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Thermal Modeling and Efficiency of Solar Water Distillation: A Review

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Abstract: - The most important aspect for sustaining life on earth is water. In spite of its abundant availability, a small percentage can be used for drinking purpose (approximate 1%). The solar water distillation comes out to be a non toxic and promising device which purifies water that uses a renewable solar energy source, Efficiency of the solar water distillation device can be enhanced by increasing evaporation rate that is a combined effect of solar radiation, cover glass temperature, water contamination density, base plate absorptivity and provide additional heat by solar water preheating system.

Various investigators uses thermal modeling technique to analyses performance of Solar water distillation device carrying above mentioned factors as basis and shows an optimum value to enhance efficiency. Present paper is a tabulated review of all these governing parameters and modeling equations available for suitable selection.

***Keywords*: -** Solar water distillation, Solar Energy, Active and Passive techniques, Thermal modeling, Heat and mass transfer relation.

I. INTRODUCTION

Water is gifted by nature but around 97% of the water in the world is in the ocean, approximately 2% of the water in the world is at present stored as ice in polar region, and 1% is fresh water available in earth for the need of the plants, animals and human life. This water is reducing day by day continuously. And this 1% water is available in rivers, lakes, and underground reservoir. This ground water has also been polluted due to industries, agricultural and population growth during the current year. Polluted water causing Sevier diseases like “water borne diseases”. The term “water borne diseases” is reserved largely for infections that predominantly are transmitted through contact with or consumption of infected water. And water borne diseases is affecting human health; nearly 70-75% diseases have infected water in India. The world is facing the scarcity of the fresh water. This has become a major problem and global challenge. Therefore, it is required to have a technology for water purification to meet the demand of the water all over the world.

A solar distillation (SD) technology is one of the solutions for purifying the brackish (more saline than fresh) and underground water.

Water salinity based on dissolved salts			
Fresh water	**Brackish water**	**Saline water**	**Brine**
< 0.05%	**0.05–3%**	**3–5%**	**> 5%**

It is a highly promising and an environment friendly technology. It produces distilled water which can be used as potable water for drinking and other purposes. The performance of solar distillation depends upon the design of solar still, operating and climatic conditions

Solar distillation is a relatively simple treatment of brackish (i.e. contain dissolved salts) water supplies. Distillation is one of many processes that can be used for water purification and can use any heating source. Solar energy is low grade energy available. In this process, water is evaporated; using the energy of the sun then the vapor condenses as pure water. This process removes salts and other impurities.

The solar power where sun hits atmosphere is 10^{17} watts, whereas the solar power on earth's surface is 10^{16} watts. The total worldwide power demand of all needs of civilization is 10^{13} watts. Therefore, the sun gives us 1000 times more power than we need. If we can use 5% of this energy, it will be 50 times what the world will require.

II. PRINCIPLES OF SOLAR WATER DISTILLATION

The basic principles of solar water distillation are simple, yet effective, as distillation replicates the way nature makes rain. The sun's energy heats water to the point of evaporation. As the water evaporates, water vapor rises, condensing on the glass surface for collection. This process removes impurities, such as salts and heavy metals, and eliminates microbiological organisms. The end result is water cleaner than the purest rainwater.

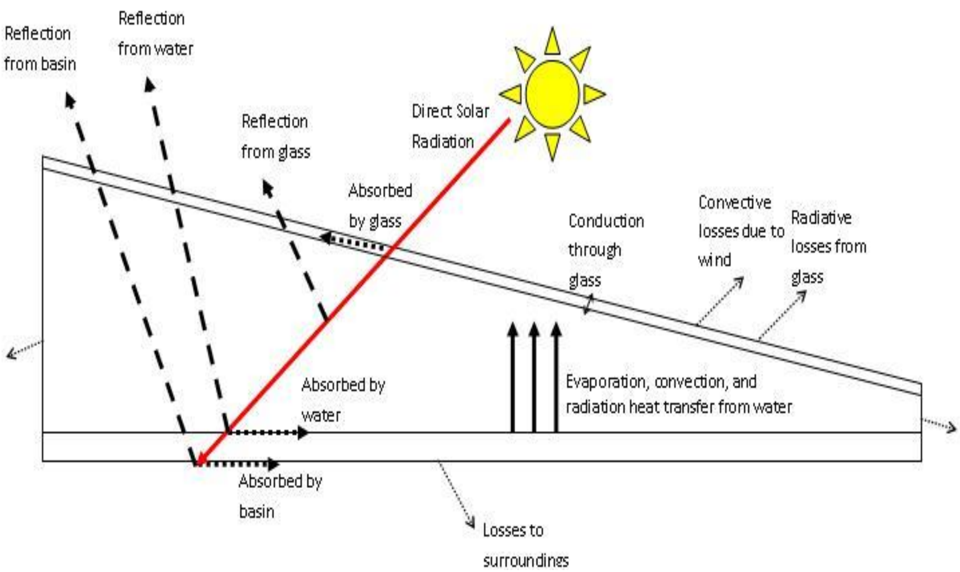

Figure 1: Simple solar water distillation process

III. DESIGN PRINCIPLE OF A SINGLE-SLOPE SOLAR WATER DISTILLATION SYSTEM

Design requirements: **[1]**

- Distills water so it is drinkable
- Has a maximum yield of distilled water
- Easy to build and repair (minimize amount of maintenance needed)
- Reliable and Easy to clean.
- Produces minimal waste at end of life
- Can withstand harsh weather conditions and degradation by heat and UV.
- Easy to use (don't need to disassemble to put the dirty water in and get the fresh water out)
- Be constructed with locally available materials, and natural building materials.
- Be light weight for ease of handling and transportation.
- Have an effective life of 10 to 20 Yrs.
- No requirement of any external power sources.
- Should also serve as a rainfall catchment surface.
- Be able to withstand prevailing winds.
- Inexpensive.
- Should be cost low.

Problems and justification:

- Dust on the transparent cover
- Algae and scaling on the inner black surface

- If it is flushed daily this may help
- Dry out ruins the still because the white salt dries to the black surface, the glass heats up and gets brittle, as well as the glass surface changes so that the condensate forms as droplets instead of a film, which decreases performance.

IV. CLASSIFICATION OF SOLAR DISTILLATION SYSTEMS

1) Active distilation
   a) High temperetur distelation
      - Auxiliary Heating
      - collector/concentretor Panel Heating
      - PV Integrated Collector (Hybrid)
   b) Normal temperetur distilation
2) Passive Distillation
   a) High Temaretur Rang (>60^{o}c)
      - Horizontal Basin solar still
      - Inclined Basin Solar still
      - Regenerative Effect Solar still
      - Vertical Solar still
      - Spharical Condensing Solar still
   b) Normal Temperature Rang(<60^{o}c)
      - Conventional Solar still
         - Singal Slop Solar still
         - Double Slope Solar still
            - Symmetrical
            - Non Symmetrical
      - New Design of Solar still
      - Inclined Solar still

Active Solar Stills

In an active solar still, an extra thermal energy is fed to the water in the basin to create a faster rate of evaporation. A broad classification of the solar stills is depicted above. Further the active solar stills are classified as:

- High temperature distillation solar stills: - hot water is fed into the basin from a solar collector panel.
- Pre-heated water application solar stills: - hot water is fed into the basin at a constant flow rate.
- Natural production solar stills:- hot water is feed into the basin once in a day.

Passive solar still

In a passive still the distillation takes place purely by direct sun light. The single slope and double slope solar stills are the conventional low temperature solar stills, operating at a temperature below 60^{o}C. Of the above two, single slope solar still is more versatile and efficient than double slope solar still.

V. HEAT TRANSFER MODE IN SOLAR WATER DISTILLATION SYSTEM

The heat transfer in solar still is mainly classified into two ways, internal and external heat transfer. The details of various heat transfers in solar still are shown in Figure 2.

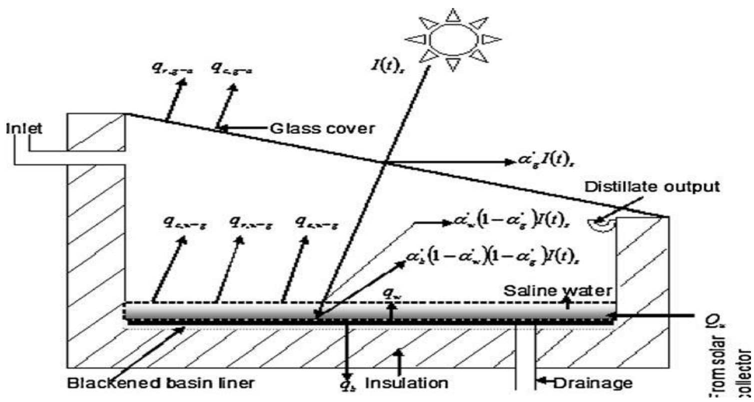

Figure 2: Energy flow diagram of single slope solar still.

5.1 Internal heat transfer

In solar still basically internal heat is transferred by evaporation, convection and radiation. The convective and evaporative heat transfers takes place simultaneously and are independent of radiative heat transfer.

5.1.1 Radiative heat transfer: – The view factor is considered as unity because of glass cover inclination is small in the solar still. The rate of radiative heat transfer between water to glass is given by

$$q_{r,w-g} = h_{r,w-g} (T_w - T_{gi}) \quad (1)$$

Where,

$h_{r,w-g}$ = Radiative heat transfer coefficient between water to glass,

$$h_{r,w-g} = \varepsilon_{eff}\, \sigma[\{(T_w+273)^2 + (T_{gi} +273)^2\}/ T_w+T_{gi}+546] \quad (2)$$

ε_{eff} = Effective emission between water to glass cover, is presented as

$$\varepsilon_{eff} = 1/ [(1/\varepsilon_g + 1/\varepsilon_w)-1] \quad (3)$$

5.1.2 Convective heat transfer: – Natural convection takes place across the humid air inside the basin due to the temperature difference between the water surfaces to inner surface of the glass cover. The rate of convective heat transfer between water to glass is given by [3]

$$q_{c,w-g} = h_{c,w-g} (T_w - T_{gi}) \quad (4)$$

Where,

$h_{c,w-g}$ = Convective heat transfer coefficient depends on the temperature difference between evaporating and condensing surface, physical properties of fluid, flow characteristic and condensing cover geometry.

The various models were developed to find the convective heat transfer coefficient.

One of the oldest methods was developed by Dunkle's [4] and his expressions have certain limitations, which are listed below.

I. Valid only for normal operating temperature (≈50^0C) in a solar still and equivalent temperature difference of $\Delta T=17^0$C.
II. This is independent of cavity volume, i.e., the average spacing between the condensing and evaporating surfaces.
III. This is valid only for upward heat flow in horizontal enclosed air space, i.e., for parallel evaporative and condensing surfaces.

The convective heat transfer coefficient is expressed as [4]

$$h_{c,w-g} = 0.884(\Delta T')^{1/3} \quad (5)$$

Where,

$$\Delta T' = (T_w - T_{gi}) + [(P_w - P_{gi})+(P_w+273)/(268.9\text{x}10^{-3} - P_w)] \quad (6)$$

$$P_w = \exp [25.317-\{5144/ (273+T_w)\}] \quad (7)$$

$$P_{gi} = \exp [25.317-\{5144/ (273+T_{gi})\}] \quad (8)$$

Chen et al. [5] developed the model of free convection heat transfer coefficient of the solar still for wide range of Rayleigh number ($3.5 \text{ x } 10^3 < Ra < 10^6$) and as follows,

$$h_{c,w-g} = 0.2Ra^{0.26}\; k_v /x_v \quad (9)$$

Zheng et al. [6] have developed a modified Rayleigh number using Chen et al. [5] model for evaluating the convective heat transfer coefficient,

$$h_{c,w-g} = 0.2(Ra')^{0.26}\; k_v /x_v \quad (10)$$

Where,

$$Ra' = (x_v^3\, \rho_v\, g\, \beta/\mu_v\, \alpha_v)\, \Delta T'' \quad (11)$$

$$\Delta T'' = [(T_w - T_{gi}) + [(P_w - P_{gi})/[\{M_a P_t/(M_a - M_{wv})\} - P_w]\, (T_w + 273.15)] \quad (12)$$

The convective heat transfer between basins to water is given by [7]

$$q_w = h_w(T_b - T_w) \quad (13)$$

The convective heat transfer coefficient between basins to water is given as,

$$h_w = K_w/X_w\, C\, (Gr \text{ x } Pr)^n \quad (14)$$

Where, C = 0.54 and N = 1/4

5.1.3 Evaporative heat transfer: - The performance of solar still depends on the evaporative and convective heat transfer coefficients. Various scientists developed mathematical relations to evaluate the evaporative and convective heat transfer coefficients.

The general equation for the rate of evaporative heat transfer between water to glass is given by [3]

$$q_{e,w-g} = h_{e,w-g} (T_w - T_{gi}) \quad (15)$$

$h_{e,w-g}$ = Evaporative heat transfer coefficient.

$$h_{e,w-g} = 16.273 \times 10^{-3} \times h_{e,w-g} \, [P_w - P_{gi} / T_w - T_{gi}] \text{ (developed by Dunkle's) [4]} \quad (16)$$

Malik et al. [8] developed a correlation based on Lewis relation for low operating temperature range and it is expressed as,

$$h_{e,w-g} = 0.013 \, h_{c,w-g} \quad (17)$$

The total heat transfer coefficient of water to glass is defined as,

$$h_{t,w-g} = h_{c,w-g} + h_{e,w-g} + h_{r,w-g} \quad (18)$$

The rate of total heat transfer of water to glass is defined as,

$$q_{t,w-g} = q_{c,w-g} + q_{e,w-g} + q_{r,w-g} \quad (19)$$

$$q_{t,w-g} = h_{t,w-g}(T_w - T_{gi}) \quad (20)$$

5.2 External heat transfer

The external heat transfer in solar still is mainly governed by conduction, convection and radiation processes, which are independent each other.

5.2.1 Top loss heat transfer coefficient: - The heat is lost from outer surface of the glass 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. The total top loss heat transfer coefficient is defined as

$$h_{t,g-a} = h_{r,g-a} + h_{c,g-a} \quad (21)$$

$$q_{t,g-a} = q_{r,g-a} + q_{c,g-a} \quad (22)$$

$$q_{t,g-a} = h_{t,g-a} (T_{go} - T_a) \quad (23)$$

The radiative heat transfer between glass to atmosphere is given by [9]

$$q_{r,g-a} = h_{r,g-a} (T_{go} - T_a) \quad (24)$$

The radiative heat transfer co efficient between glass to atmosphere is given as,

$$h_{r,g-a} = \varepsilon_g \, \sigma[(T_{go}+273)^4 - (T_{sky}+273)^4 / T_{go} - T_a] \quad (25)$$

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

The convective heat transfer between glass to atmosphere is given by [10]

$$q_{c,g-a} = h_{c,g-a} (T_{go} - T_a) \quad (26)$$

The convective heat transfer coefficient between glass to atmosphere is given as

$$h_{c,g-a} = 2.8 + (3.0 \times v) \quad (27)$$

The total internal heat loss coefficient ($h_{t,w-g}$) and conductive heat transfer coefficient of the glass (K_g/L_g) is expressed as

$$U_{wo} = [(1/h_{t;w-g}) + (L_g/K_g)] \quad (28)$$

The overall top loss coefficient (U_t) from the water surface to the ambient through glass cover,

$$U_t = h_{t,w-g} \, h_{t,g-a} / (h_{t,g-a} + U_{wo}) \quad (29)$$

5.2.2 Side and bottom loss heat transfer coefficient: - The heat is transferred from water in the basin to the atmosphere through insulation and subsequently by convection and radiation from the side and bottom surface of the basin. The rate of conduction heat transfer between basin liner to atmosphere is given by [11]

$$q_b = h_b(T_b - T_a) \quad (30)$$

The heat transfer coefficient between basin liner to atmosphere is given by [11],

$$h_b = [L_i/K_i + 1/h_{t,b-a}]^{-1} \quad (31)$$

Where,

$$h_{t,b-a} = h_{c,b-a} + h_{r,b-a} \quad (32)$$

There is no velocity in bottom of the solar still. By substituting $v = 0$, to obtain the heat transfer coefficient. The bottom loss heat transfer coefficient from the water mass to the ambient through the bottom is expressed as,

$$U_b = [1/h_w + 1/h_b]^{-1} \quad (33)$$

The conduction heat is lost through the vertical walls and through the insulation of the still and it is expressed as,

$U_s = (A_{ss}/A_s)\, U_b$ (34)

The total side loss heat transfer coefficient (Us) will be neglected because of side still area (A_{ss}) is very small compared with still basin area (A_s).The overall heat transfer coefficient from water to ambient through top, bottom and sides of the still is expressed as [11]

$U_{LS} = U_t + U_b$ (35)

5.3 Efficiency calculation

Overall thermal efficiency of solar still is,

$\eta = [\sum M_{ew} L / \sum\{I(t)_c \times A_c \times 3600\} + \sum\{I(t)_s \times A_s \times 3600\}] \times 100\%$ (36)

Where,

The hourly yield is given by the following equation

$M_{ew} = [h_{e,w-g} (T_w - T_{gi})/L] \times 3600 \times A_s$ (37)

The total daily yield is given as follows

$\text{Mew} = \sum_{i=0}^{24} \text{Mew}$ (38)

VI. LITERATURE REVIEW

6.1 Fedali Saida, Bougriou Cherif (2010), presents the thermal analysis of passive solar still. Mathematical equations for water, absorber, glass and insulator temperatures yield and efficiency of single slope basin have been derived. The analysis is based on the basic energy balance for the solar still. A computer model has been developed to predict the performance of the solar still. The operation governing equations of a solar still are solved by a Runge-Kutta numerical method. The numerical calculations indicated that the wind speed has an influence on the glass cover temperature. It was noted that in sunshine duration, temperature of various components of the distiller follows the evolution of solar radiation. [12]

6.2 Xiaohua Liu, Wenbo Chen, Ming Gu, Shengqiang Shen, Guojian Cao (2013), represented, thermal and economic performance on solar desalination system with evacuated tube collectors and low temperature multi-effect distillation. Mathematical and economic models are established based on mass and energy conservation, which conclude evacuated tube collector model, heat storage tank model, flash tank model, multi-effect distillation model and electrical heating and cooling model. Taking actual operation into account, the influence of the heating steam temperature of the first effect and the effect number of multi-effect distillation system on system performance is analyzed. The cost constitution of solar desalination system with evacuated tube collectors is shown, and the proportion of the cost of evacuated tube collector is the largest. The water cost is given out to appreciate the economic performance of the solar desalination system.

Under the calculation conditions of this paper, the following conclusions can be drawn:

- With the increasing of heating steam temperature of the first effect, the area of evaporator and fresh water cost reduce the volume of storage tank increases, but fresh water production and fresh water production per unit of collector area all change slightly.
- With the increasing of the number of effects, the volume of storage tank changes slightly, but the area of evaporator and fresh water production increase, fresh water cost reduces greatly.
- Among the cost constitution of ETC solar desalination system, the proportion of the cost of evacuated tube collector is the largest (31%), then the cost of civil installation and auxiliary equipment and the cost of manpower is second (15%). [13]

6.3 Rajesh Tripathi, G.N. Tiwari(2005), presented the thermal analysis of passive and active solar distillation system by using the concept of solar fraction inside the solar still with the help of AUTOCAD 2000 for given solar azimuth and altitude angle and latitude, longitude of the place. Experiments have been conducted for 24 h (9 am to 8 am) for New Delhi climatic conditions (latitude $28^0 35'$ N, longitude $77^0 12'$ E) during the months of November and December for different water depths in the basin (0.05, 0.1 and 0.15 m) for passive as well as active solar distillation system. Analytical expressions for water and glass cover temperatures and yield have been derived in terms of design and climatic parameters.

The following conclusions were drawn:

- The degree of agreement between theoretical and experimental results is more for active mode as compared to passive mode of operation.
- Solar fraction plays a very significant role in thermal modeling of solar still for active as well as passive mode of operation.
- Relative humidity should be measured inside the solar still, particularly, for higher depths of water in the basin.
- Temperature dependent internal heat transfer coefficients should be considered for thermal modeling of solar stills.[14]

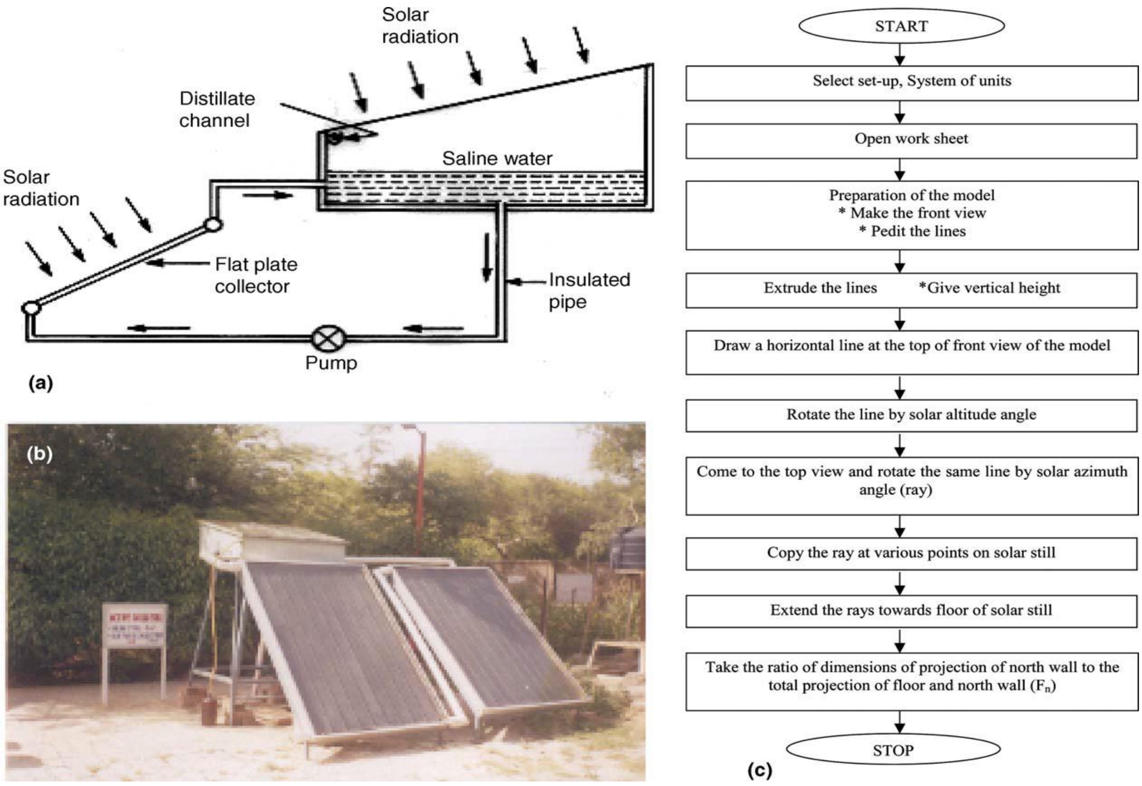

Figure 3 (a): Schematic diagram of an active solar still coupled with a flat plate collector, (b) photograph of the experimental set-up and (c) flow chart of the AUTOCAD 2000 model.

6.4 Anil Kr. Tiwari, G.N. Tiwari (2007), did experimental analysis on a setup having latitude 28.35'N for annual as well as seasonal performance. Different water depths in a single slope passive solar still of cover inclined at 30^0 for the months of June 2004 to may 2005, with six clear days per month is taken. The dominance of evaporative fraction within 32–37^0C has been noticed depending on the water depth under consideration.

On the basis of studies the following conclusions were drawn:

- The daily yield of lower water depth 0.02 m has been found 32.57% and 32.39% more than the daily yield of higher water depth 0.18 m in summer and winter respectively. The daily yield of summer, of lowest water depth (0.02 m) has been found 66.9% more than the corresponding value of winter for the same water depth.
- The annual yield obtained by lower water depth (0.04 m) is 44.28% higher than that obtained by higher water depth (0.18 m). The annual yield becomes constant for the water depths more than 0.08–0.10 m.
- In summer, unlike winter season, the evaporative energy fraction supersedes the radiative at 33^0C and at 40^0C for lower (0.02 m) and medium (0.08 m) water depths respectively, whereas it never supersedes in case of higher (0.16 m or more) water depths. The dominance of evaporative energy fraction has been observed at temperature near or more than 35^oC in both the seasons.
- Increasing the basin absorptivity from 0.40 to 0.80 can lead to 30.59% more daily yield for lower water depth whereas increase in air velocity from 0.0 m/s to 2.4 m/s can increase the daily yield by 40.06% and 50.94% for water depths 0.02 m and 0.12 m respectively.[15]

6.5 M.K. Ghosal, GN. Tiwari, N.S.L. Srivastava(2002), concerned with seasonal analysis of solar desalination system combined with a greenhouse. Analytical expressions for water temperature, greenhouse room air temperature, glass cover temperature, flowing water mass over the glass cover, hourly yield of fresh water and thermal efficiency have been derived in terms of design and climatic parameters for a typical day of summer and winter period. Temperature rise of flowing water mass with respect to distance and time in solar still unit has also been incorporated in the mathematical modeling.
Based on the above results, the following conclusions had been drawn:

- The rate of increase in the yield of fresh water becomes steady after the length (L) of south roof is 2.5 m.
- The yield and the fall in greenhouse maximum room air temperature ($\Delta T_{r,max}$,) decrease with increase of flow rate.[16]

6.6 Hikmet Ş. Aybar(2006), An inclined solar water distillation (ISWD) system, which generates distilled water (i.e., condensate) and hot water at the same time, was modeled and simulated. In the parametric studies, the effects of feed water mass flow rate and solar intensity on the system parameters were investigated. Finally, the system was simulated using actual deviations of solar intensity and environment temperature during a typical summer day in North Cyprus. The system can generate 3.5–5.4 kg (per m2 absorber plate area) distilled water during a day (i.e., 7 am till 7 pm). The temperature of the produced hot water reached as high as 60EC, and the average water temperature was about 40EC, which is good enough for domestic use, depending on the type of feed water. The simulation results are in good agreement with the experimental results. [17]

6.7 Gajendra Singh , Shiv Kumar, G.N. Tiwari (2011), devolved a double slope hybrid (PVT) active solar still which was designed, fabricated and experimentally tested under field conditions for different configurations. Parallel forced mode configuration of the solar still will produce higher yield than the other configurations and obtained as 7.54 kg/day with energy efficiency of 17.4%. The hourly exergy efficiency is also found to be highest for the same configuration and reached as high as 2.3%. The comparative yield obtained is about 1.4 times higher than that obtained for hybrid (PVT) single slope solar still. Annual yield is expected to be 1939 kg. The estimated energy payback time is found to be 3.0 years and is about 30% less than the hybrid (PVT) single slope solar still. The total cost of the fabricated still is about 14% less than hybrid (PVT) single slope solar still, experimental setup shown in figure 5. [18]

Figure 5: Integrated flat plate collectors (FPCs) and double slope solar still.

Figure 6: Photograph of hybrid (PVT) Active solar still.

6.8 Shiv Kumar (2013) did thermal and economic evaluation of a hybrid (PVT) active solar distillation system incorporating the effect of subsidy, tax benefit, inflation, and maintenance costs is presented for the climatic condition of New Delhi (India). The analysis is based on annualized costing and for the expected life spans of 15 and 30 years. Further CO2 emission/mitigation and revenue earned due to carbon credit are taken into account as per norms of Kyoto Protocol for India. Energy production factor (EPF) and life cycle conversion efficiency (LCCE) are found to be 5.9% and 14.5%, respectively, for expected life of 30 years. The energy and distillate production costs are found to be Rs. 0.85/kWh and Rs. 0.75/L, respectively, accounting the carbon credit earned. The cost payback period is estimated to be 4.2 years, if the distillate is sold out at the rate of Rs. 6.0/L in the local market, experimental setup shown in figure 6 [19]

VII. CONCLUSION

Solar energy technologies and its usage are very important and useful for the developing and under developed countries to sustain their energy needs. The use of solar energy in desalination process is one of the best applications of renewable energy. Solar still has become more popular particularly in rural areas. The solar stills are friendly to nature and eco-system. Various types and developments in solar distillation systems, theoretical analysis and future scope for research were reviewed in detail. Based on the review and discussions, the following point could be concluded.

- The condensing glass cover inclination is equal to the latitude of the place for maximum distillation.
- The total cost of the fabricated still is about 14% less than hybrid (PVT) single slope solar still. The hourly exergy efficiency is also found to be highest for the same configuration and reached as high as 2.3%. The comparative yield obtained is about 1.4 times higher than that obtained for hybrid (PVT) single slope solar still.
- Single slope passive solar still is more efficient than the double slope passive solar still.
- The thermal efficiency of double slope active solar still is lower than the thermal efficiency of double slope passive solar still.
- The energy efficiency of double slope active solar still is higher than the energy efficiency of double slope passive solar still.
- In active double effect solar still, a higher yield from the lower basin at noon is due to the high water temperature at that time.
- The hourly yield is only possible in the active mode of operation and hence commercially viable.

Solar still is suited to villages and to mass production water purification. Around the world, concerns over water quality are increasing, and in special situations a solar still can provide a water supply more economically than any other method. The two big advantages of a solar still are that it uses low grade solar energy which is available forever and there is no green house pollutant evolution as is the case with other desalination techniques using fossil fuels. Further it can be utilized in remote places where there is no electricity and fuels.

Nomenclature

Aa	Aperture area of concentrating collector (m^2)
Ac	Area of solar collector (m^2)
Ar	Receiver area of concentrating collector (m^2)
Ass	Area of sides in solar still (m^2)
As	Area of basin in solar still (m^2)
C	Constant in Nusselt number expression
C_p	Specific heat of vapor (J/kg ^oC)
C_w	Specific heat of water in solar still (J/kg ^oC)
g	Acceleration due to gravity (m/s^2)
Gr	Grashof number
$h_{c,b-a}$	Convective heat transfer coefficient from basin to ambient (W/m^2 ^oC)
$h_{r,b-a}$	Radiative heat transfer coefficient from basin to ambient (W/m^2 ^oC)
$h_{t,b-a}$	Total heat transfer coefficient from basin to ambient (W/m^2 ^oC)
$h_{c,g-a}$	Convective heat transfer coefficient from glass cover to ambient (W/m^2 ^oC)
$h_{r,g-a}$	Radiative heat transfer coefficient from glass cover to ambient (W/m^2 ^oC)
$h_{t,g-a}$	Total heat transfer coefficient from glass cover to ambient (W/m^2 ^oC)
$h_{c,w-g}$	Convective heat transfer coefficient from water to glass cover (W/m^2 ^oC)
$h_{e,w-g}$	Evaporative heat transfer coefficient from water to glass cover (W/m^2 ^oC)
$h_{r,w-g}$	Radiative heat transfer coefficient from water to glass cover (W/m^2 ^oC)
$h_{t,w-g}$	Total heat transfer coefficient from water to glass covers (W/m^2 ^oC)
h_w	Convective heat transfer coefficient from basin liner to water (W/m^2 ^oC)
h_b	Overall heat transfer coefficient from basin liner to ambient through bottom insulation (W/ m^2 ^oC)
I(t)c	Intensity of solar radiation over the inclined surface of the solar collector (W/m^2)
I(t)s	Intensity of solar radiation over the inclined surface of the solar still (W/m^2)
K_i	Thermal conductivity of insulation material (W/m ^oC)
K_g	Thermal conductivity of glass covers (W/m ^oC)
K_v	Thermal conductivity of humid air (W/m ^oC)
K_w	Thermal conductivity of water (W/m ^oC)

L	Latent heat of vaporization (J/kg)
L_i	Thickness of insulation material (m)
L_g	Thickness of insulation glass covers (m)
M_a	Molecular weight of dry air (kg/mol)
m_{ew}	Hourly output from solar still (kg/m^2 h)
M_{ew}	Daily output from solar still (kg/m^2 day)
M_w	Mass of water in the basin (kg)
M_{wv}	Molecular weight of water vapor (kg/mol)
n	Constant in Nusselt number expression
P_{gi}	Partial vapor pressure at inner surface glass temperature (N/m^2)
Pr	Prandtl number
P_t	Total vapor pressure in the basin (N/m2)
P_w	Partial vapor pressure at water temperature (N/m2)
$q_{c,w-g}$	Rate of convective heat transfer from water to glass cover (W/m^2)
$q_{e,w-g}$	Rate of evaporative heat transfer from water to glass cover (W/m^2)
$q_{r,w-g}$	Rate of radiative heat transfer from water to glass cover (W/m^2)
$q_{t,w-g}$	Rate of total heat transfer from water to glass cover (W/m^2)
$q_{r,g-a}$	Rate of radiative heat transfer t from glass cover to ambient (W/m^2)
$q_{c,g-a}$	Rate of convective heat transfer from glass cover to ambient (W/m^2)
$q_{t,g-a}$	Rate of total heat transfer from glass cover to ambient (W/m^2)
q_w	Rate of convective heat transfer from basin liner to water (W/m^2)
q_b	Rate of heat transfer from basin liner to ambient (W/m^2)
Ra	Rayleigh number
Ra'	Modified Rayleigh number
T	Time (s)
T_a	Ambient temperature (^{o}C)
T_b	Basin temperature (^{o}C)
T_{gi}	Inner surface glass covers temperature (^{o}C)
T_{go}	Outer surface glass cover temperature (^{o}C)
T_{sky}	Temperature of sky (^{o}C)
T_w	Water temperature (^{o}C)
ΔT	Temperature difference between water and glass surface (^{o}C)
U_b	Overall bottom heat loss coefficient (W/m^2 ^{o}C)
U_s	Overall side heat loss coefficient (W/m^2 ^{o}C)
U_{LC}	Overall heat transfer coefficient for solar collector (W/m^2 ^{o}C)
U_{LS}	Overall heat transfer coefficient for solar still (W/m2 ^{o}C)
U_t	Overall top heat loss coefficient from water surface to ambient air (W/m^2 ^{o}C)
V	Wind velocity (m/s)
X_v	Mean characteristic length of solar still between evaporation & condensation surface (m)
X_w	Mean characteristic length of solar still between basin and water surface (m)

Greek letters

α	Absorptivity
α_υ	Thermal diffusivity of water vapor (m^2/s)
α'	Fraction of energy absorbed
(α_τ)	Absorptance–transmittance product
β	Coefficient of volumetric thermal expansion factor (1/K)
ε	Emissivity
γ	Relative humidity
μ_v	Viscosity of humid air (Pa s)
ρ_v	Density of vapor (kg/m^3)
σ	Stefan Boltzman constant (5.67 x10^{-8} W/m^2 K^4)

Subscripts

a	Ambient
b	Basin liner
c	Collector
eff	Effective
g	Glass cover
s	Solar still

w Water

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