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Factors Influencing the Productivity of Solar Still

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Abstract: ***Solar still desalination uses a sustainable and pollution-free source to produce high-quality water. The main limitation is low productivity and this has been the focus of intensive research. A major concern while increasing productivity is to maintain economic feasibility and simplicity. In this paper, a review has been presented on the various factors influencing the productivity of the solar stills. The various studies on the factors enhancing the productivity such as area of absorption, material of absorber, cooling of cover, minimum depth of brine, water–glass cover temperature difference, inlet water temperature, vacuum technology are discussed here.***

Keywords—Solar still, Solar water desalination, Productivity, Desalination, Solar energy

I. INTRODUCTION

The shortage of drinking water is expected to be the biggest problem of the world in this century due to unsustainable consumption rates and population growth. Pollution of fresh water resources (rivers, lakes, and underground water) by industrial wastes has heightened the problem [1]. About 70% of the earth is covered by water, and sea water represents about 97% of the water on the planet, and the remaining is fresh water; thus there is a shortage of potable water in many countries around the world. The rural and remote regions in the Middle East countries do not have access to good quality drinking water and as a result they relied on low cost options for producing water from salty aquifers such as solar desalination. Many researchers have developed mathematical models, and experimentally tried to improve the design of the conventional solar still in order to increase its daily productivity [1].

Two challenges relentlessly face humanity today: (a) fresh water is a finite resource seriously impacted by pollution; (b) fossil fuels are also finite and their use in fuel-based desalination aggravates environmental pollution problems [2]. Technologies such as multistage flash, multiple effect, vapor compression, reverse osmosis, ion exchange, electro-dialysis, phase exchange, and solvent extraction are heavy energy consumers often requiring complex controls and bulky processes [3].

Desalination based on renewable energy, on the other hand, presents a sustainable and a zero-polluting alternative. Renewable resources such as solar energy allow energy diversification, are cheap and available for predictable periods of time, and help avoid dependence on external energy supplies [4]. Until recently, the availability of fossil fuels and the tolerated levels of CO_2 in the atmosphere slowed down the widespread reality of solar desalination [5]. Today, however, with the advent of climate change, conditions have changed and the competitiveness of solar desalination is on the rise.

Solar desalination is the process of converting the impure brackish water into potable drinking water using solar energy. The solar desalination methods have been used by the man kind for thousands of years [19]. Solar stills make use of a sustainable and pollution-free source (i.e., the sun) to produce high-quality water. They are classified among the most in-expensive desalination methods particularly when used in arid areas where sunshine is abundant and fresh water is scarce. Contrary to conventional plants, desalination plants based on renewable energy are still evolving and often implemented as pilot plant applications that still face operational problems [6]. No data exist on the accurate scale of operation of solar stills worldwide and many of the installed plants are experimental systems for research purposes. Systematic analytical data about real operational conditions, problems faced, and costs of produced water, installation, operation, and maintenance in many of these plants are notably missing. As to the cost of materials, transportation, and construction, this depends directly on the location and local conditions [7].

Limitations on the use of solar stills include their low productivity per unit installation area compared with fuel-based desalination technologies, their high initial costs especially if the land cost is high, the need for large installation areas, the variability of the energy source, and the limited experience with large-scale applications. System components and equipment used to enhance productivity are still expensive often hindering commercialization. Although solar energy is free, the hardware required for capturing it, converting it to useful forms, and storing it can be expensive [8]. Another challenge is the variability and intermittent character of the energy source, leading to limitations concerning the maximum exploitation capacities per time unit. The geographical distribution of solar desalination potential may not comply with the water stress intensity at a local level. A continued interest grows, however, in developing technologies that are suitable for villages and remote areas. This is especially true in countries with the greatest water need and where standard fuels required for large-scale desalination are scarce and expensive (e.g., India, Egypt, and Pakistan; [9]. Solar stills may be economically viable if small water quantities are required and the cost of pipe work required to supply an arid area with water is high [10]. They represent the best technical solution to supply remote villages or settlements with fresh water without depending on high technology and expertise [11], particularly where sunshine is abundant. Arjunan et al. [12] described seven large-size solar still installations in India that vary in capacity from 0.13 to 8 m^3/day, mostly treating seawater and in few cases saline well water. The evaporating areas for these plants vary from 50 m^2 up to 3,110 m^2 depending on capacity. Two plants consisting of 240 stills each with a capacity to clean 27.3 m^3/day of seawater have been installed in Baluchistan, Pakistan, and other similar schemes are being considered to desalinate the brackish to saline groundwater present [13].

In their simplest design, they comprise transparently roofed black- painted basins containing the water to be desalted. Water in the basin gets heated and evaporates, and the vapor condenses as it hits the roof and trickles down reaching a channel, which transmits the flow into a collection container. The stills can have various forms, shapes, and cover materials and their operation requires little maintenance besides regularly flushing the basin to remove accumulated salts. With other desalination processes, the resulting brine remains to induce a negative environmental impact. How- ever, such brine could prove to be an important source of metals that may be used in various industrial applications [14]. Disposal methods currently practiced include surface water discharge, disposal to sewers, deep-well disposal, land application, evaporation ponds, brine concentrators, and spray-drying to solids or crystallizers (i.e., zero discharge option; [15]. Discharging brine in turbulent hydrodynamic conditions such as water bodies featuring waves, currents, and supercritical flows and using diffusers to reduce salinity through mixing and dilution are often recommended [16]. Salts recovery may also be an option to utilize the large mass of concentrated salt components [17]. The major waste stream produced by solar stills is not characterized by intentionally added process chemicals, as is the case with other desalination technologies. Rather, the concentrate reflects the raw water characteristics, which is of the same composition but at a more concentrated level [15].

Although environmental impact assessment procedures have been pro- posed, technical solutions, codes, and standards are still in their early phases [16]. The environmental concerns primarily center on the contamination of surface and ground waters, underlying soil, and drinking water aquifers. Mitigation methods include additional processing to remove or di- lute any chemicals of concern, use of noncorrosive and nontoxic materials, use of diffusers, and continuous blending of cleaning wastes and concentrate or separate disposal of cleaning wastes and concentrates.

The main limitation of solar stills is their low productivity compared with conventional desalination processes, and this has been the focus of intensive research. The operating efficiency is low due to main two shortages: the first is the rejection to the atmosphere of the latent heat of condensation and the second is the difficulty in raising evaporation temperature and decreasing condensation temperature as heating, evaporation, and condensation takes place in one container [18].

A major concern in increasing the amount of distillate produced is to maintain economic feasibility and simplicity in construction, operation, and maintenance. In this article we present a critical review of the research work conducted on solar stills development. Important parameters that affect the still productivity include the use of absorbing materials and wicks, cover cooling, cover slope, still design, brine depth, inlet water flow, and initial brine temperature. Studies addressing each parameter of concern are grouped together and results are compared. Novelty in design and newly introduced features and their impact on output are then presented. Modeling efforts of flow circulation within the still and methods to estimate internal heat transfer coefficients are discussed next. Finally, costs of solar stills are presented and future research needs are outlined.

II. FACTORS AFFECTING THE PRODUCTIVITY OF SOLAR STILL

Several parameters affect the performance of a solar still. These include the presence of a dye or absorbing

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material, cover cooling by air or water flow, cover slope, still design, geographical position, water depth, inlet water flow, and initial brine temperature. Research investigations on these influencing factors are discussed in this section.

A. Absorbing Materials

Various approaches for increasing the basin absorptivity have been tested and found effective in increasing the daily yield of a solar still. These include the use of charcoal [21], black, and violet dyes, which were found to be more effective than other dyes, and their effect increases with deeper stills, floating absorber aluminum sheet [22], and black volcanic rocks, which performed better than metallic wiry sponges [23]. Table 1 [20] summarizes the increase in productivity obtained for different absorbers. These materials can store higher amounts of heat energy and increase the heat capacity of the basin in addition to increasing the basin absorption.

TABLE 1: Effect of different absorbers on productivity

Absorber	Increase in yield
Black granite gravel	17–20%
Sponge cubes	14–18%
Sponges and fins in a stepped still	96%
Potassium dichromate	26%
Charcoal	15%
Black gravel	19%
Baffle suspended absorber	20%
Absorbing black-rubber mat	38%
Black ink	45%
Black dye	60%
Rubber material	38%
Charcoal	11–18%
Soot powder	13–17%
Dyes	10%
Dyes	19.80%
Black napthylamine (172.5 mg/l)	17–28.8%
Black napthylamine (50 mg/l)	15.90%
Red carmoisine (50 mg/l)	7.40%
Red carmoisine (100 mg/l)	19.90%
Red carmoisine (100 mg/l)	19.90%
Dark green dyes (50 mg/l)	14.80%
Dark green dyes (100 mg/l)	12%
Dyes	14.60%

As noted in Table 1, the increase in yield, which is usually reported in liters per day per unit area, varies depending on the specific absorber used from as low as 7% for red carnosine, as high as 60% for black dyes, and as high as 96% for sponges and fins. An accurate comparison of the effects of different absorbers in these studies is difficult, however, due to the large variation in the experimental conditions of each study. Such conditions include geographical location, time of the year, particular still design and construction material used, brine depth, water temperature, and other site-specific factors. Aybar et al. [24] tested an inclined flat solar absorber plate with a black cloth or a black fleece and showed that the black wick still produced 2–3 times more water than a bare plate still. The collected data in this study, however, was limited to a two-week period and tests were performed over 7 hr per day.

B. Absorbing Area

The rate of evaporation of water in the solar still is proportional to the surface area of absorption of water

[25]. The productivity increases with the increase in the exposure area of the water. This can be done by using jute cloth, wick, sponges, etc in the still basin. Sakthivel et al. [26] conducted experiments in a single slope solar still with jute cloth placed in a vertical position in the middle and attached to the sides of the wall on one side as shown in Fig. 1 Jute is a long, soft, shiny vegetable fibre that can be spun into coarse, strong threads. Jute cloth is one of the easily available natural fibres in India which can absorb water. It is 100% bio- degradable and thus environment-friendly.

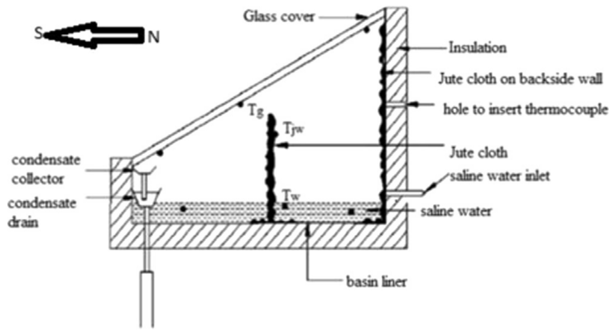

Fig. 1. Schematic diagram of a single slope solar still with vertical jute cloth [26]

The bottom edge of the jute cloth is dipped into the basin saline water. The presence of jute cloth increases the evaporation surface and also it can attain very high temperature since it has very low heat capacity. The effective area of the basin is 1 m x 0.5 m. The thickness of the still is 0.003 m. The glass cover was kept at an optimum angle of 251 with the horizontal. For lesser angles of inclination the condensing vapour may fall into the saline water. The condensed water flows down through the aluminium channel attached to the lower end of the glass cover. The condensate is collected and measured using a measurement jar. A hole is provided at the side of the still to feed the saline water and a tap is provided to drain the saline water. The thermocouples are provided at different points to measure the temperatures of the basin, water, jute cloth, air–vapour mixture, inner and outer surface of the glass cover and ambient temperature. Silicon rubber is used as a sealant to prevent any vapour leakages. The intensity of solar radiation is measured using solarimeter in the range of 1– 100 mW/cm^2. The capacity of the measuring jar used is 2 l to measure the hourly yield. The still is placed along the east–west direction and the glass cover faces south to intercept maximum intensity of solar radiation. Experiments were conducted in the conventional still and still with jute cloth simultaneously with different quantities of water from January to August 2006.

With 30 kg of saline water, the still yield with jute cloth was 4 kg/m^2 which are about 20% more than the conventional still yield. The maximum efficiency of the still with jute cloth was found as 52% whereas the efficiency of the conventional still was 44%. The efficiency of a solar still is defined as the amount of energy utilised in vaporising water in the still over the amount of incident solar energy on the still. The use of jute cloth in the still increased the area of absorption. Also any other cloth materials such as cotton can also be used in the still and comparative studies can be made.

The wick-basin type consists of two parts [19]. The first part is the tilted wick-type solar still and the second part is a conventional type still. The hot saline water from the wick type was fed to the conventional still through a pipe. The tilted wick type still had an evaporating area of 1 m^2 (1.4 m x 0.72 m) and covered with 4 mm thick glass cover. The material of the wick was blackened jute cloth. A storage tank was placed at a height of 1.5 m above the ground level. The water level was maintained constant with the use of a float valve. The wick type still was kept at an angle of 251 in summer and 451 in the winter to receive maximum solar radiation [19].

The second part is a conventional basin of area 0.8 m x 0.5 m. The cover material used was galvanised iron of 0.6 mm thick and inclined at 151 to the horizontal [19]. To prevent the combined still from direct solar radiation, a wooden sheet was set over the cover at a distance of 50 cm apart. The metallic cover was cooled with the use of a cooling system, which includes a thermally insulated reservoir with dimensions 100 cm x 25 cm x 6 cm, installed on the upper side of the still. A jute wick was used, the upper end of which was dipped into the reservoir to soak the water. The still was kept facing north to keep the metallic cover as cold as possible. This was done to enhance the condensation process.

The experimental results showed that the wick-basin type solar still has better productivity and economical than the wick-type and the basin-type conventional still. The wick-basin type could produce distillate of 85% more than the basin type and 43% more than the wick type still.

C. Cooling Of Cover

Water flow over the still cover at a very low rate has been shown to increase the still output and proper use of film-cooling parameters may increase efficiency by 20% [20]. The convective heat transfer coefficient also increases with wind velocity, leading to a decrease in the cover temperature and hence an increase in the overall yields [27]. El-Sebaii found that productivity increases with wind speed up to a certain value between 8 and 10 m/s for winter and summer conditions, respectively [28]. This value was independent of the still shape and brine heat capacity, and the wind was more effective in summer and for higher water masses. Similarly, Fath and Ghazy [29] reported that increasing the air flow rate up to 0.5 m^3/s increases productivity with no further improvement obtained with air flowing beyond this rate. It is reported that the daily distillate production is almost doubled for stills with water flowing over glass cover at a uniform velocity. On the other hand, Fath and Hosny [30] found that glass cover cooling by wet cloth for 1-, 2-, and 6-hr intervals had no effect on productivity and that continuous cooling is needed to release a significant amount of condensation energy. No effect on productivity was noted in their study for wind speed in the range of 0–5 m/s.

D. Slope of Cover and Geometry of Still

Several studies examined the effect of cover slope. For locations with latitude higher than 20°, single-sloped stills were found preferable whereas for lower latitudes, double-sloped stills facing north and south directions and having a cover inclination equal to the latitude angle received sun rays close to normal throughout the year [20].

The effects of using different shapes (Fig. 2) and having multi basins have also been studied. In multiple-effect basin stills, the floor of the upper compartment acts as the condensing surface of the lower compartment. As a result, efficiency is greater than that of a single-basin still typically by 35% or more but the cost and complexity are higher [31]. Table 2 summarizes the results of different studies conducted on cover slope and still geometry [20].

E. Temperature of Glass Cover

Several researches have demonstrated the significance of the water flowing over the glass cover of the still in the field of desalination. As shown in Fig. 2. [19], Arunkumar et al. [35] conducted experiments in a hemispherical solar still with and without the cooling water flowing on the glass cover. The experiments were done in the city of Coimbatore, Tamilnadu, India.

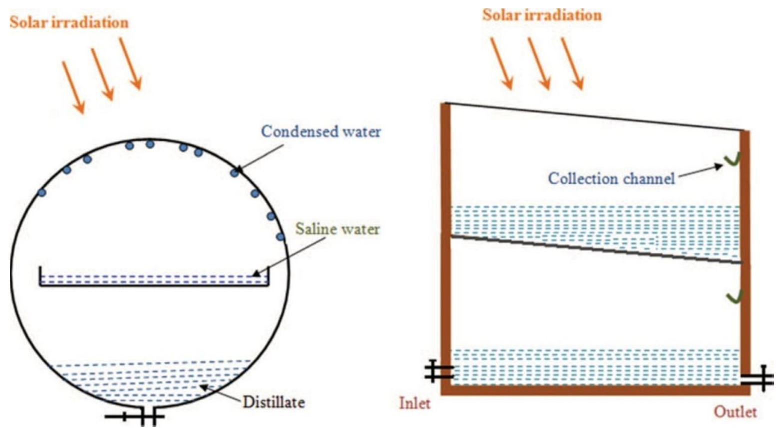

Fig. 2. Spherical solar still (left) and double-basin still (right) (Color figure available online).

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Table 2: Effect of still geometry

Scope of study	Main conclusions
Effect of multistages	{a)Maximum of 0.36 l/hr obtained for two stages Reverse wind direction reduces efficiency by 22% while forward wind direction increases efficiency by 6%.
	(b) (i) 0.8 L/hr for optimal conditions (ii) Triangular shaped multistage still have, 1.4–1.5 times more productivity than those that are rectangular.
Regenerative still	Similar to a double-effect still: 70% more productive than the conventional still
Vertical still	Low efficiency of 18.6–33.19% was attributed to high vapor and condensation heat leakage. Output ranged from 1.02 to 1.91 l/m2/day for an energy input of 13.14 to 13.68 MJ.
Effect of cover inclination	Annual yield is at its maximum when the condensing glass cover inclination is equal to the latitude of the place.
Effect of length and height	The change in length for a given height and width of a still does not affect the daily output but the change in the height of the north wall for a given height affects the daily output.
Effect of double basins	Double-basin solar stills give better performance than the single-basin still due to better utilization of latent heat of vaporization
Spherical still	30% more efficiency than the conventional still
Effect of cover slope	(a)Single-sloped stills give better yield in winter while double-slope stills are better in the summer
	(b)A double slope multiwick solar still is more economical and efficient than a simple one
	(c) Increasing the tilt angle from 5◦ to 25◦ increased the yield from 2.3 to 3.9 l/m2/day

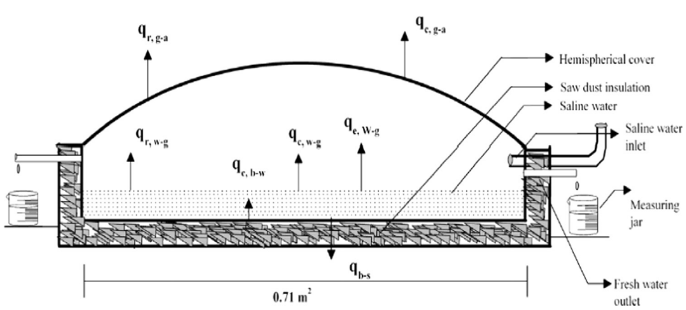

Fig. 3. Cross sectional view of a hemispherical solar still.

Saw dust was filled in the bottom of the basin to a height of 0.15m. Glass wool was insulated at the sides of the basin. The saw dust is less expensive, but its durability may be affected if it gets wet. Separate devices were designed and fabricated for injecting and collecting the flow water at the top surface of the cover. The temperatures were recorded using K-type thermocouples and digital temperature indicators. A precision pyranometer was used to measure the solar radiation. The important parameter of the solar distillation technique is the water–glass cover temperature. The conventional still had an efficiency of 34% whereas the still with cooling water system achieved an efficiency of 42% for a flow rate of 10 ml/min of feed water.

Zurigat et al. [36] conducted experiments in a solar still with two basins, with provision for cooling water to flow in and out of the second effect as shown in Fig. 4[19]. Due to this arrangement, the temperature difference between water and glass cover increased in the first effect and uses the latent heat of the condensate on the glass of the first effect to produce more fresh water in the second effect. The productivity of the regenerative still was 20% higher when compared to the conventional still. Also, if the wind speed was increased from 0 to 10 m/s, the productivity was increased by 50%.

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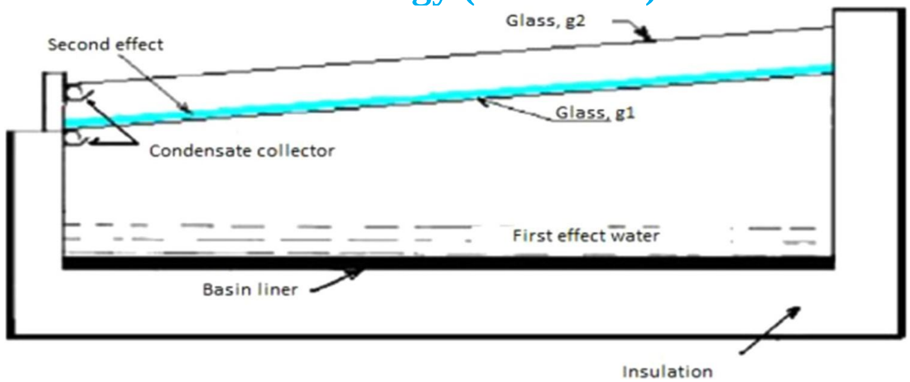

Fig. 4. Schematic diagram of a regenerative still

F. Inlet Water Temperature

Preheating the feed water to the solar still basin plays an important role in increasing the productivity of the still. Ragh Vendra Singh et al. [37] conducted experiments in a solar still with Evacuated Tube Collector (ETC). The feed water is preheated with the use of an ETC in natural mode as shown in Fig. 5 (a). Also, the effect of depth of water in the still basin on yield, energy and exergy efficiencies has been estimated. The system has been optimized to find the best combination between the size of the ETC and water depth in the still for increasing the productivity.

The ETC consists of a number of concentric borosilicate tubes which are inclined to 451 to the horizontal. The ETC was mounted over a diffuse reflector. The ETC tubes are filled with water and blackened on the outer surfaces to absorb maximum solar radiation. The tubes transfer the heat to the water inside. The heated water rises up due to low density and the cold water from the basin enters the ETC tubes due to gravity and high density. The flow rate of water depends upon the solar energy input, fluid temperature and the configuration of the collector. The complete set up was kept facing south to absorb maximum solar radiation. The natural circulation rate increases upto a maximum of 44 kg/h in an individual tube and the basin water temperature increases upto 80^oC. The productivity was 3.8 kg/m^2 for a basin water depth of 0.03 m. The variation of instant overall energy efficiency of the system was found to be in the range of 5.1–54.4% and the exergy efficiency in the range of 0.15–8.25% between 9.00 and 15.00 h. The exergy of a system is the maximum useful work possible during a process. The maximum daily energy and exergy efficiencies have been found to be 33% and 2.5% respectively. The productivity was higher with 10 evacuated tubes with water depth of 0.03 m in the basin. It was also found that the productivity does not increase proportionately with the increase in the size of the integrated ETC, due to high thermal losses.

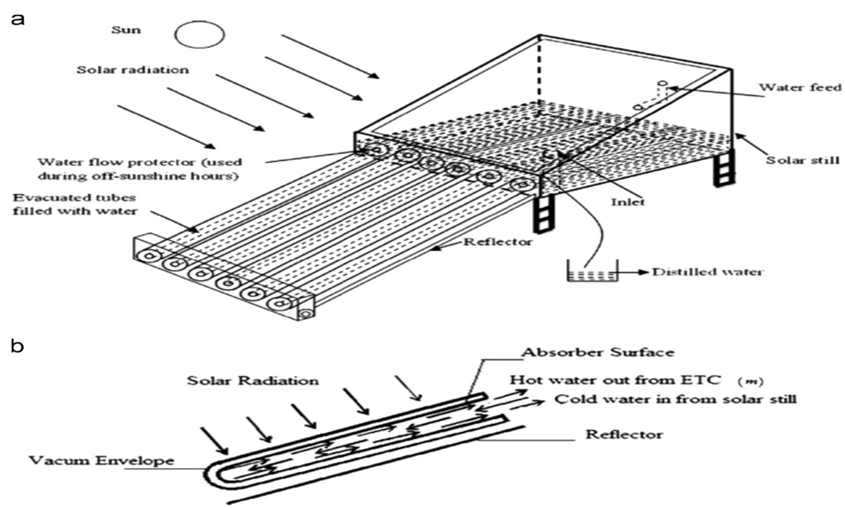

Fig. 5. (a) Schematic of the solar still with ETC. (b) Schematic of ETC with one tube [37].

G. Depth of Brine

Studies conducted on the effect of water depth in stills have shown that the highest outputs and efficiencies occur at lower depths [38]. It was observed that nocturnal distillation is significant in the case of higher water depths because of reduced ambient and stored energy. Relative humidity in the still is important particularly for large water depths and the internal convective heat transfer coefficient decreases with increasing water depth due to a decrease in water temperature. A summary of the effect of depth on productivity is shown in Table 3, which reveals a similar decreasing trend in productivity with increasing brine depth among these studies. Variations in this trend can be attributed to the particular site conditions and geographical location as well as to the type of still tested. Murugavel et al. [39] reported that for deep basins, water depth is inversely proportional to productivity during daylight but the reverse is true for overnight production.

TABLE 3: Effect of brine depth

Variation in brine depth	Type of still	Decrease in productivity (%)
2, 4, 8, 12, 16, and 18 cm	Single sloped, 30°	25%; the yield became constant for depths >10 cm
2–3.5 cm	Single sloped, 32°	26%
1.5-4 cm	1.4Single and double sloped	*9%*
3–6 cm	Single sloped, 15°	29%
2–30 cm	Double sloped	14%
3–6 cm	Double sloped, 15°	13.50%
2–7 cm	Single sloped, 32°	14%
2–5 cm	Single sloped, 8–13°	11%
1–10 cm	Single sloped, 10°	Increase by 34%
2–8 cm	Uninsulated double sloped	13.80%
1.25–30 cm	Double sloped	30%

H. Vacuum Technology

Al-Kharabsheh et al. [40] conducted experiments in a water distillation system using low grade solar heat. The system uses the gravity and atmospheric pressure to create a vacuum. The water evaporates at lower temperatures and pressure in the vacuum conditions. The set-up consists of an evaporator connected to the condenser. The vapour produced in the evaporator was condensed in the condenser and the distillate was collected. The productivity of the above system was 6.5 kg/m^2/ day and 3–4 kg/m^2/day for the conventional still.

Nassar et al. [41] conducted experiments in a solar desalination system working on the basis of evacuation. Concave mirror was used to concentrate the solar energy on the still. The still works under vacuum conditions (25 kPa absolute) to reduce the boiling point of the saline water. A condenser condenses the outlet vapour and the distillate was collected. The productivity of the still was found to be 20 l/m^2/day of the reflector compared to 5 kg/m^2/day for the conventional still. The results showed that the productivity of the still was about 303% compared with the other stills. The performance ratio was found as 900%. The vacuum pump in the still may be operated by means of photovoltaic system to provide potable water to the nearby villages.

III. CONCLUSION

The solar still remains to be the basic technique for the inexpensive production of water and is a low-tech method that can be easily adopted by local rural people. With the growing global oil crisis, the need for alter- natives to conventional desalination plants based on fossil fuels grows. The use of solar stills has so far been restricted to small-scale systems due to their relatively low thermal efficiency and production rate compared with the large areas required. They tend to be competitive, however, with other renewable-desalination technologies in small-scale production due to their relatively low cost and simplicity. As presented in this review, the effect of absorber material and absorber area, cooling of cover, temperature of glass cover, inlet water temperature, slope of cover as well as still geometry and brine depth have significant impacts on yield and efficiency. These factors should therefore be taken into account in novel designs. Promoting solar distillation further requires focusing research efforts on improving existing technology to lower costs and developing more compact installations that reduce land use. The use of solar panels, collectors, ponds, condensers, and other productivity-enhancing devices requires considerable space and thus developing more compact systems with low cost is a main challenge. The following key points can be noted to improve productivity of solar still:

Maintaining minimum water depth in the basin increases the productivity of the solar stills. The increase in the depth of water decreases the still productivity.

The use of use of water absorbing materials like jute cloth, wick and charcoal cloth increases the area of absorption and thereby increases the productivity of the stills. The use of finned plate, corrugated plate and floating thermocol insulation in the still basin also increases the performance of the solar stills.

The water–glass cover temperature difference should be increased to increase the performance of the solar stills. The glass cover can be cooled by flowing water over the glass cover at an optimum flow rate.

The inlet water may be preheated to increase the productivity of the solar stills. The evaporation and condensation rate for preheated water is more compared to the ordinary water. The water may be preheated by integrating the still with a flat plate collector, solar pond and heat pipe.

Maintaining vacuum conditions in the still improve the productivity.

The performance of the still with double basin is comparatively high than the single basin stills.

The use of hemispherical plastic cover, reflectors and condensers and other types such as weir type stills, stills with humidification–dehumidification process, multi-effect distilla- tion can improve the productivity.

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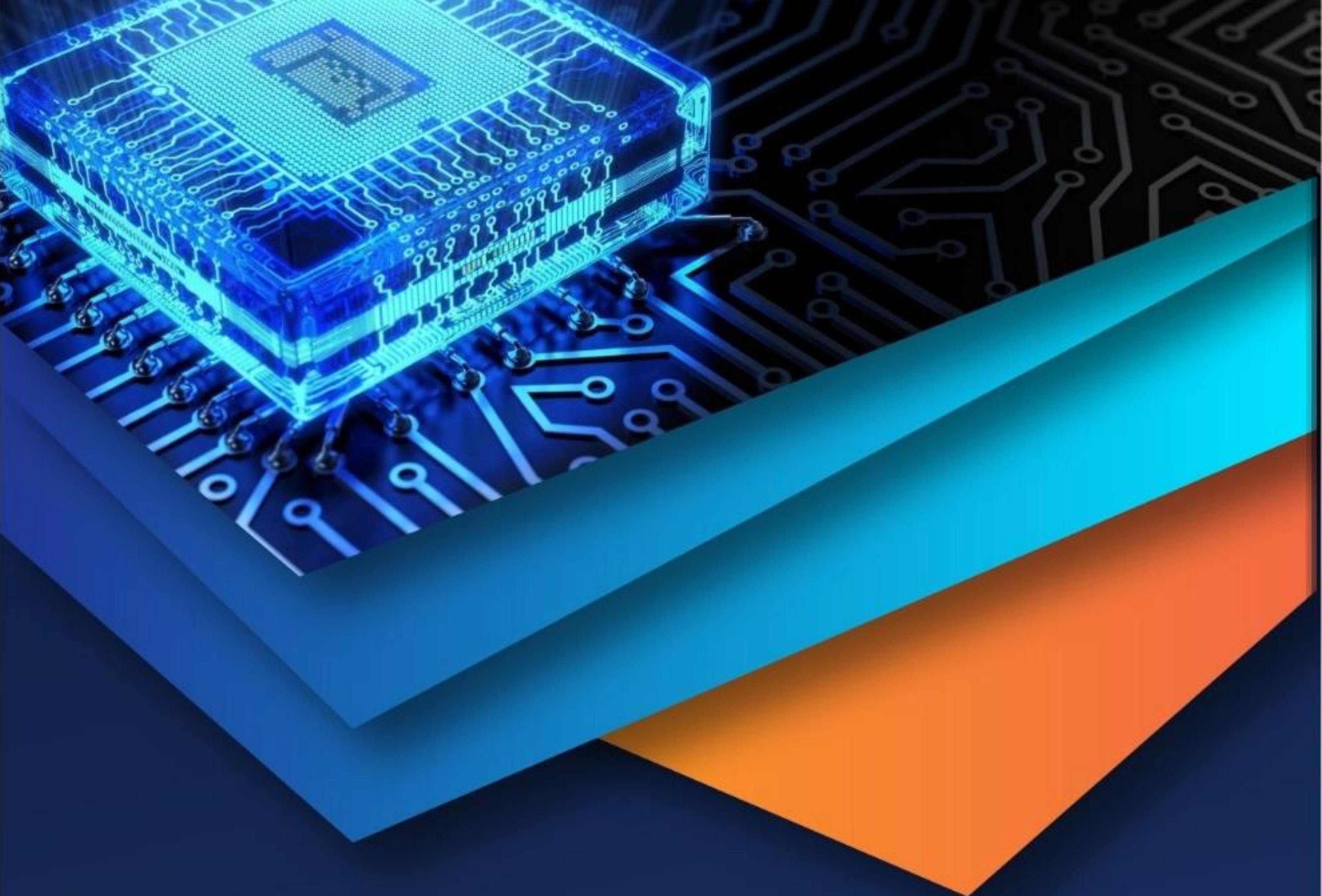

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