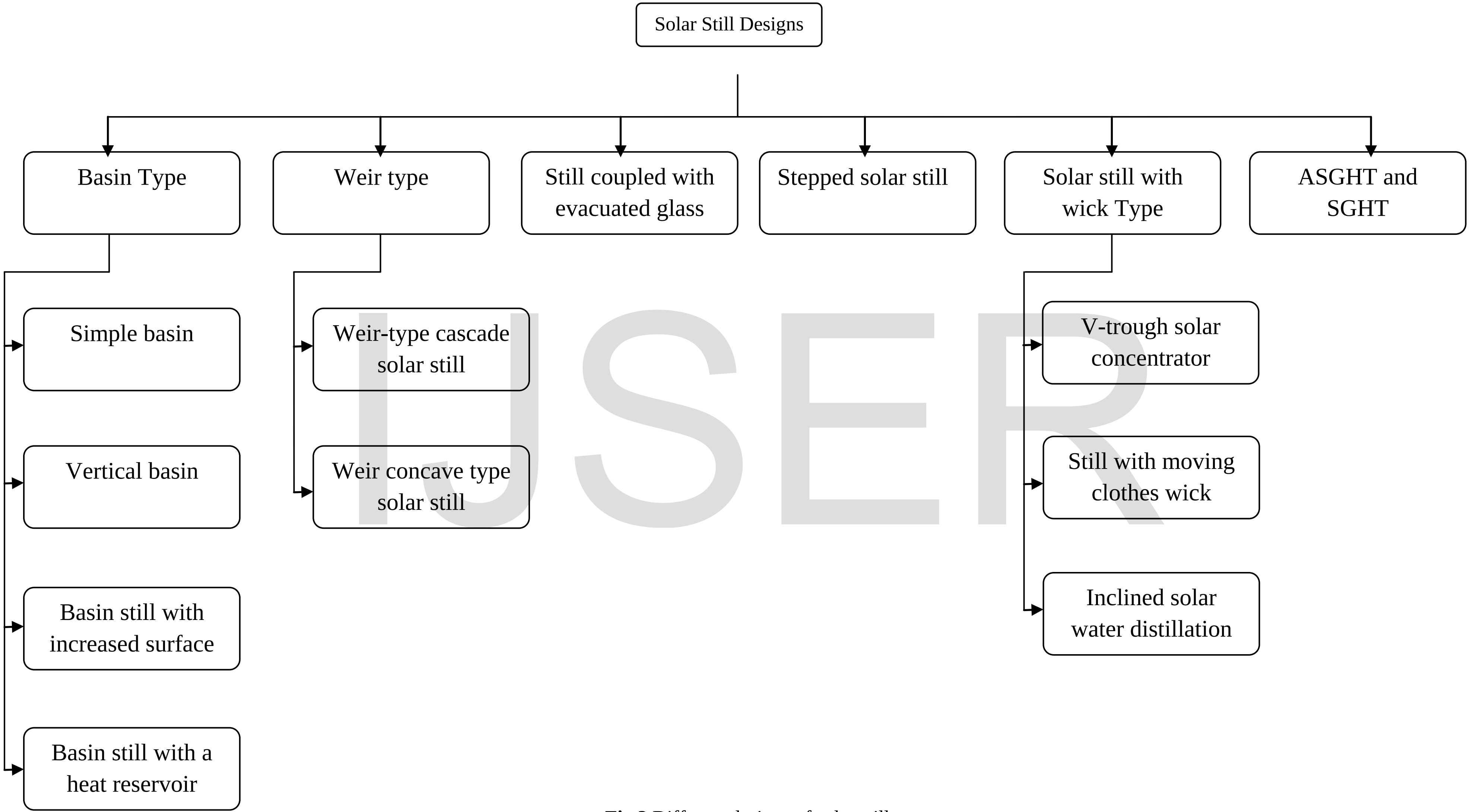

Fig.2 Different designs of solar still.

2.1.3 Basin solar still with increased surface area

Omara et al. [6] studied the improvement of the productivity of basin solar stills by increasing the surface area of absorber (base of still) and rate of heat transfer between saline water and absorber as shown in Fig. 4. The integrated fins at the base of the solar still give an average of 40 % increase in the amount of distillate water produced compared with a conventional still, while the corrugated plate as the base increases the amount of distillate water by about 21%.

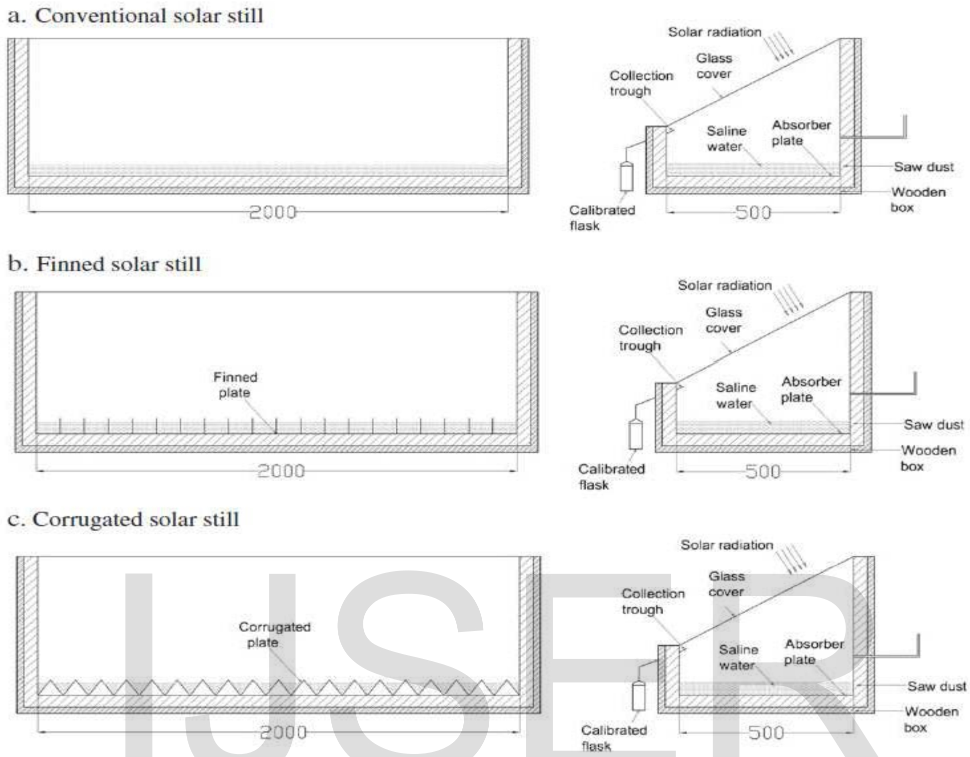

Fig. 4 Cross-section of solar still (all dimensions are in mm) [6].

2.1.4 Basin solar still with a built-in sandy heat reservoir

Tabrizi and Sharak [7] reported that the integrated heat reservoir leads to significantly higher solar still productivity during nights and cloudy days.

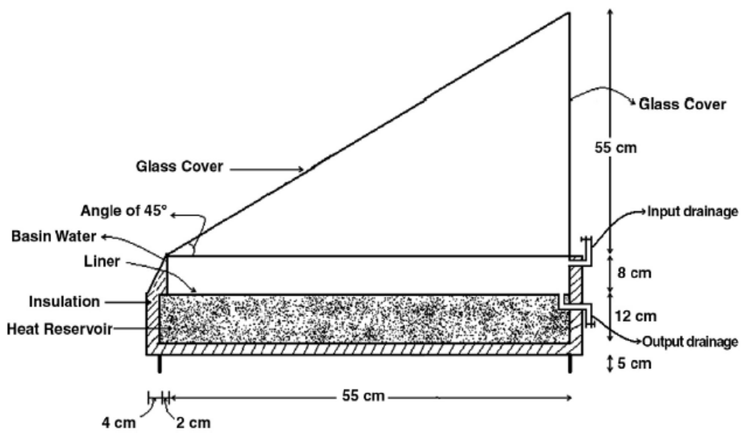

Fig. 5 A schematic drawing of the experimental set-up [7].

Figure 5 shows the schematic diagram of the solar still with built-in sandy reservoir as a storage medium. About 12% of total daily production produced in 4 hour of experiment after the sunset. They showed that for a 14-hour experiment, the still productivity was about 3000 cm^3/m^2 (basin area is $0.41m^2$). This demonstrates more than 75% increase in the still productivity in comparison with conventional basin solar still without heat reservoir.

2.2 Weir type

2.2.1 Weir-type cascade solar still

Tabrizi et al. [8] designed a weir-type cascade solar still (CSS) as shown in Fig.6 to increase the amount of distillate water production by providing a minimum air gap, proper distribution of feed water on evaporation surface and better orientation of solar beams and studied the influence of water flow rate on the internal heat and mass transfer and daily productivity of CSS and concluded that the daily productivity decreases by increasing the flow rate as the daily productivity was found to be 7.4 and 4.3 kg/m2day, for minimum and maximum flow rates, respectively.

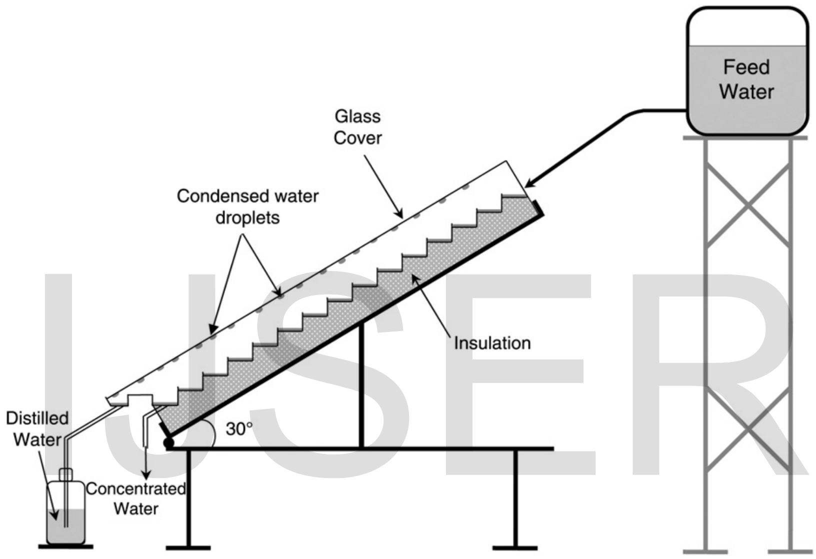

Fig. 6 Cross sectional view of a schematic diagram of cascade solar still [8].

2.2.2 Weir concave type solar still

Kabeel [9] worked with a weir concave type solar still (Figure 7) with four glass cover surfaces to study the effect of increasing the surface area or decreasing the cover temperature on distillate output. The average distillate productivity during the day time is approximately 4 L/m^2 with a system efficiency of 0.38 at solar noon. They conducted the experiments on clear days for a water depth of 10 cm in the basin. They recorded the experimental data on hourly basis and calculated the efficiency of solar still using the following relation:

$$\eta = \frac{q_{ev}}{H} = \frac{m_{ev}L}{H}$$

where:

q_{ev} is the heat of evaporation

m_{ev} is the mass of evaporated vapour

H is the total solar radiation falling upon the still surface

L is the latent heat of evaporation.

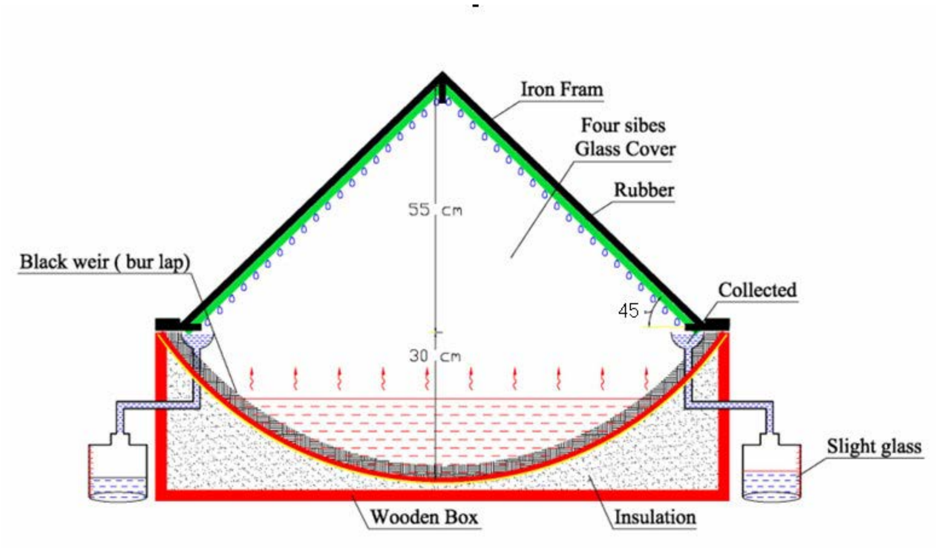

Fig. 7 Layout of a weir concave type solar still setup [9].

2.3 Solar still coupled with evacuated glass tube

Patel et al. [2] analysed the performance of a single slope active solar still coupled with evacuated glass tube solar collector for high temperature water feeding into the basin of solar still as shown in Fig. 8. Increase of 30.38% of the productivity with the presence of black dye in water for solar still containing saline water up to a depth of 10 cm.

Karuppusamy (2012) [10] experientially showed that the average increase in productivity after coupling evacuated tube to the still is 49.7% and daily productivity was 3910 ml. The daily productivity has shown 8% increase by using black gravel in still basin.

Fig. 8 Solar still coupled with Evacuated glass Tubes [2].

2.4 Stepped solar still

Assadi [11] designed and fabricated a basin type stepped solar still. The setup has 2 x 1 m^2 transparent glass cover made of glass fiber or aluminum. A basin type stepped and an aluminum type solar still with a basin depth of 1 cm and a concrete type solar still were compared and concluded that the solar still made of fiberglass showed higher efficiency as compared to metallic one.

2.5 Still with wick Type absorber

2.5.1 V-trough solar concentrator with a wick-type solar still

Mahdi and Smith [12] worked with V-trough solar concentrator with a wick-type solar still. They carried out outdoor testing with and without solar concentrator to investigate the enhancement of performance of the still by the solar concentrator. A V-trough solar concentrator (of apex angle 30 °) was combined with a flat wick-type solar still. This was attached to the outer surface of the glass cover of the flat still. The solar concentrator with the inclined wick-type solar still can lead to a greater fractional increase in still efficiency 53.4 to 63.6 % and productivity on clear days in winter than on clear days in summer.

2.5.2 Solar still with moving clothes wick driven with a DC motor

The performance of a simple solar still with moving clothes wick driven with a DC motor via a control circuit was investigated by Gad et al. The clothes wick is immersed in water when the motor is ON and the wet clothes is subjected to solar radiation when the motor is in OFF period. They showed that an ON period 30 seconds is suitable and an OFF period of 25 minutes yields maximum thermal efficiency and the solar radiation intensity on tilted surface increases to noon hours and then decrease again. The maximum solar radiation changes from day to another from 700 W/m^2 to 800 W/m^2. It is possible to operate such solar still with the computer to reduce the cost of production of distilled water [13].

2.5.3 Inclined solar water distillation system with wick as an absorbing medium

The ISWD system consists of an inclined flat solar absorber plate covered with glass. Figure 9 shows the schematic diagram of the ISWD system, which consists mainly of an absorber plate and a glass cover that creates a cavity. The fresh water generation rate increased two to three times when wicks were used instead of a bare plate as reported by Aybar et al. [14].

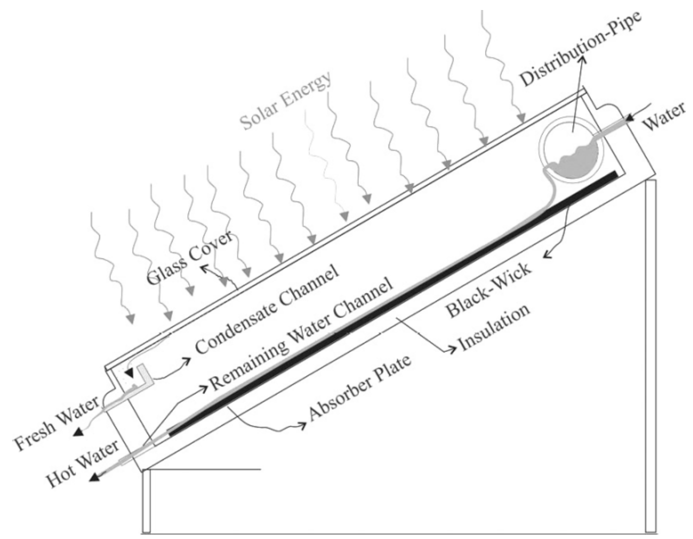

Fig. 9 Schematic diagram of the inclined solar water distillation system [14].

3 Parametric study

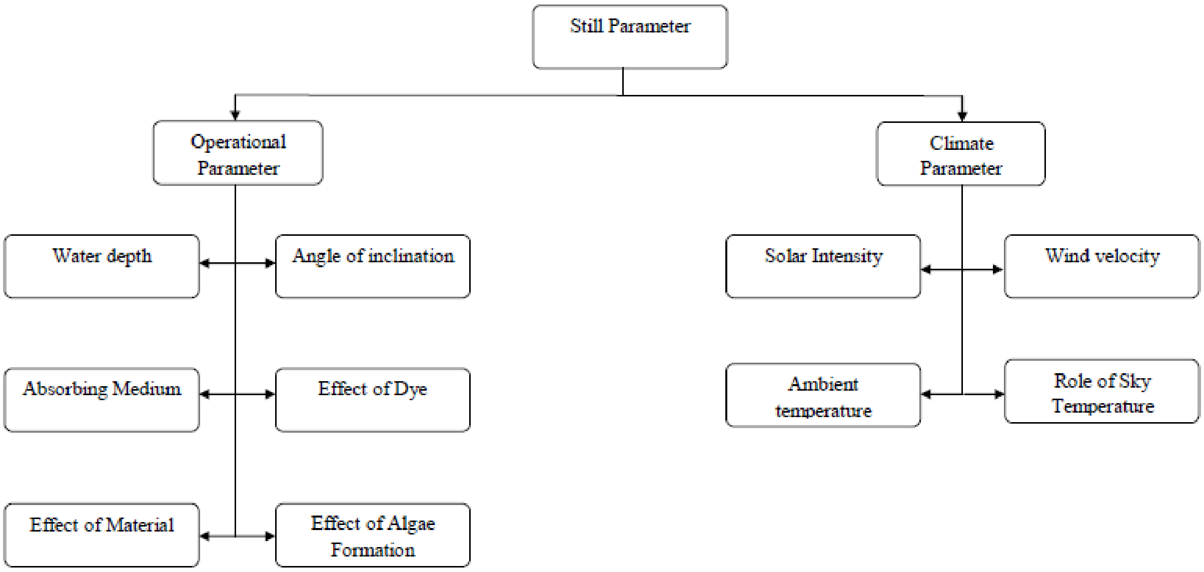

Fig. 10 Solar still parameters.

3.1 Operational Parameter

Operational parameters are those conditions that can be varied to improve the performance of the solar still. Some of these parameters and their effects are given below.

3.1.1 Water depth

Hayek and Badran [15] studied the distillate productivity of both asymmetric and symmetric stills are presented in Figs. 11 for different water depths. The production rate increased with the decrease in water depth because of the increase of the solar radiation absorbed by the bases. They conclude that through the water depth is not a critical parameter; it should be as small as possible [17].

Omara et al. (2011) showed the effect of water depth in the still basin on the productivity is shown in Fig. 12. As the water depth increased, the productivity decreased. The decrease of the water depth from 3.5 to 2 cm increased the productivity by 26% [16].

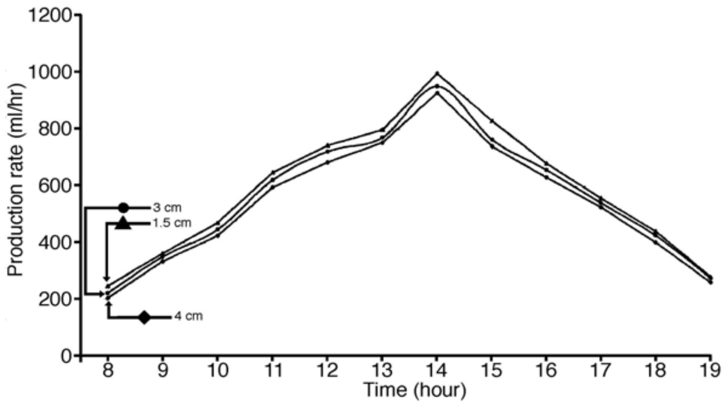

Fig. 11 The effect of water depth of the productivity of fresh water for the asymmetrical greenhouse type solar still. [17]

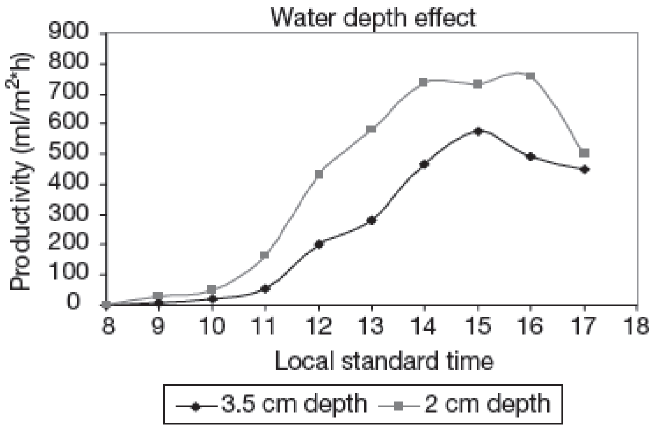

Fig. 12 The effect of water depth in the basin on the productivity. [16]

3.1.2 Angle of inclination

An optimum inclination of the condensing cover for nonsymmetrical double and single-sloped stills for receiving maximum solar radiation to give the highest yield mainly depends on the location, cover material, and season. Inclination of the condensing cover varies from season-to-season. The optimum inclination is equal to the latitude of the place. Various investigators observed that the minimum inclination of the glass cover should be at least 10° to avoid the fall of condensate back into the basin. The optimum inclination is different for the acrylic plastic cover due to the greater surface tension between the condensed water and plastic cover than that between water and glass cover as shown in Fig. 13.

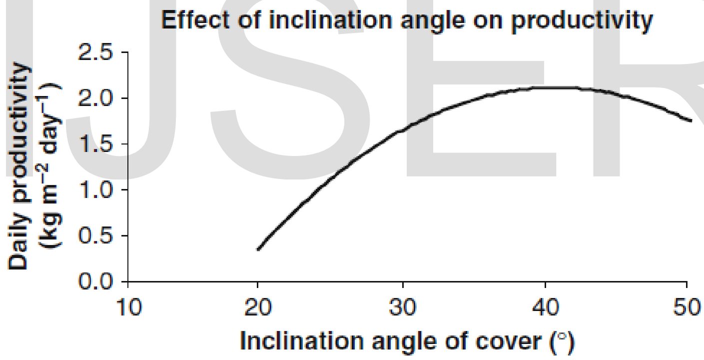

Fig. 13 Variation of the rate of distillation with the slope of the acrylic covers using a horizontal absorbing surface [3].

3.1.3 Absorbing Medium

Naim and Kawi [18] worked on a solar still with charcoal functions both as heat absorber medium and as wick. They investigated the effect of still inclination to the horizontal on the productivity of the still and noted that an inclination of 17° led to a higher productivity at latitude 32°N. Charcoal affects the performance of the solar still because of its properties: (1) wet ability (fast absorption of water), (2) large absorptivity for solar radiation due to its black color, and (3) higher scattering property than reflectivity of the solar radiation. The effect of charcoal pieces enhances the performance of a solar still on partially cloudy days and during the morning hours when solar radiation remains low. The charcoal pieces work to diffuse radiation.

3.1.4 Effect of Dye

Patel et al. [2] analysed the performance of a single slope active solar still coupled with evacuated glass tube with and without dye. The effect of dye is given in Table 1. They showed that there is an increase of 30.38% of the productivity with the presence of black dye in water for solar still containing saline water up to a depth of 10 cm and output with black dye is higher compare to other dyes, while output was lower without dye. They conclude that when number of evacuated glass were increased the temperature inside the active solar still and productivity also increases.

Table 1 Effect of dye on daily distillation [2].

Dye used	**Daily productivity for 10 cm**		**Productivity increase in %**
	With dye Without dye	**With dye Without dye**	
Black	13173	10104	30.38
Blue	12679	10104	25.48
Read	11963	10104	18.40

3.1.5 Effect of Material/Insulation

The type and thickness of the basin material affects the heat accumulation by the water mass of the solar still for the nocturnal operation of the solar still. A large amount of heat storage and low temperature leads to faster evaporation of the water. They found that productivity increases rapidly with an insulation thickness up to 4 cm; thereafter, it is affected rather slowly or at an almost constant rate.

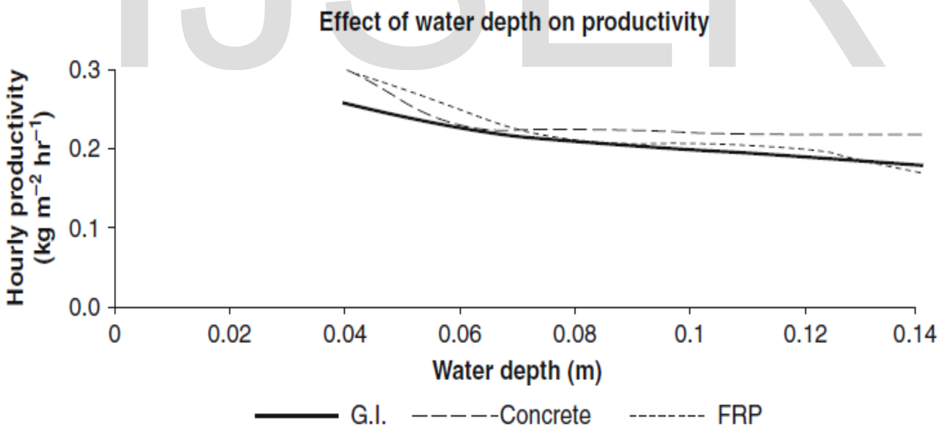

Fig. 14 Effect of water depth on the performance of solar still with lining/coating [3].

The following observations were also made by them:

1. The performance of the Fiber-reinforced plastic (FRP) solar still was the same throughout the experiment.

2. The performance of the Galvanized Iron (GI) sheet and the concrete solar still without FRP lining is poorer than that of the FRP solar still due to the large heat loss from the sides and bottom of the still.

3. The performance of the concrete solar still is poorer than that of the GI sheet solar still because some of the energy in basin water is stored in the concrete structure.

4. FRP lining inside the surface of the concrete and GI sheet solar still reduces the heat losses from the sides and the bottom appreciably. Hence, the performance of these stills is improved significantly and approaches the performance of the FRP solar still.

Figure 15 represents the variation of average production per unit basin area of mounted solar stills with thickness of insulation.

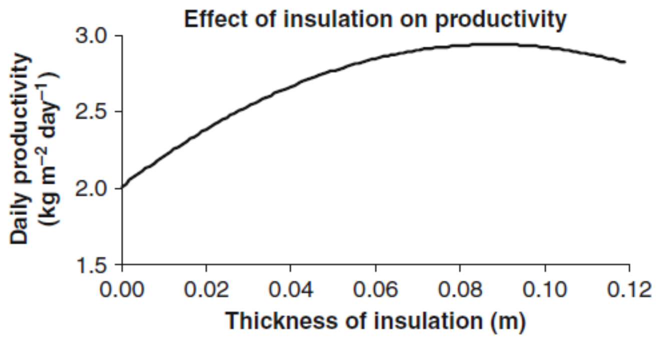

Fig. 15 Variation of average production per unit basin area of mounted solar stills with thickness of insulation [3].

3.1.6 Effect of Algae Formation

Algae formation is common in basins containing salt or brackish waters at temperatures up to 60°C. The absorption of solar radiation by the basin liner decreases with the presence of any solid or viscous solid object, which decreases the quantity of distillate. Hence, it requires periodic cleaning.

3.2 Climate Parameter

All the climate parameters combined together, affect the solar still performance.

3.1 Solar Intensity

Solar radiation has a strong effect on the distillation. Figure 16 shows the effect of global radiation on the productivity (In summer, the solar intensity is higher than that of winter, which results in a higher yield during the summer). The relation between the solar radiation and other parameter are:

1. High solar radiation, ambient temperature, but no or low wind velocity—in this kind of situation, the internal heat transfer coefficient are higher but external top heat loss reduces, which produces low yield.

2. Low solar radiation, ambient temperature, but no or low wind velocity—Because of low solar intensity, the water temperature does not rise much and hence internal heat transfer remains low, the yield of the solar still is affected adversely.

3. High solar radiation, ambient temperature, but high wind velocity—this is a good climatic condition for high yield, due to higher internal and external top heat loss.

4. Low solar radiation, ambient temperature, but high wind velocity, etc.—this kind of condition may yield more or a similar yield in comparison to the condition stated in point 2.

5. High solar radiation, low ambient temperature—this kind of situation occurs in hilly areas such as Leh, Jammu, and Kashmir, India. It produces more yields because of high internal heat transfer and top loss.

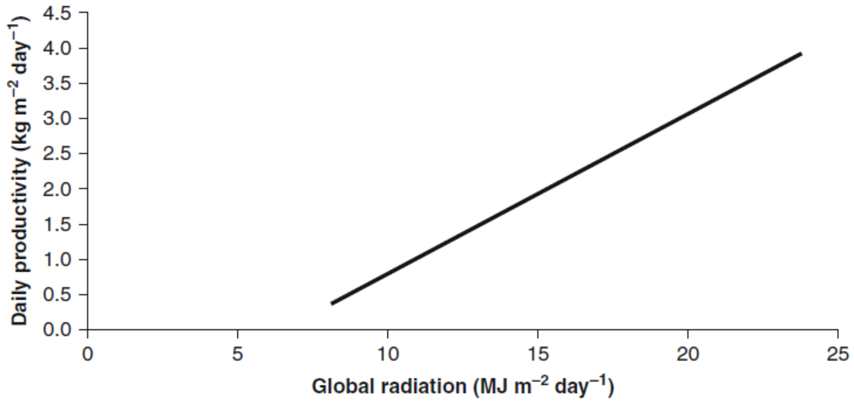

Fig. 16 Effect of solar radiation on rate of distillation [3].

3.2.2 Wind Velocity

For a better performance of the solar still, a low temperature of the upper surface of the glass (condensing cover) is an important parameter, which enhances condensation. The cooling of the condensing cover is done by the wind naturally. It is a concept that the higher the air flow over the condensing covers, the higher the convective heat loss to the ambient. Figure 17 shows the hourly variation of distillate as the wind speed varies. Bardan [16] experimentally studied the performance of a single slope solar still using different wind velocity. He attributed as the wind velocity increased, the productivity is reported to increase. The productivity was found to increase by 35% on increase in the wind velocity from 2.7 to 5 m/s.

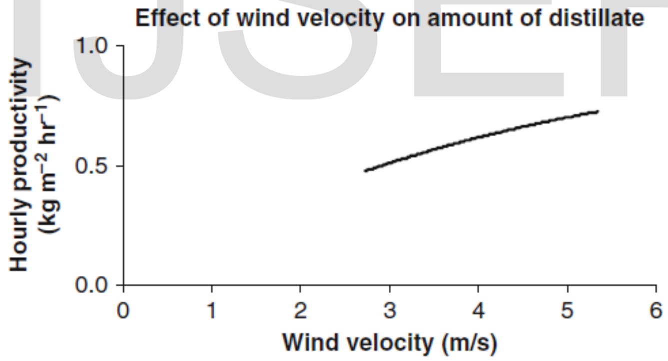

Fig. 17 Variation of hourly productivity with wind speed [3].

3.2.3 Ambient Temperature

Ambient temperature is also an important parameter that affects a solar still performance considerably. The behavior of a solar still is different during the day compared to at night. In the day time, high ambient temperature reduces the water-glass temperature difference, which results in low yield. The solar still becomes more effective during the night with a higher water depth in the basin because of the low ambient temperature and high heat storage of water. Bardan [16] experimentally studied the performance of a single slope solar still at different ambient temperature. He noted as the ambient temperature increased, the productivity is reported to increase. The productivity was found to increase by 53% was notice when the temperature increased from 28 to 32°C.

3.2.4 Role of Sky Temperature

The effect of sky temperature on daily output is observed by taking the effect of h_{cg} and h_{rg} separately using their separate equations, respectively. It is observed that with an increase of sky temperature, total output increases in a small proportion.

4 Summary

An overview of solar desalination technologies is presented. Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where the water scarcity is severe. The scarcity of water limits the socio-economic development of many countries in the world especially in developing countries. Recent developments and technical improvements in desalination technologies have significantly reduced the cost of desalination. The desalination of brackish and seawater will increase rapidly as technologies develop and demand for freshwater grows.

Collective and comprehensive research and development detailed description of various types of solar water distillation systems, performance analysis and parametric study of solar still, different solar water distillation technologies, optimization of parameters to enhance the productivity of distilled water and efficiency of solar still serves the reuse of renewable technologies.

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