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Pal, Piyush
Department of Mechanical Engineering, Motilal Nehru National Institute of Technology Allahabad

Nayak, Ajaya Ketan
Energy & Environmental Engineering, Graduate School of Engineering Science, Kyushu University

Dev, Rahul
Department of Mechanical Engineering, Motilal Nehru National Institute of Technology Allahabad

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A Modified Double Slope Basin Type Solar Distiller: Experimental and Enviro–Economic Study

Piyush Pal[1,*], Ajaya Ketan Nayak[2], Rahul Dev[1]

[1]Department of Mechanical Engineering, Motilal Nehru National Institute of Technology Allahabad, Allahabad–211004, Uttar Pradesh, India.

[2]Energy & Environmental Engineering, Graduate School of Engineering Science, Kyushu University, 6–1 Kasuga–Koen, Kasuga, Fukuoka 816–8580, Japan

*Author to whom correspondence should be addressed,
E-mail: rme1454@mnnit.ac.in, piyushpal19@gmail.com

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This paper investigates thermal performance of modified double slope basin type solar distiller (MDSBSD) located at the roof of Mechanical Engineering Department, M.N.N.I.T. Allahabad (25.45°N, 81.85°E), Uttar Pradesh, India. In this study, solar still is fabricated with FRP (basin and north wall) and Acrylic (east, west and south walls) material to enhance the heat input and yield rate. Experiments were conducted to predict their performance, exergy and enviroeconomic analysis (carbon credits), distillate quality and economic feasibility. Maximum distillate yield of 2744 ml/day was obtained at 1 cm water depth in the month of November, 2015. Maximum energy efficiency and exergy efficiency noticed were 26.74% and 1.94%, respectively. Energy payback and payback time of the solar still were around 1.33 years and 235 days, respectively and it can prevent 15.16 tons of CO_2 emission during 15 years of lifetime.

Keywords: solar energy, design modification, desalination, exergy, carbon credit.

1. Introduction

Water is one of the essential sources for sustaining the human life. The resources of water are abundant in quantity but its resources are finite in the earth. Human gets the potable or fresh water from natural resources like lakes, rivers, and underground water but due to environmental pollution and excess contaminations of chemicals, potable water also gets impure. Various types of organic, inorganic impurities and salts exist in water. The consumptions of water by human relative to the level of salt concentration is determined by Total Dissolved Solids (TDS) level. The TDS level of 300 mg/l is considered as excellent and beyond 1200 mg/l, it is assumed as unacceptable. The maximum limit of salt concentration in potable water for consumption is 550 ppm[1)]. Rapid industrialization, global climate change, increasing mechanization in agriculture and most influencing world's population are factors, due to which, the level of underground water available all over the world decreases at a very faster rate. Due to heavy exploitation of freshwater resources, the whole world faces the severe consequences and its impact on the environment. The one promising solution to this problem is transporting the fresh water to these countries or communities, but this alternative looks not feasible due to the magnitude of cost associated with transportation [2,3)]. So, one should insight into this problem, and search for alternatives, which is eco–friendly and cost–effective. Desalination is one of the promising technique for mitigating water scarcity. It is very effective in regions, which are located near to sea bodies. Depending upon the process for water purification while specific energy consumption ranges from 2.5–15 kWh/m^3, desalination methods like reverse osmosis (RO), multi–stage flash distillation (MSF), multi–effect distillation (MED), capacitive deionisation (CDI) have been available for obtaining the potable water [4)], but these techniques are energy intensive or depend upon power–grid electricity[5)]. The MSF and MED are thermal powered and using the power plant steam at low–pressure stages. The reverse osmosis process (membrane based) shares about 63% of potable water production[4)]. Capacitive Deionisation is the new desalination techniques and still needs significant improvement to be emulating technique in comparison to well–established conventional water purification techniques[5)]. In developing countries, ultrafiltration (UF), nanofiltration (NF), and membrane technologies are suitable for the supply of potable water to urban population[6)]. Solar desalination is one of the solar energy based environmental friendly technique, which can purify highly saline seawater/brackish water in water scares regions, which get the huge amount of solar radiation annually like some of the countries situated in the middle east[7]. The range of solar irradiance in the Middle East and North Africa (MENA) region ranges between 1100–2800 kWh/m^2/year[8,9]. Arab alchemists have been drafted the work on solar distillation in 1551. In the past years (1872–1970), various applications, detailed history review, theory and economic analysis of various solar distillers have been prepared[10]. Researchers demonstrated the design and fabrication of various large and laboratory scale distillation models and also presented detailed study and performance aspects of solar driven distillation techniques[11]. Sayigh and Salem in Riyadh, Saudi Arabia experimentally conducted research on single slope solar distillers, which were fabricated basin type and used concrete[12]. Different types of solar stills with different slopes of condensing glass cover having varying thickness have been analyzed. Solar still with an absorbent material like black stones, charcoal, straw, black and red sand embedded in their water trays have also been experimentally analyzed and researchers found that, the optimum slope and thickness of condensing glass cover to be 20° and 3 mm, respectively. Solar collector integrated basin type single slope solar still was experimentally performed with the daily change in salinity (salt concentration) of water mass[13]. In basin type solar distillers, for enhancing the rate of heat transfer inside solar still, absorbing material like charcoal particles have been used[14]. A review has been done on various configuration and effect of climatic, design, and operational parameters have been presented[15]. A performance analysis has been carried out for simple multi–wick distiller and double–condensing multi–wick solar still. The additional surface provides a more area for condensation of vapor, which in turn reduces the temperature of the glass cover and heat load. A 20% increase in distillate output has been observed for double–condensing solar still than its simple multi–wick solar still counterpart[16]. Wick material like waste cotton pieces, light cotton cloth, and coir mate have been used in double slope basin type solar still for reducing the mass flow rate of water. The observation suggested that black cloth gives the better performance than rest of the wicks[17]. Different nanofluids had been used in passive double slope solar still to increase the heat transfer rate. With the help of characteristics equation and thermal efficiency, the Al_2O_3 metallic nanofluids have been found better nanofluids in comparison to TiO_2 and CuO[18]. A double slope single basin solar still has been designed with mild steel plate, in which different sensible heat capacity material like iron chips, pieces of red brick and concrete cement, washed stone and quartzite rock had been used with the different layer of water. It is observed from the study, the solar still with quartzite rock (sized 3/4 in.) was the effective basin material[19]. A double slope passive solar still had been fabricated and analyzed its annual performance based on energy, exergy, and life cycle cost analysis and payback time[20]. Based on the climatic condition of New Delhi, India, the quasi steady–state linear and non–linear characteristic equations have been developed for double slope passive solar distiller. It is found from the study that, non–linear characteristic curve are more precise for demonstrating the performance of solar still[21]. Using thermoelectric modules in double slope solar still to gain in water temperature and hence improve the thermodynamic performance for the climatic conditions of Semnan (35°33' N, 52°23' E), Iran. An exergy and economic analysis have also been done to characterize the solar still. It is found from the study, the maximum exergy efficiency is 25%[22]. A thermal model developed for double slope solar still for the climatic condition of Allahabad, India[23]. Among the available technologies (thermal–based) for water purification, which used waste heat or solar heat for cooling and yield potable water is adsorption desalination. In this technique, the evaporation of water takes place in evaporator followed by silica gel absorption and desorption of water vapor in condenser regardless the feed water quality (TDS value). The absorbent like silica gel has high congeniality of water vapor due to surface forces (double bond) exist between meso–porous absorbent and an adsorbate. The specific energy consumption is below 1.5 kWh/m^2, which is lower due to the utilization of low temperature heat source[24]. A 3–bed 2– evaporator adsorption cycle using silica gel as an absorbent material has the surface area of 863.6 m^2/g and pore volume of 0.446 cm^3/g. Dehumidification and cooling produce at two temperature–levels while producing the distillate of high–grade. A two–stage adsorption is achieved through a low–pressure and high–pressure evaporators for enhancing the capacity of silica gel. The regeneration is achieved by providing the one absorber bed for enhancing the kinetics of desorption process. The performance indicators like coefficient of performance, specific daily water production, performance ratio, and specific cooling power have been analyzed[4]. A 3–stage multi–effect desalination and multi–effect desalination integrated with adsorption desalination plant have been probed with potable water as a feed and 15 °C to 70 °C temperature of the heat source. A valuable increase in distillate production and low primary consumption of energy (14.5 kWh/m^3) has been achieved[25,26]. Fig. 1 shows the energy requirements for desalination methods[25].

Table 1 shows the approximate ranges of energy demands for various desalination technologies.

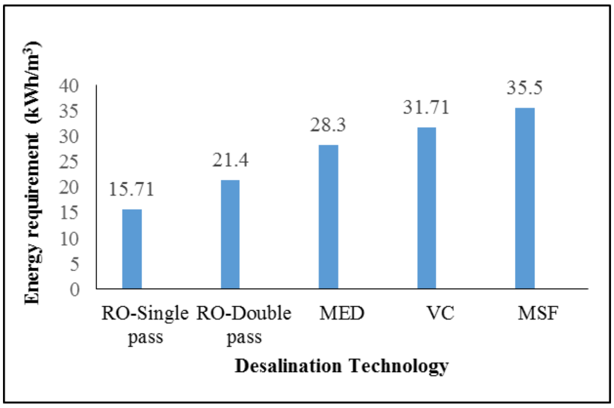

Fig. 1: Energy requirements for desalination methods.

Table1: Approximate ranges of energy demands for various desalination technologies [5].

Technology	**Energy demand (kWh/m^3)**
Multi–stage flash distillation (MSF)	9–60
multi–effect distillation (MED)	7–59
Reverse osmosis (RO)	2–7
Electrodialysis (ED)	0.3–8.8
Capacitive deionisation (CDI)	0.1–2.05

A lot of money has been spent on design and development of centralized large scale water purification systems that are difficult to maintain with the help of local expertise and technique[6]. Experiments are being conducted regularly to develop self–sustained system to meet the requirement of pure and fresh water. Rigorous research and experimental work have been carried out by various researchers or scientists on design, fabrication to increase the water temperature or increase the water–glass cover surfaces temperature difference for purification of saline/brackish/polluted water. Few works reported on GRP fabricated solar still but no work has been done so far for the FRP–Acrylic modified double slope basin type solar still for the climatic conditions of Allahabad (U.P.), India (Latitude 25°27′ N & Longitude 81°44′ E) in which east, west, and south wall are made transparent to enhance the solar thermal energy inside the solar still to stimulated the heat transfer rate. Pal et al. carried out the performance study of modified basin type multi–wick double slope solar still[27].

2. Experimental setup, working principle, and modifications

In this, basic design, calculation of equivalent thickness, working of MDSBSD and modifications introduced are discussed.

2.1 Setup design description

The length and breadth of solar still are 2 m and 1 m, respectively. The rectangular basin of dimension 2 m^2 (length 2 m and breadth 1 m) and north wall are made of Fibre–Reinforced Plastic (FRP) sheet of 5 mm thickness which is black colored from the inside to absorb the maximum amount of incident solar radiation. The north wall has a trapezoidal section with the length of 1 m and height from the solar still base to the end is 0.12 m. The height from the solar still base to the apex of the north wall is 0.38 m. The south, east and west side walls are made of the transparent acrylic sheet of 3 mm thickness. The dimension of east and west wall are 1 m in length (breadth wise dimension of solar still) and 0.12 m in height from solar still base. The dimension of the south wall is same as that of the north wall due to axis symmetry design of solar still. The area in which condensation takes place, also called effective condensing area (or transparent area) is equal to 2.86 m^2 (except north wall). The basin area of 2 m^2 is taken as effective evaporative area. The evaporation process is occurring between water surface (which is accumulating upon 2 m^2 basin surface) and inner condensing glass covers. The solar radiation is falling on the solar still and passing through all the transparent walls and glass covers. The amount of solar radiation then finally trap in the basin and inside north wall. The effective absorbing area i.e. basin and north wall, which absorbs the solar radiation (solar thermal energy) have an area of 2.50 m^2.

The calibrated thermocouples (Type–T Copper Constantan) have been used for measuring the temperature of various location in MDSBSD. The thermocouples have been calibrated with the help of Zeal thermometer. Fig. 2 shows the photograph of MDSBSD. The schematic diagram of MDSBSD and location of thermocouples have been shown in Fig. 3.

Fig. 2: Photograph of MDSBSD.

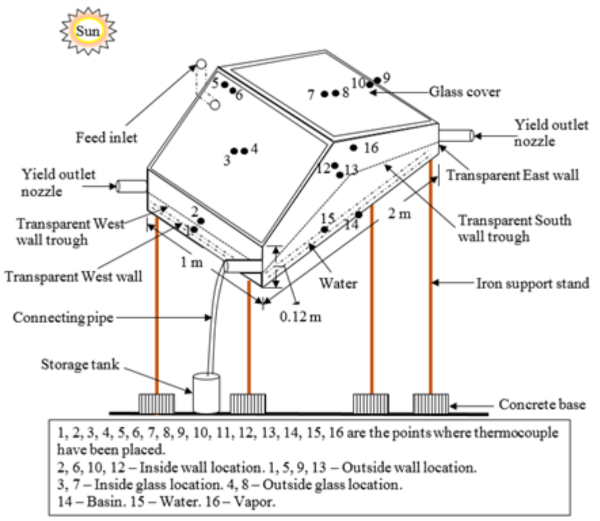

Fig. 3: Schematic diagram of MDSBSD and location of thermocouples.

For the fabrication of walls of solar still (except north wall), the rate of heat reduction or transfer through 5 mm of FRP sheet is conceptualized by equivalent thickness. The equivalent thickness for an acrylic sheet with respect to 5 mm FRP is calculated using Fourier's law of heat conduction (1–dimensional) when the two sides of FRP is maintained at T_1 and T_0 [27].

$$Q = K_{FRP} \times A_{FRP} \times \left(\frac{T_1 - T_0}{L_{FRP}} \right) = K_{ACRY} \times A_{ACRY} \times \left(\frac{T_1 - T_0}{L_{ACRY}} \right)$$

$$L_{ACRY} = \frac{K_{ACRY} \times L_{FRP}}{K_{FRP}} = \frac{0.2 \times 5\,mm}{0.351} = 3\,mm \qquad (1)$$

where, $K_{ACRY} = 0.2$ *W/m-K*, $K_{FRP} = 0.351$ *W/m-K*.

So one can use 3 mm thickness of Acrylic sheet for the designing of east, west and south walls, which is equivalently equal to 5 mm of FRP sheet. Due to variation in solar radiation, ambient temperature, and wind velocity, the study state condition for MDSBSD is not considered. Though for calculating the equivalent thickness, one can assume that the temperature inside the solar still i.e. (i) inside glass covers temperature (ii) water temperature (iii) basin temperature (iv) vapor temperature, and (v) inside wall temperature are constant throughout for every hour.

2.2 Working principle of MDSBSD

The MDSBSD works on the simple principle of distillation to purify water using solar energy as the heat source. A solar still is a simple technique to distilling water, using the heat of the sun to drive the process of evaporation from impure water contained in the solar distiller. The basic principle of solar water distillation is simple, yet effective, as distillation replicates the way nature produces rain. The south, east and west side walls are made transparent to allow the sun rays to enter the system for the whole day length. The north and the bottom surfaces are painted black to absorb the energy and prevent it from escaping and use it to heat the water. The angle of the cover has been chosen as 15° less than the 25°, the angle which was used in MDSBSD at Allahabad due to Allahabad's latitude. The 15° angle allows the height of the double slope still to be optimum at the centre since more height will cause the problem in capillary action and the water will not be fed properly for effective evaporation. Also, less height than the designed 15° angle at the centre may cause the condensed water to fall back to the basin decreasing yield and efficiency both. The water evaporated gets condensed on the inner surface of the toughened glass and is collected in the flask after it passes through well designed troughs. The incoming solar radiation from sun i.e. solar energy heats water up to evaporation point. The evaporation process creates vapour and condenses on the inner glass surfaces. After condensation, the distillate available for collection. This process discarded impurities such as heavy metals, salts, and removes microbiological organisms. The end product is clean water cleaner than the purest rainwater.

2.3 Modifications

The following modifications have been introduced to increase the heat transfer rate inside the solar still.

1. The south, east and west walls are made of the transparent acrylic sheet to allow the sun rays to enter for the whole day length increasing the heat input.
2. Condensation takes place on the ceiling of glasses as well as the south wall, thus improving the yield.
3. Efficiency is more as the heat can enter through three surfaces and yield is also increased as condensation takes place on three surfaces i.e. two inclined glass surfaces and the south wall.
4. The setup also incorporates basin which was not used in the conventional solar still and to store the energy of incoming radiations from the sun.

2.4 Advantages of FRP and Acrylic

The following are the advantages of using FRP and Acrylic as a manufacturing material for proposed solar still:

1. Acrylic has no corrosive action on the solar still. The conventional solar still were made of metals. The life of solar still deteriorates when metal comes in contact with the water[27].
2. Acrylic has high mechanical strength, extremely rigid, high heat resistance, insulating, flexible, waterproof, and transparent property[27].
3. Acrylic has good resistant to ultraviolet sunlight[27].
4. The conventional solar still were made of mild steel and for insulation, thermocol was used. Due to thermocol, the heat losses from the solar still were higher. FRP has lower conductivity value than steel

and so, the losses get reduced. FRP also have the ability to work at different temperature ranges for longer duration in different climatic conditions[27].

5. Acrylic and FRP both have lightweight and easily available in the local market. So, the cost associated with transportation and installation at the location will be lesser in comparison to conventional solar stills.

3. Experimental procedure and instrumentation

3.1 Experimental procedure

The whole solar still has been cleaned and filled the tap water up to 1 cm of depth before sunrise. All the thermocouples and thermometer has been placed at surfaces or locations for the measurement of temperatures. The solar thermal radiation, water; ambient; basin, and temperature of every location inside and outside of the solar has been recorded every hour and taken for 24 h from sunrise to next day sunrise. The experiments are carried out in a typical clear day in the month of November 2015 under the climatic condition of Allahabad, U.P., India. To collect the condensate, graduated scaled cylindrical tank was used. A stopwatch was used to precisely measure the hourly distillate yield.

3.2 Instrumentation and error analysis

Temperature measurement have been done by Type–T copper–constantan thermocouples (for the measurement of the basin, water, inside and outside locations of solar still) and FLUKE (Model 62 max) infrared thermometer (for outside locations of solar still). AMPROBE (Model SOLAR–100) solarimeter is used for solar radiation measurement. Red alcohol and Mercury in glass thermometers have also been used for temperature measurement. The accuracy, range, and error of different measuring instruments are as follows[27]: (i) Thermocouple has accuracy of ± 1 °C, range of –40 °C to 350 °C, and 10% error. (ii) Solarimeter has accuracy of ± 1 W/m^2, range of 0 to 1999 W/m^2, and 5% error. (iii) IR thermometer has an accuracy of ± 1.5 °C, range of –30 °C to 500 °C, and 5% error. (iv) Mercury in glass thermometer has an accuracy of ± 1 °C, range of –10 °C to 110 °C, and 10% error. (v) Scaled cylindrical tank has an accuracy of ± 2 ml, range of 0 to 250 ml, and 15% error.

4. Energy and exergy efficiencies

The overall energy efficiency of the solar distiller under present study is the ratio of total heat transfer rate (total yield obtained) to the total heat input into the solar still by incident solar thermal radiation and given by[28] is as follows:

$$\eta_O = \frac{\sum_{i=1}^{i=24} \dot{m}_{ew} \times L_{vap}}{\sum_{i=1}^{i=24} I(t)_{input} \times dt} \times 100 \quad (2)$$

The overall exergy efficiency of solar distiller can be defined as the ratio of useful exergy output rate to the total input exergy rate. The exergy of output is calculated as useful exergy associated with the useful evaporation rate. The expression for the exergy efficiency is defined by [22] and given as:

$$\eta_{ex} = \frac{\dot{m}_{ew} \times L_{vap}\left(1-\frac{(T_a+273)}{(T_w+273)}\right)}{I(t)_{input} \times \left(1-\frac{4(T_a+273)}{3(T_s+273)}+\frac{1}{3}\left(\frac{T_a+273}{T_s+273}\right)^4\right)} \quad (3)$$

where, L_{vap} value in kJ/kg is taken as 2260 kJ/kg.

The total input solar radiation (instantaneous) to the solar still through glass covers (east and west side) and transparent walls (east, west, and south wall) is given by Pat et al[27].

5. Results and discussion

The following is the description of results and discussion. The calibrated data was used for analysis.

Fig. 4 shows the variation of global solar radiation (W/m^2) and ambient temperature (°C) with respect to local time (h) on November 5, 2015. The ratio of diffuse radiation to global radiation was 26%[29] and this shows that the weather conditions in Allahabad, India was hazy (fully) in the month of November (winter season). The weather was cold and sunshine hour is between 7 h to 9 h. Due to winter season and latitude (25°27'N) of Allahabad, the intensity of solar thermal radiation is not much high due to tilted direction of sun rays, but with the suggested modifications, the presented solar still has gained enough amount of solar radiation. The maximum measured by Solarimeter was 876 W/m^2 at 12:00 h. The figure also shows the variation of ambient temperature. The maximum measured ambient temperature was 32.2 °C at 14:00 h.

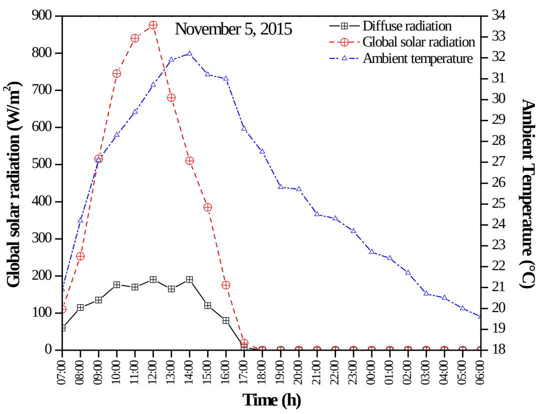

Fig. 4: Hourly variation of solar radiation and ambient temperature for a typical day at Allahabad, India.

Fig. 5 shows the hourly variation of water and basin temperature (°C) with respect to time (h) on November 5, 2015. The water and basin temperature both increases till 13:00 h afterward both decreases due to fall in radiation intensity, but after 16:00 h, the fall in basin temperature was more in comparison to water temperature. This is because of heat capacity of water mass, the water kept the heat of solar thermal radiation for longer duration and this helps in nocturnal productivity of solar still during night time. The maximum basin and water temperature were 53 °C and 44 °C, respectively at 13:00 h.

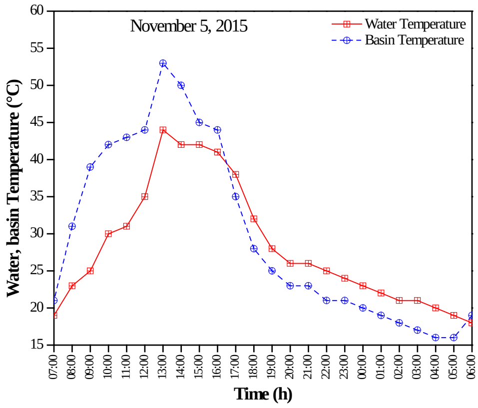

Fig. 5: Hourly variation of water and basin temperature for a typical day at Allahabad, India.

Fig. 6 shows the hourly and cumulative yield (ml) variation with respect to time (h) on November 5, 2015. The depth of water was 1 cm in the basin. The yield was increasing between 09:00h to 13:00 h due to increased amount of solar thermal radiation and transparency of walls, but after 13:00 h, yield decreases due to drop of solar intensity and water temperature. One can observe that the maximum solar radiation fall on solar still at 12:00 h, but the yield was still increasing between 12:00 h –13:00 h due to heat retention capacity of water. This prevents the drop in yield. The maximum measured hourly yield was 526 ml (263 ml/m^2) at 13:00 h. The cumulative yield for 24 hours was 2744 ml (1.372 l/m^2 day) at 1 cm water depth. When cumulative yield is compared with the thermodynamic limit (in terms of water depth) of MDSBSD, if one can reduce the water depth to 0.5 cm, the yield obtained will be nearly doubled i.e. around 5000 ml i.e. 2.50 l/m^2 day, and further reducing the water depth in solar still, a stage or limit will be achieved at which one can obtain the yield equal to the feed water amount. The higher thermodynamic limit (in terms of water depth) will reach when there is no yield production during the day at the feed water quantity. So, one can relate the thermodynamic limit of proposed solar still with the water depth in basin, but this will vary with the different months and climatic conditions of location.

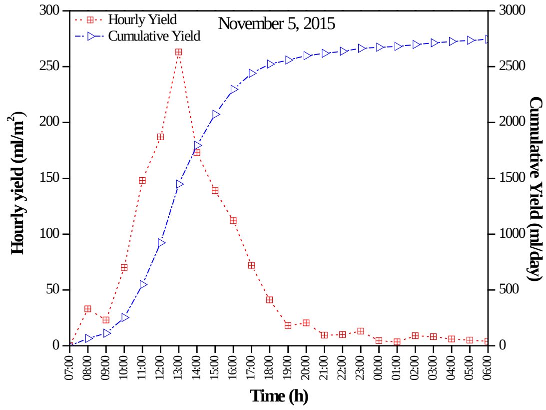

Fig. 6: Hourly variation of yield and cumulative yield for a typical day at Allahabad, India.

Fig. 7 shows the hourly thermal efficiency (instantaneous), η_i (%) and exergy efficiency (%) with respect to time (h) on November 5, 2015. Thermal efficiency was increasing till 13:00 h and afterwards efficiency drop and then again it rises. In the early hours, the efficiency was increased, but this increase in efficiency is less due to considerable increase in the solar thermal energy. The maximum efficiency occurred between 10:00 h–15:00 h was at 13:00 h due to higher productivity and higher water temperature obtained at 13:00 h. Between 13:00 h–14:00 h, efficiency drops due to fall in solar intensity and water temperature. The enhancement in total thermal energy increases till 12:00 h and then fall in solar energy because of rotation (or position) of the sun in the sky in the November month and latitude of Allahabad, India. The yield also increased till 13:00 h while the drop in total thermal energy input due to heat storage effect of water. After 13:00 h, the decrease in solar intensity and reduction in the temperature difference between the water surface and glass covers are responsible for the decrease in thermal efficiency. After 14:00 h, the efficiency again rises and maximum at 16:00 h due to very low amount of solar energy and considerable amount of yield. The maximum value of thermal efficiency was 26.74% and in between 10:00 h–15:00 h it was 16.85% (at 13:00 h). The overall thermal efficiency of solar still was 12.35%. The exergy efficiency also shows the same trend. The exergy efficiency increases between 10:00 h–13:00 h due to rise in water temperature but in between 11:00 h–12:00 h, this increment in the exergy efficiency was slower due to rise in ambient temperature. In Between 13:00 h–14:00 h, the drop in exergy efficiency was due to reduction in water temperature and increase in ambient temperature. After 14:00 h, the exergy again rises because of decreased solar intensity and fall in ambient temperature. The exergy efficiency is much lower than that of energy efficiency due to the fact that, the exergy content of the incoming solar radiation is relatively rich because of sun's surface temperature (T_S), the exergy content of the evaporative heat transfer is very low i.e. very low temperature condensate is obtained. The maximum value of exergy efficiency was 1.94% and in between 10:00 h–15:00 h it was 1.38% (at 13:00 h).

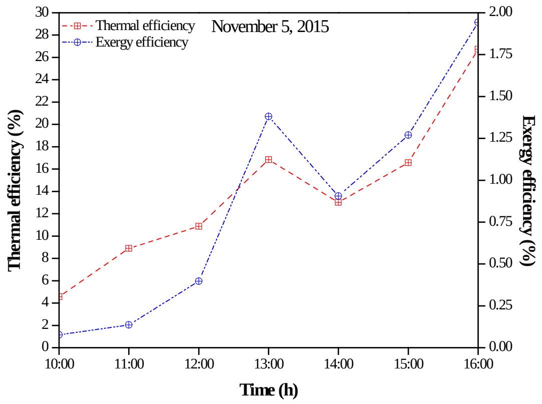

Fig. 7: Hourly variation of thermal and exergy efficiency for a typical day at Allahabad, India.

Fig. 8 shows the variation of thermal efficiency (instantaneous) with respect to term (T_w–T_a/$I(t)_{input}$) has been plotted and obtained curve is called characteristics curve. Linear and non–linear characteristics equation has also been obtained with the help of these characteristics curve. Linear characteristic curve has positive slope due to higher rate of evaporation between water and glass cover. Both the linear and non–linear curve are equally important (both have similar R^2 value) to assess the performance of solar still. The time period between 10:00 h–14:00 h is more suitable for analysis[27] due to (i) weather condition of Allahabad in winter, and (ii) in this period the solar still is in quasi–steady state and characteristics curve has minimum error.

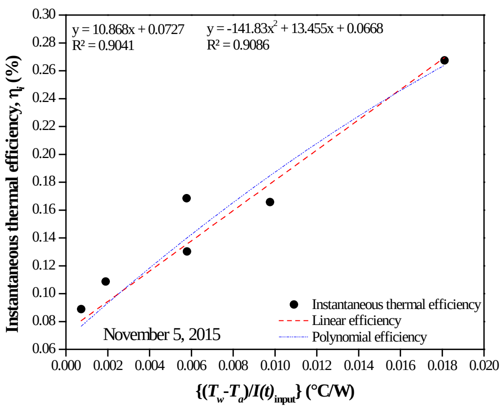

Fig. 8: Characteristic curves for the MDSBSD for a typical day at Allahabad, India

The water quality assessment have done after obtained the distillate and the parameters were under permissible limits of EPA standards[30] and WHO standards[31]. The quality parameters obtained after experimentation on November 5, 2015 were as: (i) pH = 7.5, (ii) Turbidity (NTU) = 2, (iii) TDS (mg/l) = 57, (iv) Electrical conductivity (μS/cm) = 45, and (v) Total hardness (as C_aCO_3) in mg/l = 60. These results shows that, the solar still has an ability to work under Allahabad, India climatic conditions and produce potable water.

6. Economic analysis

The payback period of the solar distiller depends upon the overall cost of design, fabrication, operating cost, maintenance cost and cost of feed water[32]. The cost of feed water is negligible. The total manufacturing cost of solar still is taken as capital cost (P_{cost}). The salvage value (*SV*), the annual maintenance cost (*AMC*), and interest rate have been taken as 15% of the capital cost, 15% of the annual first cost (*AFC*) and 12%, respectively[27]. The average daily yield of the MDSBSD is assumed as 3.50 kg/m^2. For the estimation of annual cost of distilled water (*ACDW*) per kg and per kWh. The market cost of distilled water (*MCDW*) have been assumed as Rs. 15/kg. For the economic analysis of presented solar still, 320 days are considered as clear days, in which the incident solar radiation (solar thermal energy) is responsible for yield production. The remaining 45 days are considered as fully cloudy or rainy days, in which the solar still is non–productive for the climatic condition of Allahabad (U.P.), India. The Embodied energy (E_{in}) of the different component of proposed solar still is calculated as 934 kWh. The annual solar energy retrieved (E_{sol}) by the solar still is calculated as 5500 kWh/year.

The annual first cost of MDSBSD is calculated as:

$$AFC = CRF \times P_{cost} \tag{4}$$

The annual salvage value is calculated as:

$$ASV = SFF \times SV \tag{5}$$

The total annual cost of the MDSBSD (*TAC*) is calculated as:

$$TAC = AFC + AMC - ASV \tag{6}$$

Annual yield (*AY*) of the MDSBSD is determined as:

$$AY = Average\ daily\ yield \times Number\ of\ clear\ days\ in\ a\ year \tag{7}$$

Then, the annual cost of distilled water (*ACDW*) per kg is determined as:

$$ACDW = TAC / AY \tag{8}$$

Annual useful energy (E_{out}) is calculated as:

$$E_{out} = AY \times L_{vap} \tag{9}$$

where, L_{vap} value in kWh/kg is taken as 0.627 kWh/kg.

Then, the annual cost of distilled water (*ACDW*) per kWh is obtained by:

$$ACDW = TAC / E_{out} \quad (10)$$

Table 2 shows the fabrication cost of the MDSBSD and its components. Table 3 shows the economic analysis of the MDSBSD.

Table 2: Fabrication cost of the MDSBSD.

Materials and components	Cost (Rs.)
FRP sheet	6140
Acrylic sheet	1440
Iron stand	580
Outlet nozzle	80
Black paint	120
Silicon rubber and glass putty	370
Fabrication and labor cost	2270
Total cost	**Rs. 11000**

Table 3: Economic analysis of the MDSBSD.

Cost type	Value
Total cost of still (P_{cost})	Rs. 11000
Salvage value (*SV*)	Rs. 1650
Annual salvage value (*ASV*)	Rs. 42.90
Annual maintenance cost (*AMC*)	Rs. 242.22
Annual first cost (*AFC*)	Rs. 1614.80
Total annual cost (*TAC*)	Rs. 1814.12
Annual yield (*AY*)	1120 kg/year
Annual useful energy (E_{out})	702.34 kWh/year
Annual cost of distilled water (*ACDW*)	1.62 Rs./kg
Annual cost of distilled water (*ACDW*)	2.58 Rs./kWh
Net profit (*NP*)	14985.60 Rs./year
Payback period (*PP*)	235 days

Note: NP =AY×(MCDW–ACDW)
And PP=(P_{cost}/NP)×solar still operation in a year

The energy matrices of MDSBSD i.e. energy production factor (*EPF*), energy payback time (*EPBT*), and life cycle conversion efficiency (*LCCE*) is calculated by considering the annual useful energy (E_{out}), embodied energy of the system (E_{in}), annual solar energy gain by the solar still (E_{sol}), and useful life of solar still (*n*) i.e. 15 years[33].

The energy production factor is calculated as:

$$EPF = E_{out} / AY \quad (11)$$

The energy payback time is calculated as:

$$EPBT = 1 / EPF \quad (12)$$

The life cycle conversion efficiency is calculated as:

$$LCCE = \left(\left(E_{out} \times n\right) - E_{in}\right) / E_{sol} \times n \quad (13)$$

Table 4 shows the energy production factor (EPF), energy payback time (EPBT), and life cycle conversion efficiency (LCCE) for MDSBSD.

Table 4: EPF, EPBT, and LCCE of the MDSBSD.

Energy production factor (*EPF*)	0.75
Energy payback time (*EPBT*)	1.33 years
Life cycle conversion efficiency (*LCCE*)	0.11

7. Enviroeconomic analysis (environmental cost)

It is associated with the cost of CO_2 emission and used non–traditional sources of energy in such a way that renewable sources of energy does not emit CO_2 to the environment. 0.98 kg of CO_2 is emitted per kWh (average) at source and that is equivalent to electricity production from coal per kWh. For the indian conditions, the distribution and transmission losses are considered around 40% and domestic appliances losses are around 20%, then amount of CO_2 emission is 1.58 kg per kWh[34,35]. Therefore,

The annual CO_2 emission is calculated as:

$$Annual\, CO_2\, emission = \left(E_{in} \times 1.58\right) / n \quad (14)$$

The amount of CO_2 mitigation (kg of CO_2) can be expressed as:

$$Amount\, of\, CO_2\, mitigation\left(kg\, of\, CO_2\right) = E_{out} \times 1.58 \quad (15)$$

The CO_2 mitigation (kg of CO_2) over life time is calculated as:

$$CO_2\, mitigation\left(kg\, of\, CO_2\right) over\, life\, time = E_{out} \times n \times 1.58 \quad (16)$$

Therefore, net CO_2 mitigation (tons of CO_2) over life time is determined as:

$$Net\, CO_2\, emission\left(tons\, of\, CO_2\right) over\, life\, time = \left(E_{out} \times n - E_{in}\right) \times 1.58 \times 10^{-3} \quad (17)$$

Presently CO_2 has been merchandised at € 7.07 per ton of CO_2 mitigation. So, the carbon credit earned by the system in terms of indian currency (Rs.) can be expressed as:

$$Carbon\, credit\, earned = \left(E_{out} \times n - E_{in}\right) \times 1.58 \times 10^{-3} \times 7.07 \times 76.57 \quad (18)$$

where, € 1 = Rs. 76.57

Table 5 shows the enviroeconomic analysis for the MDSBSD for the 15 years of lifetime.

Table 5: Enviroeconomic analysis of the MDSBSD.

Annual CO_2 emission	98.38 kg/year
CO_2 mitigation (kg of CO_2) over life time	16643.08 kg
Net CO_2 mitigation (tons of CO_2) over life time	15.16 tons
Carbon credit earned	Rs. 8207

8. Conclusions

In this work, a modified basin type double slope solar distiller was designed, fabricated and the experimentation was done under the climatic condition of Allahabad (U.P.), India. The following conclusion have been drawn from this study:

1. Heat input has increased due to transparent east, west and south walls and hence there was a significant increase in the yield and efficiency.
2. Water was collected from the south wall also as it is made transparent, hence, the yield of the still has improved.
3. The maximum measured solar radiation was 876 W/m^2 at 12:00 h and maximum measured ambient temperature was 32.2 °C at 14:00 h.
4. The maximum measured yield obtained was 526 ml at 13:00 h. The cumulative yield was 2744 ml/day at 1 cm water depth.
5. The maximum (instantaneous) thermal efficiency and overall thermal efficiency of proposed solar still were 26.74% and 12.35%, respectively.
6. The exergy efficiency has opposite trend with respect to ambient temperature. The maximum exergy efficiency of the proposed solar still was 1.94%.
7. The water quality parameters were well under permissible limits of EPA and WHO standards.
8. The annual cost of distilled water per kg and per kWh were Rs. 1.62 and Rs. 2.58, respectively, when the useful life and interest rate for the MDSBSD have been considered 15 years and 12%, respectively.
9. The payback period, energy production factor, energy payback time, and life cycle conversion efficiency of the proposed solar still were 235 days, 0.75, 1.33 years, and 0.11, respectively.
10. The carbon credit earned was Rs. 8207 for 15 years of lifetime of solar still. So, with the help of renewable source of energy, this proposed solar still generates pure water and efficient revenues, which propels mankind to use self–sustainable technology.

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Nomenclature

A_{ACRY}	Area of cross section of acrylic, m^2
ACDW	Annual cost of distilled water, Rs./kg or Rs./kWh
AFC	Annual first cost, Rs./year
A_{FRP}	Area of cross section of FRP, m^2
AMC	Annual maintenance cost, Rs./year
ASV	Annual salvage value, Rs./year
AY	Annual yield, kg/year
CRF	Capital recovery factor, dimensionless
E_{in}	Embodied energy of the solar still, kWh
EPBT	Energy payback time, years
EPF	Energy production factor, dimensionless
E_{out}	Annual useful energy, kWh/year
E_{sol}	Annual solar energy retrieved by the solar still, kWh/year
$I(t)_{input}$	Total input solar radiation, W
K_{ACRY}	Thermal conductivity of acrylic, *W/m-K*
K_{FRP}	Thermal conductivity of FRP, *W/m-K*
LCCE	Life cycle conversion efficiency, dimensionless
L_{ACRY}	Thickness of acrylic, m
L_{FRP}	Thickness of FRP, m
L_{vap}	Latent heat of vaporization, kJ/kg or kWh/kg
MCDW	Market cost of distilled water, Rs./kg
m_{ew}	Hourly yield of the solar still, ml/m^2
n	Still useful life in years
NP	Net profit, Rs./year
PP	Payback period, days
P_{cost}	Capital cost of the still, Rs.
Q	Conduction heat transfer, W
SFF	Sink fund factor, dimensionless
SV	Salvage value, Rs.
t	Time, h
TAC	Total annual cost, Rs./year
T_a	Ambient temperature, °C
T_s	Sun temperature, 5727 °C
T_w	Water temperature, °C

Greek letters

dt	Small time interval, h
n_{ex}	Exergy efficiency of the solar still
n_o	Overall thermal efficiency of the solar still