CHAPTER II

LITERATURE REVIEW

2.1 GENERAL

Water and the energy are the two most essential things for the sustaining of life. The need for freshwater is increasing, but most of the water sources naturally available is brackish or impure, not suitable for drinking and requires treatment. In the existing water purification and distillation methods, for mass production, electrical energy or fossil fuels are used. The recent research in distillation is focused on developing cost-effective ways of producing fresh water for human use in regions where the availability of fresh water is, or is becoming, limited. A detailed review of various studies on solar still over the years is discussed in this chapter.

In remote and arid locations where the conventional energy sources are costly and scarce, the demand for fresh water can be met by using solar stills. Solar still can be easily fabricated using locally available materials that are easy to operate and maintain described by Prem Shankar and Shiv Kumar [11]. Water is desalinated in order to convert salt water to fresh water so it is suitable for human consumption or irrigation. Distillation is a good method to obtain potable water. Distillation is used on many sea going ships and submarines. In remote and other inaccessible areas, one of the options to remove chemical contaminants from drinking water could be solar distillation using „solar stills” at the household level.

More generally, distillation refers to the removal of salts and minerals. As sunlight warms the black bottom and heat is transferred to the water, the top layer of water evaporates and covers inside of the glass cover, which is inclined towards the freshwater drain. Approximately, 1 m² of glass cover produced around 2 to 3 litres of water per day within 5 h of full sunlight obtained by Rajendra Prasad et al. [12].

Graeter et al. [13] demonstrated that the large-scale distillation typically uses extremely large amounts of energy as well as specialized expensive infrastructure,
make it very costly compared to the use of fresh water from conventional sources such as rivers or groundwater. The solar still is a simple device to distil water of its impurities. Larger solar stills are generally made of glass over a formed sheet metal. The yield of the single basin solar still is very less compared to that of other conventional desalination methods.

2.2 HISTORY OF SOLAR DISTILLATION

Solar distillation has been used in many countries for various applications since many centuries. As early as in the fourth century B.C., Aristotle described a method to evaporate impure water and then condense it for potable use. The historical solar distillation apparatus and it is exposed to the intense heat of the solar rays to evaporate water and collect the condensate into vessel placed underneath as reported by Nebbia and Menozzi [14].

A Swedish engineer, C.Wilson, was the first who designed conventional solar still for supplying fresh water to nitrate mining community in Chile, which become quite popular and was in operation for more than 40 years. During the 1950”s, interest in solar distillation was revived and in virtually all cases, the objective was to develop large centralized distillation plants. In California, the goal was to develop plants capable of producing 3,775 cubic metres of water per day. However, after about 10 years, researchers stated that large solar distillation plants were too expensive to compete with fuel fired ones. Therefore, research is now shifted to smaller solar distillation plants. In 1970, 38 plants were built in 14 countries, with capacities ranging from a few hundred litres to around 30,000 litres of water per day reported by Garzia-Rodriguez [15].

In India, the first largest solar distillation plant was installed by Central Salt and Marine Chemical Research Institute (CSMCRI), Bhavnagar with basin area of 350 m² and production of 1000 litres per day to supply drinking water in Awania village. Awania is a non-electrified village, 12 km from Bhavnagar with a population around 1400. Natu et al. [16] gave their operation experiences at Awania village distillation plant. The villagers took some time to understand the difference between the quality
of water produced by solar distillation plant and water from well after that they started using plant water regularly.

In many coastal areas where sea water is abundant but potable water is not available. Solar water distillation is one of the many processes that can be used for purification as well as distillation. Solar still is the widely used solar distillation device. A simple solar still can easily produce the water needed for drinking and cooking for households without access to potable water. Also distilled water can be used for industrial purpose as it is cleaner, reported by Abdul Jabbar N. Khalifa and Ahmad M. Hamood [17].

2.3 SOLAR DISTILLATION

Solar distillation processes can be devised in two main types: direct and indirect collection systems. The “direct method” use of solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and the other one for distillation). The direct solar energy method uses a variety of simple stills which are appropriate for very small water demands; indirect methods use thermal or electrical energy and can be classified as: distillation methods using solar collectors or membrane methods using solar collectors and/or photovoltaic for power generation.

The direct method solar still is called as passive solar still and the indirect method solar still is called as active solar still. The yield of passive solar still is very less compared to that of other desalination methods. To enhance the yield of the passive solar still, many research works are being carried out. One of the methods is active solar still and in this additional thermal energy is fed into the basin using solar collectors. An overview of solar thermal distillation technologies is presented, focusing on those technologies appropriate for use in remote villages by Kalidasa Murugavel et al. [18]. Solar energy coupled to distillation offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electric grid is either not cost effective or not feasible and where the water scarcity is severe. The classification of solar distillation is shown in Figure 2.1.
Figure 2.1 Classification of solar distillation

Figure 2.2 Classification of inclined solar still

Figure 2.2 shows the classification of inclined solar still. It is divided into two; namely, wick type and basin type. Wick type is also divided into two types namely single wick and multiple wick type and the basin type is again divided into two; namely, tilted tray and multiple effect tilted tray solar stills.

The solar still selection will include the following things.

- Quantity of fresh water required and its use.
Available water sources, such as sea, ponds, wells, swamps etc.

Proximity to nearest fresh water sources.

Availability of electric power at the site or nearby.

Cost of supplying fresh water by various methods.

Cost and availability of labor in the region.

Maintenance and daily operational requirements.

Life span of the water supply system.

Economic value of the region.

2.3.1 SINGLE SLOPE PASSIVE SOLAR STILL

Figure 2.3 Schematic of single slope passive still

Figure 2.3 shows the schematic of single slope passive still. Its function is very simple; basically a transparent cover encloses a pan of saline water. The sloping cover
traps solar energy within the enclosure. This heats up the water causing evaporation and condensation on the inner face of the sloping transparent cover. Water will rise sufficiently to kill all pathogenic bacteria anyway. This distilled water is generally potable; the quality of the distillate is very high because all the salts, inorganic and organic components and microbes are left behind in the bath. Under reasonable conditions of sunlight the temperature of the A film or layer of sludge is likely to develop in the bottom of the tank and this should be flushed out as often as necessary. The daily amount of drinking water needed by humans varies between 2 and 8 litres per person. Therefore 2 m² of still are needed for each person served.

The single basin still is the only design proven in the field. One of the main setbacks for this type of distillation plant is the low thermal efficiency and productivity. This could be improved by various passive and active methods. The solar still integrated with a heater or solar concentrator panel is generally referred to as an active solar distillation while others are referred to as passive stills. Passive solar distillation is an attractive process for saline water distillation in that the process can be self-operating, of simple construction and relatively maintenance free. These advantages of simple passive solar stills however, are offset by the low amounts of freshwater produced, approximately 2 l/m² for the simple basin type solar still and for the need for regular flushing of accumulated salts described by Chaibi [19].

2.3.2 Pyramid Type Passive Solar Still

Figure 2.4 shows the schematic of pyramid type passive solar still. In pyramid type solar still, the still consists of a shallow airtight basin lined with a black, impervious material, which contains brackish or saline water. A sloping transparent covers are provided on all the four sides. Water vapor produced by evaporation rises upward and condenses on the inner surface of the glass cover which is relatively cold. Water may be added through the still's supply fill port. Purified drinking water is collected from the output collection port as distillate reported by Mathioulakis et al. [20]. The pyramid type passive solar still is not widely used due to complicated in design and fabrication. It has low yield and so that high cost of water per kg.
2.4 MODIFICATIONS ON PASSIVE STILLS

The operating performance of a simple basin type passive still can be augmented by several techniques. Modifications using passive methods include basin stills, wick stills, diffusion stills, stills integrated with greenhouse and other configurations. These modifications are given below.

2.4.1 Double Slope Solar Still

Rahul Dev et al. [21] made a new approach to obtain the characteristic equation of a double slope passive solar still (DSPSS) based on experimental observations. The performance of DSPSS has been analysed for the composite climatic condition of New Delhi, India. To obtain the characteristic equations under quasi-steady state condition, regression curves have been plotted for instantaneous gain and loss efficiencies with respect to a non-dimensional representative factor \( \{(T_w-T_a)/I(t)\} / \{(T_w-T_a)/I(t)\}_{\text{max}} \) of climatic and operational parameters together. From the analysis, it was found that non-linear characteristic curves are more accurate for
analysing the performance, thermal testing and further design modification depending upon various parameters associated with design, climatic and operational conditions.

Zerouala et al. [22] investigated the population of Algeria and is expected to double in the next thirty years, by then it will clearly face serious water shortages. The demand in water for drinking, agriculture and industry largely exceeds the amount that fresh sources can meet, especially in the Saharan regions where rainfall is the lowest, with years of total drought. To overcome this serious water scarcity, solar distillation could be an effective solution. Their objective is to enhance the yield of the still by improving the performance of its condenser. This was achieved by cooling its outer surface. Small-scale solar powered distillation pilot units have been constructed and operated. The tests were conducted in the town of Ouargla, south of Algeria. Two series of experiments were performed. In the first series, the condenser was cooled by flowing water on the north glass cover throughout the run. This enhanced the still productivity by 11.82%. The second series consisted of lowering the glass temperature (condenser) and this was realized by an intermittent shading (12.00 h-14.00 h) of the north glass cover. The shade was assured by placing a rectangular screen at 90 cm above the north side of the still. This procedure improved the yield by just 2.94%.

2.4.2 Double Decker Solar Still

Two solar-stills (single basin and double decker) were fully fabricated and tested at the Campus of the University of Bahrain by Al-Karaghouli and Alnaser [23]. Figure 2.5 shows the schematic of double decker solar still. The first was a single-basin solar still while the second was a double-basin solar still. Both stills have the same basin area. For the double decker basin solar-still, the upper glass cover and the first basin were tilted at 12° with respect to the horizontal, while for the single-basin solar-still, the glass cover was tilted at 36° with respect to the horizontal. Both have the same basin area. The inner dimension of each still was 90 x 50 cm of effective area 0.45 m². For the double-decker basin solar still, the upper glass cover and the first basin were tilted at 12° with respect to the horizontal while for the single basin solar still; the glass cover was tilted at 36° with respect to the horizontal.
It was found that the upper glass temperature of the double basin still was higher than that of the lower glass. They found that the daily average still production for the double-basin still is around 40% higher than the production of the single-basin still. Several copper-constantan thermocouples were installed in both stills to measure the glass cover temperature, the chamber temperature, the water temperature and the ambient-air temperature. The hourly amount of extracted distilled water, the various temperatures and the insulation were monitored for a five-month period (February–June). Two types of measurements were performed; one with still-sides insulation and the other without. It was found that the monthly average amount of the total daily-distilled water production was highest in June for both types of stills. The insulation during this month is higher than that in any other month during the testing period.

Figure 2.5 Schematic of double decker solar still

For the double-basin still, with sides insulated, the June production was 1760 ml per day (3.91 l/m²/day) and in the non-sides insulation case the total daily amount was 1410 ml per day (3.13 l/m²/day). For the single-basin still, the June daily production was 1280 ml per day (2.84 l/m²/day) in the case of stills with sides insulation and 1105 ml (2.455 l/m²/day) in the case of no-side insulation.
2.4.3 Still with Sponges

Bassam et al. [24] used sponges to increase the free surface area of the water in the solar still. To increase the free surface area of the water, sponges are used at the basin water. Due to capillary action, water is sucked by the sponges. The sponge cubes increase the surface area over which water evaporation occurs. The use of sponge cubes in the basin water resulted in a significant improvement in still production. The evaporation rate of the water in the solar still is directly proportional to the exposure area of water.

2.4.4 Wick Still

In a wick still, the feed water flows slowly through a porous, radiation-absorbing pad (the wick). Two advantages are claimed over basin stills. First, the wick can be tilted so that the feed water presents a better angle to the sun (reducing reflection and presenting a large effective area). Second, less feed water is in the still at any time and so the water is heated more quickly and to a higher temperature. Shanmugasundaram et al. [25] have proven the superiority of the tilted wick type solar still and confirmed an increase in productivity by 20–50%. Simple wick stills are more efficient than basin stills and some designs are claimed to cost less than a basin still of the same output.

Abdul Jabbar et al. [26] studied an experimental wick-type solar still system. A tilted wick-type solar still was designed and constructed. Its practical aspects and performance were presented. Charcoal cloth was used as an absorber/evaporator material and for saline water transport. The results show that the daily efficiency of the still was about 53% on clear days in summer. The still efficiency decreased linearly with increase in salinity of the input saline water.

The authors Kalidasa Murugavel et al. [27] fabricated and tested a double slope single basin passive type still with basin area of 1.75 m² is under laboratory conditions for a thin layer of water in the basin. For maintaining a thin layer of water in the basin, they spread the water throughout the basin by some kinds of wick material or porous materials. In this work, performance of the still is compared by using wick materials like light cotton cloth, light jute cloth and sponge sheet of 2 mm
thickness and porous materials like washed natural rock of average size 3/8" × 1/4" and quartzite rock of average size 3/8" as spread materials.

The test results show that the still with black light cotton cloth as spread material is found to be more productive. At higher water and glass temperature region, for all basin materials, the production rate increases with the decrease of the difference between the water and glass temperatures for certain period and also the productivity decreases with the increase of water temperature for certain time during this period. They also suggested that the still productivity depends on parameters like solar radiation intensity, atmospheric temperature, basin water depth, glass cover material, thickness and its inclination, wind velocity and the heat capacity of the still. For a particular still, the basin water temperature is the function of depth with day variation of solar radiation intensity.

### 2.4.5 Stepped Solar Still

Abdullah [28] investigated the experimental performance of a stepped solar still coupled with a solar air-heater. A single slope passive solar still (conventional still) and stepped active solar still integrated with a solar air-heater collector were fabricated with an area of 0.5 m². The hot air from the solar air heater passes under the base of stepped still used to heat the saline water. The higher saline water temperature was achieved by the active stepped solar still compared to the passive solar still due to the additional thermal energy supplied by hot air. Use of aluminium filling as thermal storage material beneath the absorber plate keeps the operating temperature of the still high enough to produce distillate water during the lack of sunshine, particularly at night. The daily productivity (24 hour) for both conventional still and stepped still reaches approximately 3350 and 4350 ml/ m²/day for conventional still and stepped solar still respectively. In this case the increase in distillate production for stepped solar still is approximately 30% higher than that for conventional still. Also, the effect of water flow over the glass cover was studied. Results showed that, water productivity increased by 112% over conventional still, when the system was coupled with a solar air-heater and glass cover cooling, for stepped solar still. The productivity of the stepped still is increased by integrating aluminium filling by about 53% over conventional still.
2.4.6 Diffusion Still

Diffusion solar stills are comprised of two separate units. One is a hot storage tank, coupled to a solar collector and the other is the distillation unit, which produces the distilled water. One of the most recent designs of this type of still is that described by Graeter et al. [13] and Rheinlaender and Graeter [29] of a four-effect still. The evaporation process in a four-effect still for the distillation of sea and brackish water was experimentally investigated in a test facility under different modes and configurations of heat recovery and natural or forced convection in the four distillation chambers (“effects”). The theoretical distillate output from a 4-effect distillation unit is 8.7 kg/m²h with an energy input of 2.0 kW/m², for an active cross-section of 1 m² of the apparatus, representing 4m² of evaporator and 4 m² of condenser surface.

A transient mathematical model was presented for a triple-basin solar still by El-Sebaii [30]. It was based on an analytical solution of the energy-balance equations for the various elements of the still. The energy-balance equations were solved analytically using the elimination technique. System performance was investigated by computer simulation. Numerical calculations were performed on typical summer and winter days in Tanta for different water masses in each effect and the still and also for various wind speeds (V) to study the effect of these parameters on the daily productivity of the system. It was observed that the daily total productivity of the still decreases with the increase of water mass in each basin. The total productivity was a maximum for the least water mass in both the lower and middle basins without dry spots over the base of each effect. Moreover, it was found that the daily total productivity of the still increases with the increase of V up to a typical velocity (V”), beyond which the increase in productivity becomes insignificant.

2.4.7 Solar Still Greenhouse Combination

Most studies published in the last decade have focused on small-scale systems for solar distillation with capacities below 25 m³/day and used in remote areas. Some of these have proposed solar distillation processes used in combination with water efficient greenhouse concepts based on solar energy reported by Chaibi [19].
2.4.8 Multiple – Effect Basin Still

Multiple-effect basin still has two or more compartments. The condensing surface of the lower compartment is the floor of the upper compartment. The heat given off by the condensing vapor provides energy to vaporize the feed water above. Multiple-effect solar distillation systems are more productive than single effect systems due to the reuse of latent heat of condensation.

2.4.9 Externally Heated Solar Still

The temperature of saline water in the basin can be increased through additional (external heating). For this purpose the still is integrated with a

- Solar heater
- Solar concentrator
- Waste heat recovery system.

Circulation through the heater or the concentrator could either be through natural circulation (Thermo syphon) or through forced circulation using a pump.

2.4.10 Desalination with Humidification – Dehumidification

One of the problems that negatively influence the still performance is the direct contact between the collector and the saline water. This may cause corrosion and scaling in the still and thereby reduce the thermal efficiency. A conventional solar still equipped with a self-sustainable humidification-dehumidification open air flow stream to enhance the system productivity was investigated by Al-Hallaj et al. [31]. This modification maintained higher temperature difference between the saline water to be evaporated and the condensing surface. Accordingly, higher driving force for the evaporation-condensation processes was provided. This was achieved by insulating the condensing surface from the incoming radiation and by the continuous removal of the latent heat of condensation by the cooling water. The accuracy of the experimental results was validated against a linear model. Variations in the parameters that influence solar studies limited the value of the coefficient of determination for the lumped efficiency of the system at 0.74.
2.4.11 Indirect Solar Distillation

Indirect solar distillation methods involve two separate systems: the collection of solar energy, by a conventional solar converting system, coupled to a conventional desalination method. Desalination using thermal processes (phase change) can be accomplished using multistage flash distillation (MSF), multiple effect evaporation (MEE), vapor compression (VC) and freeze separation (FS).

2.4.12 Multi – Stage Flash Process

Several medium scale plants for MSF desalination using solar energy have recently been implemented. Solar-powered MSF plants can produce 6–60 l/m²/day, in comparison with the 3–4 l/m²/day typical of solar stills. One of the most common type of solar collectors used are salinity gradient solar ponds, such as the desalination plant in Margarita de Savoya, Italy, with a capacity of 50–60 m³/day, or in El Paso, Texas, with a capacity of 19 m³/day.

2.4.13 Multiple – Effect Distillation

Many multiple-effect distillation (MED) plants of medium capacity powered by solar energy were built worldwide. 13 years operation of the MED-plant designed for a maximum capacity of 120 m³/day with 18 stack type stages and pre-heaters was installed.

2.4.14 Freezing

While freeze distillation proposed as a method for distillation for several decades, only demonstration projects have been built to date. The concept is appealing in theory because the minimum thermodynamic energy required for freezing is less than for evaporation since the latent heat of fusion of water is 6.01 kJ/mole while the latent heat of vaporization at 100°C is 40.66 kJ/mole. In practice heat losses will occur and the average daily yield which might be expected from a solar still is 4 – 5 l/m²/day. Today’s state-of-the-art single-effect solar stills have an efficiency of about 30 – 40% was reported by Mink et al. [32].

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2.4.15 Solar Still with Mini Solar Pond

Figure 2.6 Schematic of solar still with mini solar pond

Figure 2.6 shows the schematic of solar still with mini solar pond. In an attempt to improve the daily productivity of the single effect solar stills, a single-slope single-basin solar still integrated with a shallow solar pond (SSP) was studied to perform solar distillation at a relatively high temperature. Velmurugan and Srithar [33] reviewed that Solar pond is an artificially constructed pond in which significant temperature rises are caused to occur in the lower regions by preventing convection. To prevent convection, salt water was used in the pond. Those ponds were called “salt gradient solar pond” [33]. In the last 15 years, many salt gradient solar ponds varying in size from a few hundred to a few thousand square meters of surface area have been built in a number of countries. Nowadays, mini solar ponds are also being constructed for various thermal applications. In this work, various design of solar pond, prospects to improve performance, factors affecting performance, mode of heat extraction, theoretical simulation, measurement of parameters, economic. Water turbidity and wall shading effect reduces the performance of the solar pond. A mini solar pond can also be used for enhancing productivity of a solar still. Around 59% solar still productivity increases when it is integrated with a mini solar pond.
Velmurugan et al. [34] integrated a mini solar pond, on a stepped solar still and a single basin solar still set-up for effluent distillation process. Initially, water from the effluent settling tank was allowed to pass through the mini solar pond where it was heated. Then hot effluent water enters into stepped solar still and the distilled water is produced. The excess water from the stepped solar still enters into the single basin solar still. Thus, distilled water is produced in both single basin solar still and stepped solar still.

Srithar [35] experimentally made industrial effluent was evaporated in a single basin solar still and an integrated vapor adsorption solar still separately. To preheat the saline water, a mini solar pond was integrated with these stills. Both the stills were operated with mini solar pond and tested individually. In single basin solar still, maximum productivity is obtained, when it is modified with sponge, pebbles and sand. The vapor adsorption solar still was modified with sand, pebble and sponge to enhance their productivities. When mini solar pond, pebble, sponge and sand are used in vapor adsorption solar still, maximum productivity was obtained.

Velmurugan et al. [36] carried out experiments with different salinity in the mini solar pond. A Mini solar pond was used to store the solar thermal energy. The heat energy stored by the mini solar pond was used for preheating saline water in single basin solar still and vapor adsorption solar still. It was found that the optimum value of salinity in solar pond water was 80 g/kg. Industrial effluent was used as raw water in the solar stills. For settling the effluent, an effluent settling tank was designed and fabricated.

The performance of single basin solar still and vapor adsorption solar still were calculated. To enhance the productivity, the single basin solar still was modified with sponge, pebbles and sand. Also, the vapor adsorption solar still was modified with sand, pebble and sponge. Maximum productivity of 32.32% enhancement was obtained for vapor adsorption solar still was integrated with sand and sponge. It was found that the productivity increases with increase in solar intensity and water glass temperature difference and decreases with increase in wind velocity. Economic analysis was made and payback period is calculated as 417 days.
2.4.16 Solar Still with Fins

Velmurugan et al. [37] designed, installed and tested an experimental setup of solar still with fin kept in the North–South direction, with the inclination of $10^\circ$, which is the latitude of Madurai. Five rectangular solid fins are integrated at the basin of the solar still to increase the area of the basin considerably. Adding fins in the basin of a conventional single basin still decreased the preheating time required for evaporating the still basin water. While using fins in the solar still, the area of the absorber plate increased. Productivity of the solar still increases with increase in absorber area. Hence, absorber plate temperature and saline water temperature increased. As the temperature difference between water and glass increases, productivity increased.

In their work, five fins with height, length and breadth 35, 900 and 1 mm respectively, were used. Experimental results showed that the average daily saw dust saline water production of distilled water in solar still increases by 30%, when fins were integrated in basin of the solar still and found that the yield was increased by 52%. Also, while using fins in the solar still, the area of the absorber plate increased. Hence, absorber plate temperature and saline water temperature increased. As the temperature difference between water and glass increases, productivity increased.

2.4.17 Solar Still with Black Gravels

Velmurugan and Srithar [38] studied the influence of black gravel on the productivity of the solar still. They added pebbles in the solar still and found that the productivity increased by 20% than the conventional solar still. To store the thermal energy in solar still, some energy storing materials were used. Black rubber, gravel, metallic wiry sponges and surfactant additives are some of the energy storing materials widely used in solar stills. Nafey et al. [39] studied the influence of black gravel on the productivity of the solar still. To absorb and retain the heat obtained by solar radiations, sensible heat storage materials like gravels or pebbles are used in this modification to increase the temperature of water. Black Pebbles of 20-30 mm size are used. Pebbles absorb more energy due to its highest volumetric heat capacity. Addition of pebbles in the basin surface increases the water temperature thereby increasing the evaporation rate.
2.4.18 Solar Still with Phase Changing Material

Omar Ansari et al. [40] experimentally investigated distillation of the brackish water using a passive solar still with a heat energy storage system put under the basin liner of the distillation device is dealt with the help of transient mathematical models. Phase change materials (PCMs) are used to store energy in the process of changing the aggregate state from solid to liquid. The energy balance equations for the various elements of the still as well as for the PCM are formulated and numerically solved. In meteorological conditions taken on 15th June 2011 at the Errachidia city (Latitude: 31°58′N, Longitude: 4°20′W), Morocco, numerical calculations have been carried out for three kinds of PCMs which have different melting temperatures. To validate the simulation results, the brackish water temperature was compared with the analytical expression and the existing results in the literature. The obtained results show that the excess energy produced during sunshine times was stored in a PCM for use later during the night.

Furthermore, it is also intended for designers in order to choose the right material of the heat storage to improve the performance of this distillation device. The energy balance equations for the various elements of the still as well as for the PCM are formulated and numerically solved. To validate the simulation results, the brackish water temperature is compared with the analytical expression and the existing results in the literature.

2.4.19 Effect of Varying the Water Depth on Solar Stills

Muafag Suleiman and Tarawneh [41] carried out the performance evaluation of double slope solar still by varying the water depth, (0.5 cm, 2 cm, 3 cm and 4 cm) with saline water TDS of 5000 ppm, under the same climatic conditions at Mutah University and observed that the productivity is strongly dependent on the climatic, design and operational conditions. The obtained results showed that the decreased water depth has a significant effect on the increased water productivity, while the performance characteristics showed that the water productivity was closely related to the incident solar radiation intensity. It is necessary to evaluate some important parameters affecting the system productivity. The effect of water depth in the basin on
the water productivity was evaluated. In the same time, the effects of the design and operational parameters on the solar distillation process were also investigated. The air tightness and the good insulation are two essential design parameters that should be highly considered in order to minimize the vapor leak and heat loss tendencies.

Kalidasa Murugavel et al. [42] studied with an inclined still and found that the higher surface area and thin water surface are its advantages and maintaining continuous wetness along the inclined surface and loss of heat through raw water drain are the problems. Two symmetrical greenhouse solar stills were constructed and the experimental investigation regarding the effect of water depth on the still productivity was carried out. Because the solar still productivity was strongly dependent on the design and operational conditions, the accepted thermal performance which was achieved was due to the improved design parameters and optimized operational technique.

The distillate is more in the case when water is flowing over the glass cover in a very thin layer. The combined wick and basin could produce high efficiency compared to the normal basin type stills. The reduction in salinity of the feed water could improve the productivity. The average daily amount of distillate of the still with the external reflector is larger than that of the still without the reflector. The fresh water generation rate increased two to three times when wicks were used instead of a bare plate.

2.4.20 Cover Tilt Angle

Abdul Jabbar and Khalifa and Ahmad M. Hamood [26] studied a large number of studies on the effect of cover tilt angle on productivity in different seasons and latitude angles. The investigation that tackle the detailed effect of the cover tilt angle on productivity. A relation between the cover tilt angle and productivity of simple solar still in various seasons is established together with a relation between the optimum tilt angle and the latitude angle. Kalidasa Murugavel et al. [43] reviewed the progress of solar still effectiveness of the single basin passive solar still. They suggested that the orientation of the glass cover depends on the latitude and surface heating of water mass.
2.4.21 Vacuum Solar Still

Al-Hussaini and Smith [44] studied the effect of applying vacuum inside the solar still and found that the solar still’s water productivity increased by 100% when vacuum was applied. The effect of vacuum inside the still is to avoid any heat transfer due to convection in the still. The heat loss from the water in an insulated still is due to evaporation and radiation only. In the presence of vacuum, the effect of the non-condensable gas, which reduces the rate of condensation, was also avoided. Evaporation at a low temperature using vacuum condition, leads to a good improvement in the still with the reduction of pressure. The productivity of the solar still working at low pressure is higher when compared to that of similar solar still operating under atmospheric pressure. This increases the rate of evaporation and in turn increases the efficiency.

Ganeshwar and Nimlakhandan [45] designed a solar still which maintained a vacuum in the evaporating chamber, exploiting the natural gravity law and the barometric pressure head and developed a model. They demonstrated the correlation between the predictions made by the theoretical model with the measured performance data and produced yield of 7.5 l/m²/day of evaporation area using direct solar energy alone. With the addition of (PV/T) panel of 6 m² area they system produced 12 l/m²/day of fresh water at an efficiency range of 65% to 90%. The average specific energy feed was calculated as 2930 kJ/kg of fresh water.

Tiwari et al. [46] conducted indoor simulation experiment and found that the production rate was higher for 30° cover inclination. Glass temperature affected the condensation rate at its lower surface. Lower glass surface temperature increases the circulation of air inside the still which enhances convective and evaporative heat transfer between basin water and glass. Also cooler glass lower surface increased condensation.

2.5 EFFECT OF VARIOUS FACTORS

Kaisan Muhammad Usman and Sabi’u Bala Muhammad [47] studied in their research, water sample was collected from Kwakwalawa river, North Western Nigeria. 25 litres of the water sample was used to fill a single slope solar still and the
whole set up exposed to the solar energy. The corresponding values were measured for some meteorological variables like: solar radiation, ambient temperature, relative humidity and wind speed during each interval. It was observed that the maximum yield recorded corresponds to the highest value of wind speed.

The relative humidity varied inversely with the yield. It has been observed that solar radiation varies parabolic ally with time, with its maximum value at 13.00 hr. Solar radiation also varies linearly with yield. Finally the yield of the distilled water increased as the ambient temperature increased, with the maximum yield recorded at the maximum value of the ambient temperature. When the ambient temperature started to decline, the yield also started to decline equally.

Ghassan et al. [48] designed, manufactured and tested three similar solar still basins and pyramidal glass covers attached to the basin at an angle \( \alpha = 45^\circ \). The three basins have divided into three models (M1, M2 and M3). Before taking the measurement of the distilled water three different amount of water used, so for the (model M1) 3 litres of water, (model M2) 6 litres and (model M3) 9 litres, to study and evaluate the effect of water depth in the basin. The average daily output was found to be (3.924) litres/day for model (M1), (3.116) litres/day for model (M2) and 2.408 litres/day for model (M3) for basin area of 1 m\(^2\) based on data of selected day.

El-Sebaii [49] studied the effect of wind speed \( V \) on the daily productivity \( P_d \) of some active and passive solar stills by computer simulation. He also made comparisons with the results reported in the previous studies about the effect of wind speed on productivity have been carried out. Numerical calculations have been carried out on typical summer and winter days in Tanta in order to correlate \( P_d \) with \( V \) for different masses of basin water \( m_w \) for the passive stills and various thicknesses \( d_w \) or mass flow rates \( m_w \) of the flowing brine for the active stills.

El-Sebaii [50] also studied the effect of wind speed on passive solar still performance based on inner/outer surface temperatures of the glass cover and found that the wind velocity \( V \) on the daily productivity \( P_d \) of a passive solar stills by computer simulation. Their numerical calculations indicated that, when \( T_g_i = T_g_o \) there is a critical mass (depth) of basin water beyond which \( P_d \) increases as \( V \)
increases until a typical velocity \( V_t \). For basin water masses less than the critical mass, \( P_d \) was found to decrease with increasing \( V \) until \( V_t \). After \( V_t \), the change in \( P_d \) becomes insignificant.

Aboul-enein et al. [51] investigated on a single-basin solar still with deep basin and found that the influence of cover slope on the daily productivity of the still. Effect of heat capacity of basin water on the daylight and overnight productivities was also studied. They inferred that the productivity of the still decreases with an increase of heat capacity of basin water during daylight and the reverse is the case overnight.

Abdul Jabbar Khalifa [52] studied the effect of cover tilt angle on productivity in different seasons and latitude angles are cited in this article. The investigation that tackle the detailed effect of the cover tilt angle on productivity report contradictory conclusions about the effect of tilt angle on productivity and the value of the optimum tilt angle. A relation between the cover tilt angle and productivity of simple solar still in various seasons is established together with a relation between the optimum tilt angle and the latitude angle by an extensive review of the literature.

Sampathkumar et al. [53] described that the performance of a solar still could neither be predicted nor improved by some of the uncontrollable parameters like intensity of solar radiation, ambient temperature and wind velocity. But, there are certain parameters such as depth of water, glass cover angle, fabrication materials and temperature of water in the basin and insulation thickness, which affects the performance of the solar still that could be modified for improving the performance. The still performance can be increased by reducing the water depth and thereby increasing the evaporation rate. The temperature difference between water in the basin and condensing glass cover also has a direct effect in the performance of the still.

Still with cover cooling: Increasing the temperature difference between the basin (heat source) and the cover (heat sink) lead to increase the water evaporation rate reported by Schiffler [54]. In stills with cover cooling, cooling water or saline solution is fed in the gap of a double glass cover to maximize the temperature difference. The cost, as such, is increased.
Hassan E.S. Fath [55] found that adding a passive condenser in the shaded region of a single slopped still increases the still efficiency by 45%.

Injecting black dye in the seawater increases the yield of solar still reported by Hassan E.S. Fath et al. [56].

Medugu and Ndakuwong [57] designed and tested a solar still in Mubi, Nigeria and carried out a theoretical analysis of the heat and mass transfer mechanisms inside this solar still. The measured performance was then compared with results obtained by theoretical analysis. They observed that the instantaneous efficiency increases with the increase of solar radiation and with the increase of feed water temperature. The distillation efficiency of the still was in clear greement with the theoretical analysis within the range of 99.64%.

Abdullah [58] investigated the experimental performance of a stepped solar still coupled with a solar air-heater. A single slope passive solar still (conventional still) and stepped active solar still integrated with a solar air-heater collector were fabricated with an area of 0.5 m². The hot air from the solar air heater passes under the base of stepped still used to heat the saline water. The higher saline water temperature was achieved by the active stepped solar still compared to the passive solar still due to the additional thermal energy supplied by hot air. Use of aluminium filling as thermal storage material beneath the absorber plate keeps the operating temperature of the still high enough to produce distillate water during the lack of sunshine, particularly at night. Results indicate that the daily productivity (24 for both conventional still and stepped still reaches approximately 3350 and 4350 ml/m²/day for conventional still and stepped solar still respectively. In this case the increase in distillate production for stepped solar still is approximately 30% higher than that for conventional still. Also, the effect of water flow over the glass cover was studied. Results showed that, water productivity increased by 112% over conventional still, when the system was coupled with a solar air-heater and glass cover cooling, for stepped solar still. The productivity of the stepped still is increased by integrating aluminium filling by about 53% over conventional still.
Runsheng Tang and Etzion [59] made a comparative study on the water evaporation rate from a wetted surface and that from a free water surface. To perform this comparison, two identical ponds were constructed, internally measuring 116 × 116 × 22 cm. In one of the ponds, white towels were stretched over a densely perforated PVC panel supported by pieces of waterproof polystyrene to make the towels afloat on the water surface of the pond. The other pond was simply filled with water and the surface of water was kept exposed to the ambient. The rates of water evaporation from both ponds to the ambient under a wide range of climatic conditions were recorded and correlated with wind velocity, water temperature, air temperature and relative humidity.

A comparison of water evaporation rates from both wetted cloth surface and free water surface has shown that when wind velocity across the water surfaces is very low, the rate of water evaporation from the wetted towels” surface is greater than that from the free water surface. When wind velocity is higher, this is reversed and the evaporation rate from the free water surface was higher. Omar Ansari et al. [60] studied the effect of inclination of the external reflector on a simple inclined solar still in winter. Its practical aspects and performance are presented. The experimental investigation on the productivity with internal and external reflector would be around 2.45 times that of simple still with no reflectors.

2.6 ACTIVE SOLAR STILL

Many active distillation systems have been developed to overcome the problem of lower distillate output in passive solar stills. In active solar still additional thermal energy is fed into the basin water using solar collectors to increase the basin water temperature. Different solar energy collectors may be used in order to convert solar energy to thermal energy. In most of them, a fluid is heated by the solar radiation as it circulates along the solar collector through an absorber pipe. This heat transfer fluid is usually water or synthetic oil. The fluid heated at the solar collector field may be either stored at an insulated tank or used to heat another thermal storage medium. In order to increase this temperature difference few researchers studied the effect of coupling the solar still to a flat plate solar collector. Their results showed that the solar still performance could be improved significantly, but of course the system cost
increased. In some cases the daily productivity of the simple still increased from about 4 l/m²/day to about 8 l/m²/day for the coupled one described by Sampathkumar et al. [61].

2.6.1 Salinity - Gradient Solar Ponds

This is a shallow pond with a vertical saltwater gradient, so that the denser saltier water stays at the bottom of the pond and does not mix with the upper layer of fresher water. Consequently, the lower salty layer gets very hot (70–85°C). This heat can be used to make electricity (with additional heating from traditional sources), provide energy for distillation and to supply energy space heating in buildings. A solar pond (SP) is a thermal solar collector that includes its own storage system. A solar pond collects solar energy by absorbing direct and diffuse sunlight.

2.6.2 Flat - Plate Collector

Flat-plate collectors (FPCs) are used as heat transfer fluid, which circulates through absorber pipes made of either metal or plastic. The absorber pipes are assembled on a flat plate and they usually have a transparent protective surface in order to minimize heat losses. They may have different selective coatings to reduce heat losses and to increase radiation absorption is illustrated by Zambolin and Del Col. [62].

2.6.3 Evacuated Tube Collector

Heat losses are minimized in evacuated tube collectors (ETCs) by an evacuated cover of the receiver. This cover is tubular and made of glass. In addition, a selective coating of the receiver minimizes the losses due to infrared radiation.

There are two different technologies of evacuated tubes: (1) Dewar tubes two coaxial tubes made of glass, which are sealed each other at both ends; and (2) ETC with a metallic receiver, which requires a glass to metal seal. Usually a number of evacuated tubes are assembled together to form a collector described by Sampathkumar [63, 64].
2.6.4 Parabolic Trough Collector

A parabolic trough is a linear collector with a parabolic cross-section. Its reflective surface concentrates sunlight onto a receiver tube located along the trough’s focal line, heating the heat transfer fluid in the tube. Parabolic troughs typically have concentration ratios of 10 to 100, leading to operating temperatures of 100–400°C. Parabolic trough collectors (PTCs) require sun tracking along one axis only. In this way, the receiver tube can achieve a much higher temperature than flat-plate or evacuated-tube collectors.

2.7 SELECTION OF MATERIALS

In general, the aim of any solar still design is to maximize distillate yield for a given set of environment and operating condition. The material selection is based on the two main factors like; cost of materials and availability. A basin still basically consists of the following five essential components (i) basin, (ii) glazing, (iii) insulation, (iv) still structure and (v) distillate trough.

Solar radiation that passes through the transparent cover is absorbed by saline water and the basin liner of a solar still. So, the basin liner acts as an absorber of solar radiation and it is important for the liner to have a relatively high absorptance of solar radiation. Increasing the absorptance of the liner increases the proportion of solar radiation that is converted to thermal energy which is transferred to the water layer on the top part of the liner. In turn, this augments the distillate yield from the solar still. The basin contains saline water for distillation. It needs to be (i) water proof, (ii) dark so that it will absorb the sunlight and convert it to heat and (iii) it should have a relatively smooth surface to make it easier to clean. Common metal sheets used in solar collector are copper, aluminium, galvanised iron and steel demonstrated by Vinothkumar and Kasturibai [65]. The important property of a metal for application in solar engineering is thermal conductivity. The copper and aluminium have relatively high thermal conductivities than Galvanised Iron (GI) sheet but also relatively higher cost. Based on the above consideration GI sheet was selected as basin material and painted black to absorb maximum solar radiation.
A transparent cover is fitted on the top of the solar still to allow solar radiation to reach saline water in the basin. Normally, single glazing is used in solar distillation system reported by Boukar and Harmim [66] ideally, the glazing material should be strong enough to resists high wind, rain, hail, storm and earth movements. The glazing material must be wettable as wettability allows the condensing vapors to form sheets of water on the inner side of a glass cover rather than as water droplets. In solar distillation system, plastics and glass are used as the common cover material. Solar stills with glass covers perform better than those with plastic covers reported by Qiblawey and Banat [67] even though plastics have the advantages of low cost and flexibility. By considering the long life and better performance, the ordinary window glass was used with thickness of 0.005 m.

Heat loss from the bottom and sides of a solar still is undesirable because it reduces distillate yield. Consequently, it is necessary to minimize this loss by insulating the relevant surfaces. This enables most of the absorbed solar radiation to contribute to the evaporation of saline water and thereby augment the distillate yield. The important property of an insulator is the coefficient of heat conduction. Materials with low values of coefficient of heat conduction are suitable for use as insulators due to their relatively high resistance to flow of heat. The common insulation materials are plastic foam, pine fibre board, polyurethane foam, urea formaldehyde foam and saw dust Sampathkumar et al. [68]. Due to easy availability, low cost and relatively low value of coefficient of heat conduction saw dust was used as a insulation material in sides and bottom with the thickness of 0.05 m.

Basin of saline water, bottom and side insulation layers were all housed in a similar box and the top of the solar still unit was covered by a glass. So a strong box was required to support these components. In addition, it was advantageous to make the box from a material with a relatively low coefficient of heat conduction value to avoid adding another insulation layer on the sides of the still. Consideration was therefore given to structural materials that could also acts as insulator on the still. The common materials used are steel, wood and plywood. Among these, plywood has the low values of density and thermal conductivity. Therefore, plywood was chosen as a structural material for the solar still box.
2.8 THERMAL MODELING

The internal heat transfer is responsible for the transportation of pure water in the vapor form leaving behind all impurities in the basin, whereas the external heat transfer through a condensing cover is responsible for the condensation of pure vapor as distillate. The performance of the solar still depends on the values of convective and evaporative heat transfer coefficients. Therefore, it is important to know the variation of these coefficients accurately. Many researchers have been developed the empirical relations for convective and evaporative heat transfer coefficients. The most important and oldest relationship for convective and evaporative heat transfer coefficients for the solar still was developed by Dunkle [69]. In theoretical analysis of simple solar still, the relations that he derived for the heat and mass transfer within the still is formed the basis for many research efforts since then. They found out that the mass transfer rate depends on the temperature difference between the water surface and the glazing.

Clark [70] and Mowla and Karimi [71] developed the model for basin type solar still on the basis of indoor experiments in steady state for ideal condition and proposed the different values of „C” and „n” for different ranges of Grashoff number. However, the results found to be conflicting as it is impracticable to achieve ideal condition for solar still in actual field conditions. They developed a correlation for evaporative heat transfer coefficient based on Lewis relation for low operating temperature range. In their relation the physical properties of saturated air were assumed 50°C, neglecting the effect of vapor pressure.

Sanjay Kumar and Tiwari [72] developed the model to determine the convective mass transfer coefficient for different Grashoff number with changing values of “C” and “n” and validated with experimental results for summer conditions. They proposed the values of C (0.0322) and n (0.4144) for \(1.794 \times 10^6 < \text{Gr} < 5.724 \times 10^6\), using regression analysis after performing experiments in actual field conditions.

Tiwari et al. [73] developed the thermal models for all types of solar collector integrated active solar stills based on energy balance equations in terms of inner and outer glass temperature. The authors have drawn the following points;
(i) The maximum values of total heat transfer coefficient for active solar still integrated with flat plate collector, concentrating collector, evacuated tube collector and ETC with heat pipe are 43, 86, 67 and 76 Wm\(^2\)C\(^{-1}\) respectively illustrated by Sampathkumar et al. [74].

(ii) The overall thermal efficiency of active solar stills integrated with FPC, concentrating collector, ETC and ETC with heat pipe is 13.14, 17.57, 17.22 and 18.26% respectively.

(iii) The overall average thermal and exergy efficiency of FPC integrated active solar still are in the range of 5.6 – 19.1 and 0.25 – 0.85% respectively.

Sanjay Kumar and Tiwari [75] presented the parametric study of passive and active solar stills integrated with a flat plate collector. Computer based thermal models were developed based on two assumptions: \( T_{gi} = T_{go} \) and \( T_{gi} \neq T_{go} \). The results show that (i) there is an effect of the inner and outer glass temperature on the daily yield of both active and passive solar stills. (ii) the mean estimated error involved in predicting the hourly yield of the passive solar still and active solar still using the thermal model based on the assumption that \( T_{gi} = T_{go} \) is 6% and 3% respectively. Hence, the thermal model of solar stills should be developed based on the assumption that \( T_{gi} \neq T_{go} \). (iii) the results of the thermal model for the active solar still for Number of collector = 1 show that the daily yield values are 3.08 kg and 2.85 kg for \( T_{gi} = T_{go} \) and \( T_{gi} \neq T_{go} \) respectively.

Dwivedi and Tiwari [76] evaluated the internal heat transfer coefficients of single and double slope passive solar stills in summer as well as winter climatic condition by various thermal models. They found that the Dunkle’s models can be used for determination of internal heat transfer coefficients in lower water depths. Gaur and Tiwari [77] developed the theoretical model for optimizing the number of collectors used in hybrid photovoltaic/thermal active solar still and found that the numerical value of evaporative heat transfer coefficient is very high as compared to convective and radiative heat transfer coefficients.

Performance of a passive solar still is based on productivity, efficiency as well as internal heat and mass transfer coefficient is discussed by Irfan Ali et al. [78]. Hence performance directly proportional to internal heat transfer coefficient and distillate
output from solar still. Internal heat and mass transfer coefficient in the solar still based on three parameters called convection, radiation and evaporation, hence there are three heat transfer coefficient called convective heat transfer coefficient, radiative heat transfer coefficient and evaporative heat transfer coefficient.

The energy received by the basin plate is equal to the summation of the energy gained by the basin plate, energy lost by convective heat transfer between basin, water and side losses.

\[
\text{energy received by basin plate} = \text{energy gained by basin plate} - \text{energy lost by convective heat transfer between basin, water and side losses}
\]

\[
(1) \quad (\text{---}) \quad (2.1)
\]

\[
(1) \quad (\text{---}) \quad (\text{---}) \quad (2.2)
\]

where
- incident angle on an inclined surface
- incident angle on a horizontal surface
- diffuse radiation on a horizontal surface, W/m²
- global radiation on a horizontal surface, W/m²

The energy received by the saline water in the still \( (1) \) solar radiation and convective heat transfer between basin and water are equal to the summation of energy lost by convective heat transfer between water and glass, radiative heat transfer between water and glass, evaporative heat transfer between water and glass and energy gained by the saline water:

\[
(1) \quad (\text{---}) \quad (2.3)
\]

The energy received by the glass cover (from sun and convective, radiative and evaporative heat transfer between water and glass is equal to the summation of energy lost by convective and radiative heat transfer between glass and sky and energy gained by the glass:

\[
(1) \quad (\text{---}) \quad (2.4)
\]
The change in basin temperature ( ), saline water temperature ( ) and glass temperature ( ) were computed by solving Equations 2.1 and 2.3.

The heat transfer process in a solar still can be broadly classified into internal and external heat transfer processes based on energy flow in and out of the enclosed space. The internal heat transfer is responsible for the transportation of pure water in the vapor form leaving behind impurities in the basin itself, whereas the external heat transfer through the condensing cover is responsible for the condensation of pure vapor as distillate.

Natural convection takes place across the humid air inside the basin due to the temperature difference between the basin water to inside surface of the glass. The rate of convective heat transfer between water to glass.

The convective heat transfer rate inside the solar still can be expressed in terms of water temperature ( ) and inner glass temperature ( ) by the following relation:

\[
\text{ ( )} \quad (2.5)
\]

In the above expression, \( \dot{\lambda} \) is the convective heat transfer coefficient between water mass and inner glass surface and can be calculated as follows:

\[
\dot{\lambda} \left( \frac{\text{water mass}}{\text{inner glass surface}} \right) \quad (2.6)
\]

The saturation vapor pressures at water temperature and glass cover inner surface temperature are evaluated by the following expressions:

\[
* \quad \left( \quad \right) + \quad (2.7)
\]

\[
\left[ \quad \left( \quad \right) \right] \quad (2.8)
\]

The radiation heat transfer occurs through a mechanism that involves the emission of internal energy of the object. The energy transfer by radiation is the fastest and it suffers no attenuation in a vacuum. Also, the radiation heat transfer occurs in solids as well as in liquids and gases. Even it can occur between two bodies separated by a
medium which is colder than both the bodies. In a solar still, the radiative heat transfer occurs between water and inner glass at the inner side and between outer glass and ambient at outer side.

The view factor plays a major role in determining the rate of radiative heat transfer. In solar still, the view factor is assumed as unity since the inclination of glass cover with horizontal is small.

The radiative heat transfer coefficient between water and inner glass can be obtained by the following relation

\[
\quad \quad \quad \quad (2.9)
\]

where \( \quad \) is the radiative heat transfer coefficient between water mass and inner glass surface and evaluated by

\[
\quad \quad \quad \quad (2.10)
\]

The effective emittance between water mass and glass cover is given as

\[
\quad \quad \quad \quad (2.11)
\]

Evaporation occurs at the liquid-vapor interface when the vapor pressure is less than the saturation pressure of the liquid at a given temperature. The evaporation heat transfer occurs in the solar still between water and water-vapor interface.

The rate of evaporative heat transfer between water mass and inner glass surface is given by

\[
\quad \quad \quad \quad (2.12)
\]

In the above expression, \( \quad \) is called as evaporative heat transfer coefficient between water mass and inner glass surface. The evaporation takes place inside the solar still by addition of heat in the water by means of solar radiation. Dunkle”s developed a model to evaluate the evaporative heat transfer coefficient as follows

\[
\quad \quad \quad \quad (2.13)
\]
The total internal heat transfer rate is the summation of convective, radiative and evaporative heat transfer rates between water mass and inner glass which is given as

\[
\text{(2.14)}
\]

\[
\text{(2.15)}
\]

The total heat transfer between water mass and inner glass is obtained by the following expression as

\[
\text{(2.16)}
\]

The external heat transfer in solar still refers to the heat transfer between the solar still and atmosphere. It is mainly governed by conduction, convection and radiation processes, which are independent to each other. The heat is lost from glass outside to atmosphere through convection and radiation modes. The glass and atmospheric temperatures are directly related to the performance of the solar still. So, top loss is to be considered for the performance analysis. The temperature of the glass cover is assumed to be uniform because of small thickness.

\[
\text{(2.17)}
\]

The heat energy from the outer glass surface is lost to the atmosphere by convection and radiation heat transfer processes.

The convection loss from glass cover outer surface of the solar still to the atmosphere is given by

\[
\text{(2.18)}
\]

The convective loss heat transfer coefficient is expressed in terms of wind velocity (v) velocity is given as

\[
\text{(2.19)}
\]

Another direct expression for total top loss heat transfer coefficient in terms of function of wind speed is given as
But, there is no significant variation in the performance of the distillation system by considering the above two Equations.

The radiation loss from glass cover outer surface of the solar still to the atmosphere is given by

\[
(\quad) \tag{2.21}
\]

The radiative loss heat transfer coefficient is given as

\[
\left(\frac{(\quad)}{(\quad)}\right) \tag{2.22}
\]

where

\[
(\quad) \tag{2.23}
\]

The total top loss heat transfer rate is the summation of convective and radiative loss heat transfer rates which is given as

\[
(\quad) \tag{2.24}
\]

\[
(\quad) \tag{2.25}
\]

The total top loss heat transfer coefficient between glass cover outer surface and atmosphere can be obtained by the following relation:

\[
(\quad) \tag{2.26}
\]

Also, the total top loss heat transfer coefficient can be determined directly in terms of wind velocity \((v)\) by the following expression:

\[
(\quad) \tag{2.27}
\]

But, no significant variation is observed in the performance of the solar still by using either of the above two expressions. The overall heat loss coefficient from glass cover inner surface to the ambient is given as

\[
(\quad/\quad) \tag{2.28}
\]
\[(\frac{\theta}{\gamma}) \quad (2.28)\]
The overall top heat loss coefficient from water mass to the atmosphere through the
glass cover is expressed as

\[
(2.29)
\]

The heat energy is lost from water to the atmosphere through basin liner and
insulation by conduction, convection and radiation processes.

The heat transfer coefficient between basin liner to the atmosphere is

\[
[ \quad ]
\]

(2.30)

where

\[
(\quad)
\]

(2.31)

The above expressions are used to calculate the heat transfer coefficient by
assuming the velocity of wind (v) at the bottom of the solar still as zero.

The overall bottom heat loss coefficient between water mass and atmosphere is
given by

(2.32)

The overall side heat loss coefficient between water mass and atmosphere is
expressed as

\[
(2.33)
\]

The overall side heat loss coefficient \((A_s)\) is neglected since the area of side walls
losing heat \((A_s)\) is very small compared with area of basin \((A_b)\) of the solar still.

Therefore, the overall external heat loss coefficient from water mass to the
atmosphere through top, bottom and sides of the solar still is expressed as

(2.34)
2.8.1 Yield and Thermal Efficiency

Following Dunkle, the rate energy lost from water surface by evaporation per m^2 is given by

\[
\text{(2.35)}
\]

\[
\text{—— (2.36)}
\]

The condensation rate is given by

\[
\text{—— (2.37)}
\]

The hourly distillate output per m^2 from distiller unit is given by

\[
\text{—— (2.38)}
\]

\[
\text{—— (2.39)}
\]

\[
\text{(2.40)}
\]

where

\[
\begin{align*}
&\text{hourly saturated vapor pressures at saline water temperature} \\
&\text{hourly saturated vapor pressures at inner glass temperature.} \\
&\text{heat loss coefficient by convection from water surface to glass,}
\end{align*}
\]

The absorptivity of the still basin \( \alpha_h \) is taken as 0.95. The convective heat transfer between basin and water is taken as 135 ( ). The side loss coefficient from basin to ambient is taken as 8 kg and the absorptivity of the water is taken as 0.05. The mass of basin without fin is taken as 1.5 kg. The absorptivity of the glass is taken as 0.0475. The exposure area of saline water and basin are taken as 0.27 . The area of the glass is taken as 0.4 . The specific heat of saline water can be calculated.

The still efficiency is defined as the ratio of heat energy used for vaporizing the water in the basin to the total Solar Intensity of radiation absorbed by the still. The daily efficiency ( ) is obtained by summing up the hourly condensate
production \( (\cdot) \) multiplied by the latent heat of vaporization \( (\cdot) \) and divided by the daily average solar radiation \( (\cdot) \) over the still area \( (\cdot) \).

The hourly yield form the solar still can be calculated as

\[
(2.41)
\]

By substituting eqn. (2.12) in (2.41), we get

\[
(2.42)
\]

where

\[
(2.43)
\]

The daily yield is also calculated as

\[
(2.44)
\]

The instantaneous thermal efficiency is calculated as

\[
(2.45)
\]

The still efficiency is defined as the ratio of heat energy used to vaporizing the water in the basin to the total solar intensity of radiation absorbed by the still. The daily efficiency \( (\cdot) \) is obtained by summing up the hourly condensate daily average solar radiation \( (\cdot) \) over the still \( (\cdot) \) and divided by the

The overall thermal efficiency of passive solar still is determined by the following expression:

\[
(2.46)
\]

where \( = \) mass of distillate collected in kg/hr

\( = \) Area of the basin in

\( (\cdot) = \) Solar radiation with respect to time and
= Latent heat of vaporization in

It can be calculated in terms of water vapour temperature by using the following expressions:

For

\[(2.46)\]

For

\[(2.47)\]

2.9 LIFE CYCLE COST ANALYSIS

The success of any engineering system depends on the techno economic analysis and socio viability of the system. A person who is purchasing the solar still should know the cost of distilled water and the payback period. Howe and Tleimat [79] have reported that the solar distillation plant of capacity less than 200 kg/day is more economical than other type of plants.

Mukherjee and Tiwari [80] carried out cost analysis of three types of solar stills namely a single slope fiber reinforced plastic solar still, a double slope fiber reinforced plastic solar still and a double slope concrete solar still. The results revealed that the cost of distilled water produced from conventional double slope stills is minimum. Sinha et al. [81] have carried out the techno economic analysis on an active solar distillation system by considering the effect of subsidy, salvage value and maintenance cost of the system.

Madani and Zaki [82] presented the life cycle cost analysis of passive solar still using porous basin and found that the cost is $ 20 per m$^3$ for a 50 m$^3$/day solar still. Techno economic analysis of multi-stage stacked tray solar still coupled with a solar collector have been reported by Adhikari and Kumar [83]. Tiwari and Tiwari [84] conducted the techno economic analysis of a single slope passive solar still based on the annual performance. The results showed that the cost per litre and the payback period for single slope passive solar still are ₹ 0.38 and 0.65 years respectively at
most favorable conditions. Also they presented the effect of initial investment, life of solar still, interest rate, maintenance cost and selling price and the payback period.

Khanna et al. [85] presented the economic analysis of passive solar still based on the following parameters; land cost, installation, direct labor, initial raw materials, maintenance and medical expenses. The result shows that the cost of distilled water is less than ₹2 per litre even in the very first year. Kabeel [86] proposed the simple economic analysis which states that the payback period of the solar still depends on the overall cost of fabrication, maintenance cost, operating cost and cost of feed water. Their economic analysis proved that the approximate payback period of fin type solar still is one year.

Velmurugan et al. [38] evaluated the cost analysis of a stepped solar still. The results show that the cost of water is $0.19 for conventional solar still, $0.3 for integrated with fin, $0.32 for integrating with fin and adding pebble in basin, $0.33 for integrating with fin and adding sponge in basin and $0.39 for integrating with fin and adding pebble and sponge in basin. The payback of all modification for solar still is more than two years. They also presented the economic analysis of solar stills by connecting a mini solar pond, stepped solar still and a single basin solar still in series and found the payback period is less than a year.

2.10 QUALITY OF DESALINATED WATER

In rural India, various surface and ground water sources are the means of the drinking water supply. Due to over exploitation of these sources, increasing industrialization and indiscriminate use of agrochemical in agricultural activities, many of these sources are getting contaminated. In India salinity and hardness are very widespread problems for underground water. In arid, semi-arid and coastal areas plenty of underground water is available but it is highly saline (2000 ppm to 3500 ppm) composed of dissolved salts and therefore, unfit for human consumption. Water-related diseases are among the most common causes of illness and death, affecting mainly the poor in developing countries. An improved water management practices have great potential to reduce the vector-borne disease burden.
Ibrahim Bathusa and Saseetharan [87] studied the water quality in eight major ponds in Tamil Nadu and concluded that, all the ponds were not safe for public use and may lead to poor ground water quality. They also inferred that, in most of the places, the quality of water was not found suitable for irrigational and drinking activities because of high concentrations of electrical conductivity and total hardness.

More number of scientists performed tests on solar distilled water. According to the report of SPRERI (Anon 1996), a sample was prepared in the lab having high fluorine content and distilled in solar still. The content of fluorine reduced from 7.74 to 1.08 mg/litre. The permissible limit for fluorine is 0.6 to 1.2 mg/litre. Zein and Dallal [88] and Zeinab S. Abdel Rehim and Ashraf Lasheen [89] observed that chlorine (Cl) content reduced to almost zero from 26600 ppm and hardness from 6627 ppm to 9 ppm.

Solar still produce demineralized water from brackish water with the help of solar energy. Most of the work done on the solar stills was directed towards the achievement of the highest possible efficiency. However, the quality of the distilled water and its possible applications were discussed by Rahbar and Esfahani [90] and Imad Al-Hayek and Omar O. Badran [91]. They performed chemical analysis to find out its possible use as potable water and compared the results with tap water. They concluded that the condensed water has to be mixed with brackish water to produce potable water. Hence this demineralized water can be used for drinking purposes by mixing it with saline water in the required ratio. The demineralized water produced by the solar stills is found to have a TDS less than 25 mg/litre. When the water is used for drinking purposes, this needs to be mixed with saline water so that the TDS meets the mineral requirements of human body. As the maximum desirable limit of TDS as per Indian Standard is 1500 ppm, the potable water to be supplied with the help of the solar still may be prepared to have same TDS. Rajiv Gandhi National Drinking Water Mission (RGNDWM) has set up a norm that 40 litres of water per day should be made available for every person in the rural area.

The Government of India provides a subsidy for the drinking water supply to community if a solar distillation plant is installed for drinking water purpose. The subsidy may be higher in remote areas than in urban areas. Keeping this in view, the
area required for solar still can be decided by knowing the salinity of brackish water to be demineralized. The following equations based on mass balance of salt in water are used to determine the quantity of saline water to be mixed with demineralized water to obtain required TDS (1500 ppm) in potable water reported by Zein and Dallal [88].

\begin{align}
\text{(2.48)} \\
\text{(2.49)}
\end{align}

where , and are volumes of brackish water, distilled and drinking water and , and are their respective salinities.

2.11 SUMMARY OF LITERATURE REVIEW

The review of literature revealed the following,

- Single basin single slope passive solar still is more economic and easy for maintenance during operation. But the yield is very low.
- Galvanized iron sheet for basin material and Thermo cool for insulation material is more suitable for solar still fabrication due to easy availability and low cost.
- Single basin single slope passive solar still made up of copper sheet gives higher distillate water yield because of its higher thermal conductivity.
- The annual yield is maximum when the condensing glass cover inclination is equal to the latitude of the place.
- In order to increase the basin water temperature in passive solar distillation unit, passive solar stills are modified with various methods like black coating inside bottom of the still basin, use of gravels and incorporating the fins.
- Only few articles are available for the use of vacuum pump in solar still application. Also, solar still coupled with a vacuum pump to maintain low pressure inside the solar still is hardly found in literature in practice.
- The glass inside temperature and the glass outside temperature are not equal in reality and therefore it should be considered during thermal modeling.
➢ The life of the solar still, maintenance cost, interest rate and selling price are the basic parameters for calculating the life cycle cost analysis.

➢ The water produced from solar still is used for drinking purposes, the distilled water should be mixed with saline water, so that the TDS meets the mineral requirements of human body.

It is evident from the literature review that the studies on solar still to enhance the distillate yield are the need of the hour. Therefore, experimental and theoretical studies on passive solar stills are carried out and the details are discussed in the following chapters.