Ultra Engineer Vol. **4**(1 & 2), 07-15 (2016)

A Review on Advanced Designs of Solar Desalination Systems

BHAVIK BHALARA[1], RAJIV VARSHNEY[2] and ARUN KUMAR YADAV[3]

[1]M.E Scholar, Radharaman Institute of Technology and Science, Bhopal, India.
[2]Associate Prof, Radharaman Group of Institutes, Bhopal, India.
[3]Asst. Prof, Radharaman Institute of Technology and Science, Bhopal, India.

(Received: May 06, 2016; Accepted: June 21, 2016)

ABSTRACT

One of the prime difficulties of human society is the availability of fresh water for drinking and other industrial and day to day purposes. Solar still is one of the economical methods for converting saline, brackish water into fresh water using the sun energy which is freely and readily available. The chief design parameters influencing the productivity of solar stills are glass inclination, area of absorber plate, area of free surface of water and depth of water.The present article aims to describe different types of solar stills, their specification, advantages, disadvantages, applications and innovations in the field of desalination. Also, the different CFD analyses done by various reseerachers on solar still are discussed. The energy, exergy analysis and cost analyses done by various authors are also reported in the article.

Keywords: Solar Desalination system, CFD analyses, energy.

INTRODUCTION

The increase in population, industrialization and agriculture development in rural areas are creating an imbalance between demand of drinking water and supply of fresh water[1]. The solar desalination systems have low maintenance and operating cost and are compatible with the environment in spiteof high investment[2]. It is estimated that about 6.3 billion people are living on earth in which 400 million people are at living in water scarce areas, and the people who are living in water shortage areas could increase to four billion by mid-century[3]. Solar still is extensively used for desalination in small scale. Its manufacturing is quite simple, can be constructed by locally available materials and people. Skilled persons are not required for its operation; it has low maintenance but has a low productivity[4]. It is estimated that about 97% of available water sources are saline and/or consist of harmful bacteria and 2% are frozen in glaciers and polar ice caps. Therefore, only 1% of the world's water can be used for drinking and domestic purposes[5]. Solar desalination systems are helpful to find out a solution in remote areas for drinking water problems. Potable water is produced by solar basin stills as they are very simple[6]. Three-fourths of the surface of the earth is covered by water which is considered as one of the important elements for lifeon earth[7]. As the demand for fresh water in arid countries raised after World War II the regular use of desalination technologies got started[8]. Broadly, desalination technologies are classified into two categories namely, evaporative thermal desalination technologies and membrane distillation technologies. Evaporative thermal desalination involves a process in which the pure water is obtained through phase change by supplying heat to the saline water. It incorporates alternate cycles of evaporation and condensation. In membrane distillation technology, the salts are separated from saline water solution with the help of pressure driven membranes and fresh water is obtained without any phase change[9]. Many authors gave a review on various designs of solar stills. For example, Kaviti et al. studied various designs of solar still to maintain the minimum depth of water using steps, wicks in the stills to increase the productivity. Efforts were made to analyses the present scenario of different designs which were used to improve the productivity of inclined solar stills[10].

The detailed descriptions of various new innovations in solar still are described in following section.

Different types of solar still

Basin type of Solar still

(Single-sloped, Double-sloped)

Ayoub and Malaeb modified a solar still by introducing a slowly-rotating hollow cylinder which remarkably increases the evaporative surface area. This modification gave 200 to 300% increase in distillate. Unit production cost estimates ranges between 6 and 60 $/m3 depending on water output, discount rates, service lifetime and initial capital cost. These projections were within documented cost ranges for renewable-based technologies. To find the system's feasibility in real market value, different aspects that introduced environmental degradation costs and carbon-trading schemes for fuel-based desalination were performed. Costs reported for fuel-based brackish water and seawater desalination were accommodated to incorporate unaccounted costs related to environmental harm. This analysis further justify the economic feasibility of the modified solar still[13].

Double Condensing Chamber type of Solar still

Ayoub and Malaeb modified a solar still by introducing a slowly-rotating hollow cylinder which remarkably increases the evaporative surface area. This modification gave 200 to 300% increase in distillate. Unit production cost estimates ranges between 6 and 60 $/m^3$ depending on water output, discount rates, service lifetime and initial capital cost. These projections were within documented cost ranges for renewable-based technologies. To find the system's feasibility in real market value, different aspects that introduced environmental degradation costs and carbon-trading schemes for fuel-based desalination were performed. Costs reported for fuel-based brackish water and seawater desalination were accommodated to incorporate unaccounted costs related to environmental harm. This analysis further justify the economic feasibility of the modified solar still[13].

Vertical type of Solar still

Tanaka constructed vertical multiple-effect diffusion solar still which included a series of closely spaced parallel and vertical partitions which were in contact with saline-soaked wicks, coupled with a flat plate reflector and a glass cover and analysed in outdoor experiments at Fukuoka, Japan. To increase distillate productivity the vertical partitions were given on it to reduce the diffusion gaps between partitions. The overall daily productivity of the solar still with 6- effect and 5 mm diffusion gaps was 13.3 kg/m^2 day at maximum when the global solar radiation on a horizontal surface was 13.4 to 15.7 MJ/m^2 day and radiation on the glass cover was 20.2 to 22.9 MJ/m2 day. The solar stills productivity would be higher than or approximately equal to other types of multiple-effect diffusion stills[14].

Conical type of Solar still

Gad et al. estimated the heat transfer coefficients of a conical solar still. The increase in productivity was done by decreasing the shadow effect. Faculty of Engineering Sheben El-Kom, Egypt, designed and manufactured the conical solar still. The still base area was 0.8 m2, and the acrylic cover of still was inclined at 31 which was equal to the city latitude. The experimental results of conical solar stills were compared with a conventional type solar still. The daily productivity for conventional and conical solar stills was 1.93 and 3.38 L/m2 day, respectively. Evaluation of heat and mass transfer coefficients were done and Nusselt and Sherwood numbers were calculated with the help of evaporation measurements and Chilton–Colburn analogy. Maximum value of the total heat transfer coefficient were 66 and 32 W/m2 C for conical and conventional solar stills, respectively[15].

Inverted Absorber type of Solar still

Dev and Tiwari designed an inverted absorber solar still which was a box type in order to heat the basin from both top and bottom sides by the help of a curved reflector. Due of this, the high water temperature was obtained in this still in comparison to that of the single slope solar still. Linear and non-linear characteristic equations were developed based on derived analytical expressions of instantaneous gain and loss efficiencies using experimental data for the climatic condition of Muscat, Oman. The results showed the behaviour of the inverted absorber solar still which was non-linear. These results were also compared with the obtained characteristic equations of the single slope solar still under similar operating and climatic conditions. The annual costs of distilled water per kg-m2 was found to be Rs. 0.95/- and Rs. 0.54/ for inverted absorber solar still and Single Slope, respectively[16].

Wahab and Al-Hatmi studied an inverted solar still which was integrated with a refrigeration cycle at different water depth and feeding saline water temperatures. Many experiments were performed under the climatic conditions of Muscat, Sultanate of Oman in the month of July. When the feed saline water temperature was 35°C, it was found that the daily output obtained was 6670, 4940 and 3930 ml/day at water depths 8, 6 and 4 cm, respectively. When feed saline water temperature was 30°C, the daily produced distilled water was 9500, 10080 and 6400 ml/day at water depths 8, 6 and 4 cm, respectively. For refrigerated inverted solar still, it was observed that higher daily production of fresh water as compared to the conventional inverted solar still. By increasing water depth the daily production of refrigerated inverted solar still was found to be increased in comparison to the conventional inverted solar still where an opposite action was reported[17].

Wick type of Solar still (Tilted, Multiple)

Omara et al. gave a new hybrid desalination system consisting of evacuated solar water heater, jute geotextile and solar still. An evacuated solar water heater was combined with the desalination stills to evaluate the continuous productivity. Two same portable solar wick and one basin solar stills were designed to augment the systems performance. Jute linen woven fabrics were stitched to the plane wick and combined with solar still. The jute fabrics were used to decrease the rate of water flow to a proper rate. Theoretical analysis was verified through experiments. Water productivity was increased by 114% over conventional still for double layer square wick solar still at 30° base slope angle. The daily average efficiency of double layer square wick solar still was 71.5%. During experimentation, the output was increased by 215% when hot brackish water was fed during night time[6].

Mosleh et al. utilized a combination of a twin-glass evacuated tube collector and heat pipe with a parabolic trough collector. The results showed that, rate of production and efficiency can reach to 0.27 kg/m2 h and 22.1% when aluminum conducting foils were used in the space between the heat pipe and the twin-glass evacuated tube collector. When oil was used as a medium for the heat transfer, an increase in output and efficiency was found to be 0.933 kg/(m2 h) and 65.2%, respectively[18].

Multiple-effect type of Solar still (Diffusion)

Huang et al. developed a novel solar still with spiral-shape multiple-effect diffusion unit. The test results of a 14-effect unit coupled with vacuum-tube solar collector showed that the highest daily fresh water output was 40.6 kg. The measured highest distillate depending on the area of glass cover, solar absorber, and evaporating surface was 34.7, 40.6, and 7.96 kgm^{-2} d^{-1}, respectively. The measured solar distillation efficiency was 2.0–3.5. The performance improvement was primarily due to the lateral diffusion process in the spiraled still cell. The vapor flow generated by heat input was able to flow freely and laterally through the spiral channel when solar heat input was high. Heat and mass transfer at the outer cell increased due to the larger area of evaporation and condensation at the outer cell[19].

Chong et al. developed a multiple-effect diffusion solar still with a bended-plate design in multiple effect diffusion units (MDU) to solve the peel-off problem of wick material. The MDU was coupled with a vacuum tube solar collector so that for high productivity it could produce a high temperature gradient. A heat pipe was used to transfer the solar heat to the MDU. A model of MEDS-1L was built and tested outdoors. Four performance indexes were made for the performance evaluation of MEDS, which included daily pure water production per unit area of glass cover, evaporating surface, solar absorber and solar distillation efficiency. The outdoor test results of MEDS-1L showed that the solar collector supply temperature reaches 100°C at solar radiation 800 W m^{-2}[20].

Inclined weir type of Solar still

Tabrizi et al. designed a cascade solar still for water purification. They studied the effect of water flow rate on the internal heat and mass transfer and daily productivity of cascade solar still. Dunkle's relation was used to predict the still behaviour, but it was unable to satisfy the cascade solar still behaviour due to the complex geometry and operational conditions. Hence, the internal heat and mass transfer coefficients were determined using the experimental data obtained. The results showed a decrease in the daily output as well as internal heat and mass transfer rates with water flow rate increment. The daily productivity for minimum and maximum flow rates was found to be 7.4 and 4.3 kg/m2day respectively[31].

Hansen et al. experimentally evaluated the performance of an inclined type solar still using different wick materials on different absorber plate configurations. The new materials were characterised for absorption, porosity, capillary rise, heat transfer co-efficient and water repellence to choose an appropriate material for the solar still. Water coral fleece material with porosity (69.67%), absorbency (2 s), capillary rise (10 mm/h) and heat transfer coefficient (34.21W/m2°C) was found to be the most suitable wicking material for higher productive solar still. Performances of the still were evaluated with different wick on the various absorber plate configurations. Maximum productivity of the still was 4.28 l/day using water coral fleece with weir mesh–stepped absorber plate[21].

Hybrid type of Solar still

Kumar and Tiwari fabricated and investigated the performance of two solar stills (single slope passive and single slope photovoltaic/thermal (PV/T) active solar still) at solar energy park, IIT New Delhi (India) for composite climate. Photovoltaic operated DC water pump was re-circulate the water through the collectors and transfer it to the solar still. The designed hybrid (PV/T) active solar still was self-sustainable and can be used in remote areas. Experiments were performed for 0.05, 0.10, and 0.15 m water depth, round the year 2006–2007 for both the stills. It was observed that maximum productivity of 2.26 kg and 7.22 kg were obtained from passive and hybrid active solar still, respectively at 0.05 m water depth. The daily output from hybrid active solar still was around 3.2 and 5.5 times higher than the passive solar still in summer and winter month, respectively. The design of the hybrid active solar still also provides higher electrical and overall thermal efficiency, which was approximately 20% higher than the passive solar still[22].

Kumar et al.developed simple empirical relation to estimate the glass cover temperature for water and ambient temperatures in basin type hybrid (PV/T) active solar still. The empirical relation developed was based on outdoor experimental results of water and ambient temperature in the range of 14°C to 92°C, and 14°C to 36°C, respectively. The results obtained for glass cover temperature were validated with the experimental as well as using a numerical results of solar still. The proposed glass cover temperature was obtained with a maximum relative error of 1.12% compared to the value obtained through a numerical solution. The maximum relative error in evaporative mode of energy transfers from water surface was 1.2%[23].

Various types of solar still according to their design

Hemispherical type of Solar still

Arunkumar et al.developed a new design of solar still with a hemispherical top cover for water desalination with and without flowing water over the cover. The productivity of the system was enhanced by decreasing the temperature of the cover by flowing water over it. The performance of this new still was observed in Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore (11°North, 77° East), India. The efficiency was increased from 34% to 42% with the top cover cooling effect. Daily variations of water temperature, cover temperature, air temperature, ambient temperature and distillate output[24].

Tubular typeof Solar still

Chen et al. fabricated a solar-powered or residual heat-powered three-effect tubular solar still to analyze the characteristics of heat and mass transfer and parameters of water production by desalination and studied a normal-pressure and fixed-temperature heating in and fixed-power heating. The experimental results showed that there exists a direct-proportion linear relationship between the temperature and water production by desalination at normal pressure, that at negative pressure, the water production is many times, increasing with the decrease of interior pressure, and reaching as high as 1.12 kg/h when the temperature is at 80 °C and the interior pressure is close to the saturation vapor pressure of 50 kPa at the first level. The water yield by desalination increases as the heating power (b300 W) increases, the optimal heating power is 300 W and its corresponding performance ratio has the highest value of 1.3[25].

Zeng et al. designed and fabricated a group of multi-effect tubular desalination devices which are driven by solar or waste energy. The performances of the devices were individually tested and analyzed under the conditions of fixed heating power and controlled heating temperature. The experimental results indicated that the performance ratio of the two-effect and the three-effect devices working under environmental pressure reached about 1.4 and 1.7 respectively under conditions of fixed heating power. The yield of the devices under negative pressure was improved. When the fixed heating power was 300 W, the yield reached about 20.08 kg/(m2•d). The results indicate that the devices have excellent application prospects[26].

"V" type of Solar still

Suneesh et al. presented a "V" type solar still with a Cotton Gauze Top Cover Cooling (CGTCC) with and without air flow over the glass cover. Water flowing over glass cover was unevenly distributed over the width of the glass cover. A new method of water distribution was presented for increased distillate output. The performance of this still was analysed in Tamilnadu, India climatic conditions. The daily output with no CGTCC (water flowing over bare glass) was 3300 ml/m2. Using CGTCC the daily productivity increased to 4300 ml/m2, and with CGTCC and air flow, it further increased to 4600 ml/m2. The CGTCC without air flow was found to be more cost-effective than the basic still[27].

Multi-effect active type of Solar still

Huang et al. designed a solar still with spiral-shape multiple-effect diffusion unit. The test results of a 14-effect unit coupled with vacuum-tube solar collector (absorber area 1.08m2) show that the highest pure water production was 40.6 kg d^{-1}. The daily highest productivity based on the area of glass cover, solar absorber, and evaporating surface was 34.7, 40.6, and 7.96 kgm^{-2}, respectively, which were much higher than the published results. The solar distillation efficiency was found to be 2.0–3.5. The performance improvement was mainly due to the lateral diffusion process in the spiraled still cell. When solar heat input is high, the vapour flow generated by heat input can flow freely and laterally through the spiral channel down to the end. Moreover, the larger evaporating and condensing area at the outer cell increase heat and mass transfer at the outer cell[19].

Tanaka fabricated and tested a vertical multiple-effect diffusion solar still, consisting of a glass cover and a series of closely spaced vertical and parallel partitions in contact with saline-soaked wicks, coupled with a flat plate reflector in outdoor experiments at Fukuoka, Japan. The vertical partitions reduce the diffusion gaps between partitions and increase distillate productivity. The overall daily output of the still with 6- effect and 5 mm diffusion gaps was about 13.3 kg/m2 and maximum when the global solar radiation on a horizontal surface was 13.4 to 15.7 MJ/m2 day and radiation on the glass cover was 20.2 to 22.9 MJ/m2 day. The productivity of the still was greater than or approximately equivalent to other types of multiple-effect diffusion still[14].

Various mathematical models of solar stills

Rahbar et al. analysed the 2-D CFD simulation in computation of heat and mass transfer in a tubular solar still. There was acceptable agreement between the results of CFD simulation and experimental data as reported in the literature. CFD simulation indicates a recirculating zone with a clockwise direction inside the enclosure. The most condensation was observed on the upper side of the glass cover. New relations were proposed to estimate water productivity, heat and mass transfer coefficients in the tubular solar still and characteristic curves were suggested to estimate water-productivity in different operational conditions. The results of curves showed direct effect of water temperature and inverse effect of glass temperature on the performance of a tubular solar still[28].

Ibrahim and Elshamarka fabricated and tested a modified basin type solar still equipped with an air-cooled condenser. The system was operated at reduced pressure in batch-wise mode. Performance was observed to be better for the modified still as compared to the conventional one. Moreover, the system was simulated using a mathematical model and solved numerically using MATLAB. The developed model is validated against experimental results. The parametric study using the validated model is carried out to find the better performance of the constructed system[29].

Parameters affecting the Performance of solar still

There are different performance parameters for various designs of solar still. Forgetting a basic idea of thermal efficiency, exergy analysis, energy analysis, heat transfer analysis, performance evaluation; for a generalized system are discussed in this section. These parameters are used for prediction of performance and productivity of single slope solar still using different operational parameter[30].

Losses due to Heat transfer[30]

Losses due to heat inside the still[30]

- Radiative heat loss
- Convective heat loss
- Evaporative heat loss

Losses due to heat outside the still[30]

- Top losses
- Bottom and side losses

Losses due to heat inside the still[30]

Radiation loss coefficient

There are differences in temperature between any two bodies and a radiation heat transfer will occur between them. So the water surface and glass cover are considered as infinite parallel planes. Radiation between the water and the glass is given by[30]:

$$q_{rw} = h_{rw}\left[T_{g}-T_{a}\right] = 0.96\sigma(T_w^4 - T_g^4)$$

Where h_{rw} may be obtained from the equation:

$$h_{rw} = \varepsilon_{eff}\,\sigma[\{T_w^2 + T_g^2\}(T_w + T_g)]$$

Convective loss coefficient

Convection occurs across the humid air in the enclosure by free convection, due to the temperature difference of humid air between the water surface and the glass cover. It can be defined by the equation[30]:

$$Q_{cw} = h_{ew}\left(T_w - T_g\right)$$

Evaporationlosscoefficient

Due to condensation of the rising vapour on the glass cover, there are heat loss by evaporation between the water surface and the glass cover. It can be shown by the following equation[30]:

$$q_{ew} = h_{ew}\left(T_w - T_g\right)$$

Losses due to heat outside the still

The energybalance for the different components of the still is[30]:

(A) Glass cover

$$\alpha_g I + [q_{rw} + q_{cw} + q_{ew}] = [q_{rg} + q_{cg}]$$

(B) Basin bottom (basin liner)

$$\alpha_b I = q_b + \left[q_{bg} + q_s(A_s/A_{ss})\right]$$

(C) Water mass

$$\alpha_w I + q_b = (mc)_w\{dt_w/dt\} + \{q_{rw} + q_{cw} + q_{ew}\}$$

Top loss coefficient

Due to the minor thickness of the glass cover,uniformity of the glass temperature may be assumed. The expression of external radiation and convection Losses from the glass cover to outer atmosphere can be written as[30]:

$$q_g = q_{rg} + q_{cg}$$

$$q_{rg} = h_{rg}\left[T_g - T_a\right]$$

$$q_{cg} = h_{cg}\left[T_g - T_a\right]$$

$$h_{rg} = \frac{\varepsilon g\sigma[T_{g4} - T_{sky4}]}{T_g - T_a}$$

Where,

$$T_{sky} = T_a - 6$$

Substituting q_{cg} and q_{rg}

$$q_g = h_{1g}[T_g - T_a]$$

Where h_{1g} is theconvectionandradiation heat transfer coefficient fromglassto the ambient air

$$h_{1g} = h_{rg} + h_{cg}$$

$$h_{1g} = 5.7 + 3.8V$$

Sides and Bottom loss coefficient: Heat is also lost or transferred from the water in the basin to the ambient through the insulation and by radiation, convection and conduction from the bottom or side surface of the basin. Hence the bottom loss coefficient U_b can be written as:

$$U_b = \frac{1}{[1/h_w + 1/(K_i/L_i) + 1/(h_{rb} + h_{cb})]}$$

$$h_b = \frac{1}{[1/(K_i/L_i) + 1/(h_{rb} + h_{cb})]}$$

Analysis ofExergy

Exergy efficiency of a passive solar still can be calculated By the following formula[30]:

$$\eta(ex) = \frac{Ex(evaporation\ )}{Ex(in)} \times 100$$

Where

$$\text{Ex(evaporation}=\sum_{i=1}^{24}\left(1-\frac{T_a}{T_w}\right)\times q_{ew};$$

$$q_{ew} = A \cdot h_{ew} \cdot (T_w - T_g)$$

$$\text{Ex(in)=Ex(sun)} = A_s x I_g x[1\text{-}(4/3)\ (T_a/T_s) + (1/3)\ (T_a/T_s)^4]$$

Analysis of Energy

Theoretical and system efficiency of solar still can be evaluated by performing simple energy analysis[30].

P_w = Partial pressure of vapour at water surface

$$= \exp\left(25.31 - \frac{5144}{T_w + 273}\right)$$

P_g=Partial pressure of vapour at glass surface

$$= \exp\left(25.31 - \frac{5144}{T_g + 273}\right)$$

h_{ew}=Convective heat transfer coefficient from cover to atmosphere, W/m^2/°C

$$= 0.884\left[\left(T_w - T_g\right) + \left\{\frac{(P_w - P_g)(T_w)}{(268{,}900 - P_w)}\right\}\right]^{(1/3)}$$

h_{ew}= Evaporative heat transfer coefficient from water to cover, W/m^2/°C

$$= 16.273 \times 10^{-3} h_{ew}\left[\frac{(P_w - P_g)}{(T_w - T_g)}\right]$$

Evaporative Heat transfer coefficient

$$q_{ew} = h_{ew}\left(T_w - T_g\right)$$

Yield of solar desalination system

$$mw = \left(\frac{q_{ew}}{L}\right) \times 3600$$

Theoretical efficiency of solar desalination system

$$\eta_{th} = \{q_{ew}/I_g\}$$

System efficiency of solar desalination system

$$\eta_s = \left(\frac{Actual\ amount\ of\ pure\ water}{Theoritical\ amount\ of\ water}\right)$$

I_g=Total solar radiation, W/m2 and L= latent heat of vaporization, J/kg; 2256 KJ/Kg.

Different cost saving analysis of various designs for solar still

To provide a small scale of potable water needed in remote isolated locations a solar still was designed and its objective was to maintain the minimum cost. To determine the total cost of fabricated still following method can be adopted[30].

Estimated price of solar still

For obtaining the average value of the cost of distillateoutputitis assumed: n is the expected still lifetime, V is the variable cost, C is the totalcost [30]:

C=F+V

Investment return period of solar still

The payback period of the solar still depends on overall cost of feed water operating cost, maintenance cost, and fabrication. The cost of feed water is negligible [30].

Overall fabrication cost to be considered=C.
Cost per liter of distilled water= C_w.
Productivity of the solar still(l/m^2/day)=m.
Cost of water produced per day= C_w×m.
Maintenancecost/day=M
Net earnings= Cost of water produced-maintainance cost
Payback period= Investment/Net earnings.

Water cost per liter

The cost of one liter of water from conventional still can be evaluated based on yearly productivity. Cost per liter of solar distillation process is obtained based on the following formulae[30].

Cost per liter of solar still is obtained based on the following formulae.
Average daily productivity= m.
Yearly productivity = m × operating days.
Cost per liter=(Total cost (C))/(yearly productivity).
Operating day may assume as 300 sunny days in a year.

CONCLUSION

From the above survey it can be concluded that there has been ample work done on improving the performance of the solar stills at small and large scale as well. Different researchers have modified the still in various ways according to the geographical conditions. Researchers have enhanced the output using wicks, fins, baffle plate, pebble and sponges etc. Moreover, by adding additional basin, using external and internal reflectors, introducing a slowly-rotating hollow cylinder, including closely spaced parallel and vertical partitions, inverted absorber, evacuated solar water heater, twin-glass evacuated tube collector and heat pipeand spiral-shape multiple-effect diffusion unit the performance was improved. The change in geometry of traditional solar still with conical solar still, hemispherical top cover, tubular solar still were also carried out by the researchers. Further, various new empirical relations were developed for the new designs and CFD analyses were also done. The energy, exergy analysis and cost analyses done by various authors are also reported in the article

REFERENCES

1. El-Zahaby A.M, Kabeel A, Bakry A.I, El-agouz S, Hawam O.M, “Augmentation of solar still performance using flash evaporation”, *Desalination* **257** (2010) pp. 58–65.
2. Ziabari Fatemeh Bakhtiari, Sharak Ashkan Zolfaghari, Moghadam Hamid, Tabrizi Farshad Farshchi, “Theoretical and experimental study of cascade solar stills”, *Solar Energy* **90;** pp. 205–211 (2013).
3. http://www.ceemeng.mit.edu/Stevens.pdf.
4. Velmurugan V, Pandiarajan S, Guruparan P, Subramanian L. Harihara, Prabaharan C. David, Srithar K, “Integrated performance of stepped and single basin solar stills with mini solar pond”, *Desalination* **249**; pp. 902–909 (2009).
5. Velmurugan V, Gopalakrishnan M, Raghu R, Srithar K, “Single basin solar still with fin for enhancing productivity”, *Energy Conversion and Management* **49**; pp 2602–2608 (2008).
6. Omara Z.M, Eltawil Mohamed A, ElNashar ElSayed A, “A new hybrid desalination system using wicks/solar still and evacuated solar water heater”, *Desalination* **325**; pp. 56–64 (2013).
7. Sampath kumar K., Arjunan T.V., P., Senthilkumar P., “Active solar distillation — A detailed review”, *Renew. Sustainable Energy Rev.* **14**; 1503–1526 (2010).
8. Kabeel A.E, Hamed A.M, S.A. El-Agouz, “Cost analysis of different solar still configurations”, *Energy* **35**; pp. 2901-2908 (2010) .
9. Kumar Vishwanath. P, Kumar Anil, Prakash Om, Kaviti AjayKumar, “Solar stills system design: A review”, *Renewable and Sustainable Energy Reviews* **51;** pp 153–181 (2015).
10. Kaviti Ajay Kumar, Yadav Akhilesh, Shukla Amit, “Inclined solar still designs: A review”, *Renewable and Sustainable Energy Reviews* **54**; pp 429–451 (2016).
11. Rajaseenivasan T, Murugavel K. Kalidasa, “Theoretical and experimental investigation on double basin double slope solar still”, *Desalination* **319**; pp. 25–32 (2013).
12. Tanaka Hiroshi, “Monthly optimum inclination of glass cover and external reflector of a basin type solar still with internal and external reflector”, *Solar Energy* **84;** pp 1959–1966 (2010).
13. Ayoub George M, Malaeb Lilian, “Economic feasibility of a solar still desalination system with enhanced productivity”, *Desalination* **335**; pp 27–32 (2014).

14. Tanaka Hiroshi, “Experimental study of vertical multiple-effect diffusion solar still coupled with a flat plate reflector”, *Desalination* **249**; pp 34–40 (2009).
15. Gad H.E, El-Din Sh. Shams, Hussein. A.A, Ramzy Kh, “Thermal analysis of a conical solar still performance: An experimental Study”, *Solar Energy* **122**; pp 900–909 (2015).
16. Dev Rahul, Tiwari G.N, “Characteristic equation of the inverted absorber solar still”, *Desalination* **269**; pp 67–77 (2011).
17. Wahab-Abdul Sabah A, Al-Hatmi Yousuf Y, “Study of the Performance of the Inverted Solar Still Integrated with a Refrigeration Cycle”, *Procedia Engineering* **33;** pp 424 – 434 (2012).
18. Mosleh H. Jafari, Mamouri S. Jahangiri, Shafii M.B., Sima A. Hakim,” A new desalination system using a combination of heat pipe, evacuated tube and parabolic trough collector”, *Energy Conversion and Management*, **99** pp. 141–150 (2015) .
19. Huang Bin-Juine, Chong Tze-Ling, Wu Po-Hsien, Dai Han-Yi, Kao Yeong-Chuan, “Spiral multiple-effect diffusion solar still coupled with vacuum-tube collector and heat pipe”, *Desalination* **362**; pp. 74–83 (2015).
20. Chong Tze-Ling, Huang Bin-Juine, Wu Po-Hsien, Kao Yeong-Chuan, “Multiple-effect diffusion solar still coupled with a vacuum-tube collector and heat pipe”, *Desalination* **347**; pp. 66–76 (2014).
21. Hansen R. Samuel, Narayanan C. Surya, Murugavel K. Kalidasa, “Performance analysis on inclined solar still with different new wick Materials and wire mesh”, *Desalination* **358**; pp 1–8 (2015).
22. Kumar Shiv, Tiwari Arvind, “Design, fabrication and performance of a hybrid photovoltaic/ thermal (PV/T) active solar still”, *Energy Conversion and Management* **51**; pp 1219–1229 (2010).
23. Kumar Shiv, Tiwari G.N, Gaur M.K, “Development of empirical relation to evaluate the heat transfer coefficients and fractional energy in basin type hybrid (PV/T) active solar still”, *Desalination* **250;** pp 214–221 (2010).
24. Arunkumar T, Jayaprakash. R, Denkenberger. D, Ahsan Amimul, Okundamiya M.S, Kumar Sanjay, Tanaka Hiroshi, Aybar. H.S, “An experimental study on a hemispherical solar still”, *Desalination* **286**; pp 342–348 (2012).
25. Chen Zhili, Yao Yang, Zheng Zihang, Zheng Hongfei, Yang Yi, Hou Li'an, Chen Guanyi, “Analysis of the characteristics of heat and mass transfer of a three-effect tubular solar still and experimental research”, *Desalination* **330,** pp 42–48 (2013) .
26. Zheng Hongfei, Chang Zehui, Chen Zhili, Xie Guo, Wang Haijiang, “Experimental investigation and performance analysis on a group of multi-effect tubular solar desalination devices”, *Desalination* **311**; 62–68 (2013).
27. Suneesh. P.U, Jayaprakash. R, Arunkumar. T, Denkenberger. D, “Effect of air flow on “V” type solar still with cotton gauze cooling”, *Desalination* **337**; pp 1–5 (2014).
28. Rahbar Nader, Esfahani Javad Abolfazli, Fotouhi-Bafghi Ehsan, “Estimation of convective heat transfer coefficient and water productivity in a tubular solar still CFD simulation and theoretical analysis”, *Solar Energy* **113;** pp 313–323 (2015).
29. Ibrahim Ayman G.M, Elshamarka Salman E, “Performance study of a modified basin type solar still”, *Solar Energy* **118**; pp 397–409 (2015).
30. Yadav Saurabh, Sudhakar. K, “Different domestic designs of solar stills: A review”, *Renewable and Sustainable Energy Reviews* **47**; pp 718–731 (2015).
31. Tabrizi Farshad Farshchi, Dashtban Mohammad, Moghadam Hamid, Razzaghi Kiyanoosh, “Effect of water flow rate on internal heat and mass transfer and daily productivity of a weir-type cascade solar still”, *Desalination* **260,** pp. 239–247 (2010).