World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:10, No:1, 2016

Experimental Study on Modified Double Slope Solar Still and Modified Basin Type Double Slope Multiwick Solar Still

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***Abstract*—**Water is essential for life and fresh water is a finite resource that is becoming scarce day by day even though it is recycled by hydrological cycle. The fresh water reserves are being polluted due to expanding irrigation, industries, urban population and its development. Contaminated water leads to several health problems. With the increasing demand of fresh water, solar distillation is an alternate solution which uses solar energy to evaporate water and then to condense it, thereby collecting distilled water within or outside the same system to use it as potable water. The structure that houses the process is known as a 'solar still'. In this paper, 'Modified double slope solar still (MDSSS)' & 'Modified double slope basin type multiwick solar still (MDSBMSS)' have been designed to convert saline, brackish water into drinking water. In this work two different modified solar stills are fabricated to study the performance of these solar stills. For modification of solar stills, Fibre Reinforced Plastic (FRP) and Acrylic sheets are used. The experiments in MDSBMSS and MDSSS was carried on 10 September 2015 & 5 November 2015 respectively. Performances of the stills were investigated. The amount of distillate has been found 3624 Ml/day in MDSBMSS on 10 September 2015 and 2400 Ml/day in MDSSS on 5 November 2015.

***Keywords*—**Contaminated water, Conventional solar still, Modified solar still, Wick.

I. Introduction

WATER is essential to sustain human life. It is abundant, but not infinite in quantity. Man is dependent on rivers, lakes, and underground water to get fresh water, but these sources are not always clean. Salts and organisms will be present and the maximum salt level in fresh water for human consumption is only 550 ppm [1]. With the present rise of world population, intensified agriculture, possible climate change and industrial growth in certain parts of the world, the available annual water supply will probably be insufficient on a world basis. Unfortunately, a major portion of the fresh water supply is not available where it is needed. The problem can be partially solved by transporting potable water to some of these communities, but the costs involved are of such magnitude that this proposition is not feasible. Some other way of obtaining potable water will have to be found. One of the promising options to solve this problem of water shortage appears to be desalination. Desalination methods are already mitigating water shortages in parts of the world adjacent to the sea or saline bodies of water by desalination plants. Solar desalination can be used to purify either seawater or brackish water in areas which lack potable water and have abundant solar radiation such as some of those located in the Middle East [2]. Solar distillation has been long known and the earliest documented work is that of the Arab alchemists in 1551. A very comprehensive review of the history, theory, applications and economics of solar stills has been prepared [3]. It describes the work done in various countries from 1872 to 1970. Large installations and small laboratory scale models are described. Reviewed, thoroughly, the work on solar distillation. They have described the design and performance of a wide range of solar stills, conventional single slope solar still (CSSS) gives a quite inefficient performance in the purification of water. In the same way, the conventional double slope solar still (CDSSS) also has low efficiency and does not come up to the expectations. These solar stills have some major disadvantages e.g. (i) ineffective use of incident solar radiation, (ii) insufficient collection of distilled water, (iii) replacement of existing material by new materials [4]. Experimentally tested several single sloped concrete basin type solar stills in Riyadh, Saudi Arabia [5]. The stills had various thicknesses and slopes of glass cover and their water trays were covered with different solar absorbent materials e.g. black and red sand, black stones, straw and charcoal. They found the optimum thickness and slope of the glass cover to be 3 mm and 200 respectively. Experimentally, the effect of salinity of the input water on the performance of a single basin-type solar still connected with a solar collector [6]. Used charcoal particles as absorber medium inside a basin-type solar still [7]. A comprehensive review has been done on different types of solar stills [8]. A double-condensing and multi-wick still. Excess vapor can then be condensed on the additional surface, reducing the heat load on the glass cover and glass cover temperature, which in turn enhances evaporation rate. The experimental results showed a 20% increase in still productivity over the simple multi-wick still [9]. A basin type double slope solar still with mild steel plate. They used different wick materials like light cotton cloth, sponge sheet, coir mate and waste cotton pieces in the basin to minimize the mass of water flow. They pointed out that, the still with light black cotton cloth is the effective wick material [10]. The effect of charcoal cloth on the performance of a single basin type solar. The charcoal cloth is an odor absorbing media which has carbon imbedded into the fabric. Charcoal cloth was used as an absorber/evaporator material

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and for brackish water transport. They found that, charcoal cloth is a good material for use as an absorber/evaporator and also as a water transport medium [11]. Modified the solar still by keeping jute cloth in vertical position in the middle of the basin water and another row of jute cloth is attached with the wall of the still. They found that the efficiency increases by 8% and cumulative still yield with jute cloth increased by about 20% [12]. A concave wick surface for evaporation, whereas four sides of a pyramid shaped still were used for condensation. The concave shaped wick surface increases the evaporation area due to the capillary effect. Results showed that average distillate productivity in day time was 4.1 l/m2 [13]. A flat plate reflector to improve the productivity of tilted wick solar still and analyzed the proposed system numerically [14]. A solar desalination system with a solar collector was developed and tested outdoor [15]. The results showed that, the yield was about two to three times more than that of a conventional single basin solar still under the same conditions.

II. Methodology

In the methodology, basic design, calculation of equivalent thickness, working of modified double slope basin type multi-wick solar still & working of modified double slope solar still and modifications introduced in two different solar stills are discussed.

A. Design of Parameters

The basin and the north wall are made of Fibre-Reinforced Plastic (FRP) sheet of 5 mm thickness which is blackened from the inside. The south, east and west side walls are made of transparent acrylic sheet of 3 mm thickness (which is equivalent thickness of acrylic sheet with respect to thickness of FRP).

B. Calculation of Equivalent Thickness

For the same rate of heat flow 5 mm thickness of Fibre-Reinforced Plastic (FRP) sheet is replaced by:

$$Q = \frac{k_{FRP}.A_{FRP}.(T_1 - T_0)}{L_{FRP}} = \frac{k_{ACRY}.A_{ACRY}(T_1 - T_0)}{L_{ACRY}}$$

$$L_{ACRY} = \frac{k_{ACRY}.L_{FRP}}{k_{FRP}} = \frac{0.2 \times 5}{0.351} = 3\ mm$$

$$K_{ACRY} = 0.2\ W/mk,\ k_{FRP} = 0.0351\ W/mk$$

Q = Rate of Heat Transfer through the FRP sheet,

when its two sides are maintained at Temperature T_1 and T_0

So we used 3 mm thickness of Acrylic sheet for the designing of east, west and south walls, which is equivalently equal of 5 mm of FRP sheet.

TABLE I
EQUIVALENT THICKNESS FOR DIFFERENT MATERIALS

Material	Thermal Conductivity of Material, $k_{Material}$ (W/mk)	Density g/cm^3	Coefficient of Linear Expansion K^{-1}	$k_{Material}$/ k_{FRP}	Equivalent Thickness of Material (mm)
PVC	0.14	1.4	52	0.398	2
PET	0.18	1.45	70	0.512	2.6
Acrylic	0.2	1.18	72	0.569	**3**
Polycarbonate	0.22	1.2	65	0.626	3.1
Pyrex Glass	1.3	2.52	8.5	3.7	18.5
Spinal	14.7	4.1	9.17	41.88	209.4

C. Design of Modified Double Slope Basin Type Multiwick Solar Still (MDSBMSS)

MDSBMSS consist of a rectangular base, four walls, two glass covers, 3 troughs, 4 outlet pipes and one inlet pipe. Base and north wall are made of opaque Fibre Reinforced Plastic (FRP) of thickness 5 mm, whereas three walls (East, West and south walls) are made of transparent acrylic sheets of thickness 3 mm. the height of the walls has been kept 12 cm at East-West ends and 38 cm at the centre. An inlet pipe (with a cap) has been provided through the north wall in order to supply brackish water at the start of the experiment. 3 troughs have been placed at the inside surface of the walls to collect distillate from the walls and glass cover and to guide it in to the collecting jar placed outside. There are 19 steel rods which support the wick system installed as latest modification to the conventional still.

The angle of the cover has been chosen as 15° less than the 25°, the angle which was used in single slope solar stills 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 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.

TABLE II
DESIGN SPECIFICATION OF MDSBMSS

Parameters	**Specification**
Orientation	East-West
Body material	Base and north wall made of FRP, other 3 walls made of Acrylic, east and west glass covers of toughened glass
Basin area and colour	1 m × 2 m
Thickness of FRP	5 mm
Thickness of Acrylic	3 mm
Height at ends	0.12 m
Height at centre	0.38 m
Glass cover dimension	1.03 m × 1.03 m × 0.004 m
Quantity of glass	2
Inclination angle	15°
Colour of north wall inside	black
Number of inlet to saline water	1
Number of outlets with troughs at the ends	4

Fig. 1 Experimental Setup of MDSBMSS installed at MNNIT Allahabad

D. Working of Modified Double Slope Basin Type Multiwick Solar Still (MDSBMSS)

Due to replacement of opaque FRP walls by transparent acrylic walls (except North wall) in Modified Double Slope Solar Still, its working principle has been modified. It relies mainly on the theory of Molecular Collision, which is explained below.

The inside space of solar still is filled with air and vapor molecules which possess some molecular kinetic energy and in complete random motion. Due to random movement they undergo molecular collision and some molecules come in contact with inner surfaces of walls and glass covers. The transparency of the walls allows the solar radiation to be incident on the water inside the still from very early in the morning (during the sun rise itself). It causes the temperature inside the still to increase which raises the kinetic energy of the vapor molecules. It results in increase of molecular collision and the vapor molecules close to the walls strike to it. On striking they stick to it due to adhesion force and release heat for a phase change from vapor to liquid state through the process of condensation and yielding starts.

As the day proceeds, more solar radiation is incident on the walls and glass covers. A large fraction of this radiation is absorbed by the basin liner which transfers this heat to the water through convection. Some fraction of heat is also transferred to the surroundings through basin liner by conductive effect. The water starts evaporation and the water vapor molecules come in contact with the walls and glass covers through molecular collision and condensation process continues. The distillate obtained from condensation trickles down to the troughs and carried away to the collecting bottles places outside the still b means of outlet pipes. No distillate is obtained from north walls, as the molecules which come in contact with it get additional heat from it (as it blackened) and hence no condensation occurs. The north wall cools down by continuously transferring heat to vapor.

The water moves up the wicks through capillary action and a layer of water is formed on the wick layer of jute 12 cm below the glazing cover. The incident solar radiation has dual advantage of heating the water in the basin as well as evaporating the water's thin film from the wick layer. The water evaporated gets condensed on the inner surface of toughened glass and is collected in flask after it passes through well designed troughs.

Fig. 2 Jute-Wick arrangement in MDSBMSS setup

TABLE III
DESIGN SPECIFICATION OF MDSSS

Parameters	Specification
Orientation	East-West
Body material	Base and north wall made of FRP, other 3 walls made of Acrylic, east and west glass covers of toughened glass
Basin area and colour	1 m × 2 m
Thickness of FRP	5 mm
Thickness of Acrylic	3 mm
Height at ends	0.12 m
Height at centre	0.38 m
Glass cover dimension	1.03 m × 1.03 m × 0.004 m
Quantity of glass	2
Inclination angle	15°
Colour of north wall inside	black
Number of inlet to saline water	1
Number of outlets with troughs at the ends	3

E. Design of Modified Double Slope Solar Still (MDSSS)

MDSSS consist of a rectangular base, four walls, two glass covers, 3 troughs, 4 outlet pipes and one inlet pipe. Base and north wall are made of opaque Fibre Reinforced Plastic (FRP) of thickness 5 mm, whereas three walls (East, West and south walls) are made of transparent acrylic sheets of thickness 3 mm. the height of the walls has been kept 12 cm at East-West ends and 38 cm at the centre. An inlet pipe (with a cap) has been provided through the north wall in order to supply brackish water at the start of the experiment. 3 troughs have been placed at the inside surface of the walls to collect distillate from the walls and glass cover and to guide it in to the collecting jar placed outside. The angle of the cover has been chosen as 15° less than the 25°, the angle which was used in single slope solar stills at Allahabad due to Allahabad's latitude. The 15° angle allows the height of the double slope still to be optimum at the centre. 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.

F. Working of Modified Double Slope Solar Still (MDSSS)

Due to replacement of opaque FRP walls by transparent acrylic walls (except North wall) in Modified Double Slope Solar Still, its working principle has been modified. It relies mainly on the theory of Molecular Collision, which is explained below.

The inside space of solar still is filled with air and vapor molecules which possess some molecular kinetic energy and in complete random motion. Due to random movement they undergo molecular collision and some molecules come in contact with inner surfaces of walls and glass covers. The transparency of the walls allows the solar radiation to be incident on the water inside the still from very early in the morning (during the sun rise itself). It causes the temperature inside the still to increase which raises the kinetic energy of the vapor molecules. It results in increase of molecular collision and the vapor molecules close to the walls strike to it. On striking they stick to it due to adhesion force and release heat for a phase change from vapor to liquid state through the process of condensation and yielding starts.

As the day proceeds, more solar radiation is incident on the walls and glass covers. A large fraction of this radiation is absorbed by the basin liner which transfers this heat to the water through convection. Some fraction of heat is also transferred to the surroundings through basin liner by conductive effect. The water starts evaporation and the water vapor molecules come in contact with the walls and glass covers through molecular collision and condensation process continues. The distillate obtained from condensation trickles down to the troughs and carried away to the collecting bottles places outside the still by means of outlet pipes. No distillate is obtained from north walls, as the molecules which come in contact with it get additional heat from it (as it blackened) and hence no condensation occurs. The north wall cools down by continuously transferring heat to vapor.

Fig. 3 Experimental Setup of MDSSS installed at MNNIT Allahabad

III. Results and Discussions

The performance of both experimental setups installed at the terrace of heat and mass transfer & solar energy lab, Mechanical Engineering Department, Motilal Nehru National Institute of Technology Allahabad, Uttar Pradesh, India (Latitude 25.45° N, Longitude 81.85° E), have been observed and the readings were taken after every hour. Solarimeter was used to measure the Solar Radiation. The temperatures of all the surfaces (both inside and outside) were measured by thermocouple using automatic temperature sensor.

Figs. 4-11 have been plotted taking the measurements obtained after every hour from 7 AM in the morning till the next day for 24 hours at water depth of 5 cm on dated 10 September 2015 for MDSBMSS and water depth of 1 cm on dated 5 November 2015 for MDSSS.

Fig. 4 shows the variation of solar radiation on different walls & glass surfaces with respect to time. Graph shows that the radiation incident on the west glass surface is increasing as sun moving from east to west, where the temperature rises during the daytime up to the maximum value at 13:00 h on 10 September 2015.

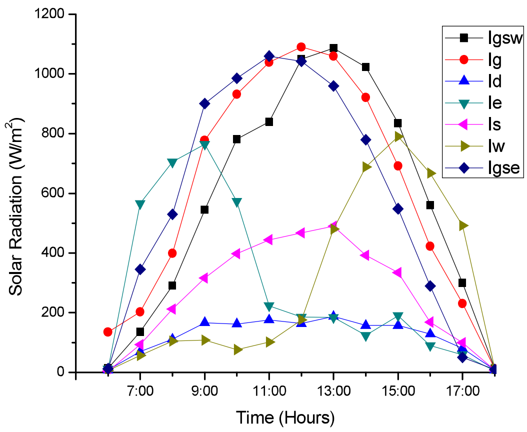

Fig. 4 Solar radiation Vs Time on 10 September, 2015

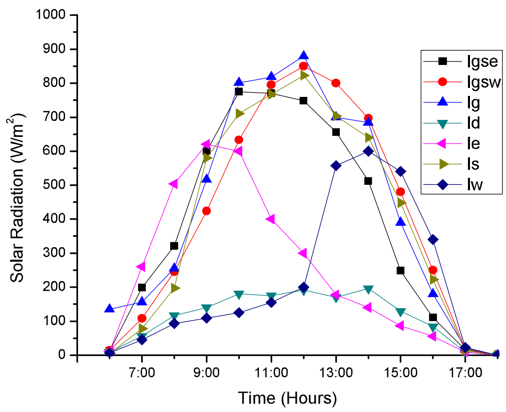

Fig. 5 Solar radiation Vs Time on 5 November 2015

Fig. 5 shows the variation of solar radiation on different walls & glass surfaces with respect to time. Graph shows that the radiation incident on the west glass surface is increasing as sun moving from east to west, where the temperature rises during the daytime up to the maximum value at 12:00 h on 5 November 2015.

Fig. 6 shows that variation of global solar radiation (Ig) with respect to time on two different date. Graph shows that as sun moving from east to west global solar radiation also increases and 12:00 h global solar radiation had maximum value and after that it decreases. Ig on 10 September 2015 had greater values than Ig on 5 November 2015 because the solar intensity in the month of September was higher than the solar intensity in November.

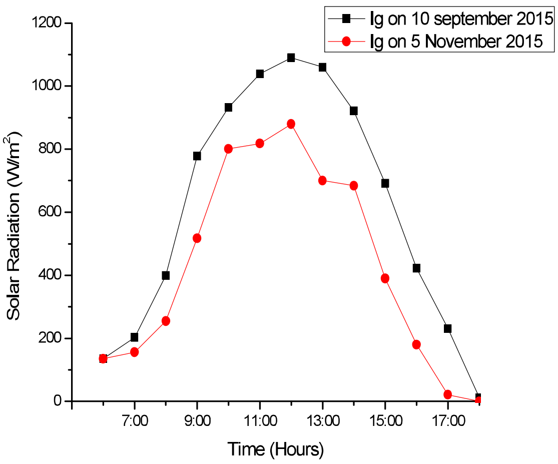

Fig. 6 Global Solar Radiation (I_g) Vs Time

Fig. 7 shows the hourly variation of water & basin temperatures w.r.t. time. At the start of the day the water temperature was at 29°C and basin temperature was at 40°C, as the day proceeds both increases. At 12:00 h the basin temperature was at its maximum value of 73°C and water temperature was maximum value of 51°C at 13:00 h. Basin temperature falls suddenly to value of 43°C at 16:00 h from 72°C at 15:00 h and afterwards it decreases. Water temperature decreases after 13:00 h and suddenly it raises to 47°C and then it decreases but next day after 02:00 h it again raises.

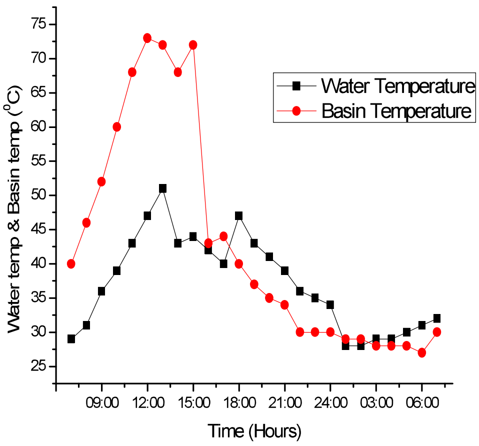

Fig. 7 Water and basin temperature Vs Time on 10 September 2015

Fig. 8 shows the hourly variation of water & basin temperatures w.r.t. time. At the start of the day the water temperature was at 20°C and basin temperature was at 18°C, as the day proceeds both increases. At 16:00 h the basin temperature was at its maximum value of 41°C and water temperature was maximum value of 52°C at 13:00 h.

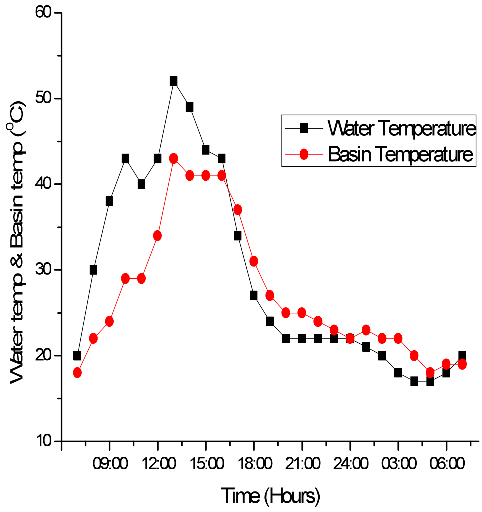

Fig. 8 Water and basin temperature Vs Time on 5 November 2015

Fig. 9 shows the hourly yield w.r.t. time, it can be deduced from the figure that the yield keeps on increasing from morning till afternoon 14:00 h with maximum of 448 Ml. The amount of distillate has been found in 3624 Ml/day.

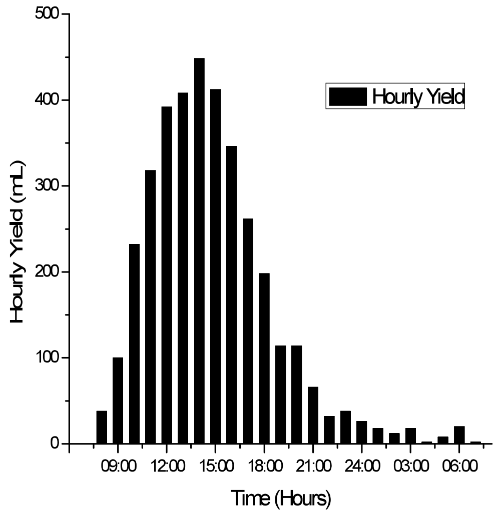

Fig. 9 Hourly yield Vs Time on 10 September 2015

Fig. 10 shows the hourly yield w.r.t. time, it can be deduced from the figure that the yield keeps on increasing from morning till afternoon 13:00 h with maximum of 452 Ml. The amount of distillate has been found in 2400 Ml/day.

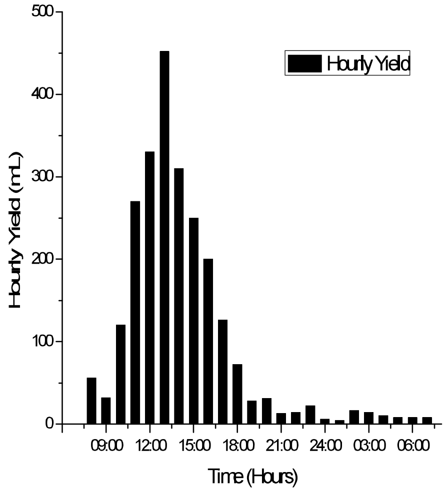

Fig. 10 Hourly yield Vs Time on 5 November 2015

Fig. 11 shows the comparison of hourly yield obtained from MDSBMSS & MDSSS on 10 September 2015 and 5 November respectively. It can be inferred from the figure that in case of MDSBMSS the maximum yield was 448 Ml at 14:00 h and 452 Ml at 13:00 in case of MDSSS, it is due to evaporation of water from basin as well as water's thin film from the wick layer, so more water evaporation in case of MDSBMSS.

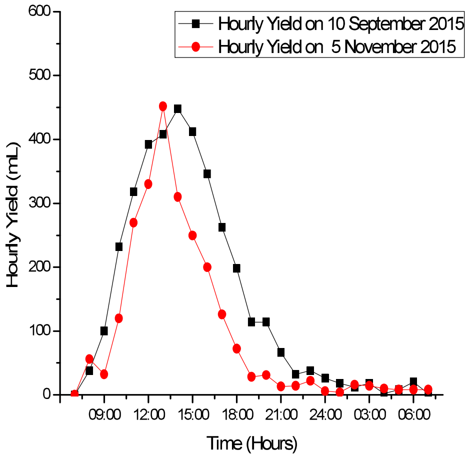

Fig. 11 Hourly yield Vs Time on 10 September 2015 & 5 November 2015

IV. CONCLUSIONS

The following conclusions can be made from the results:

1. The temperature difference between inner and outer walls of the north wall made of FRP and east and west wall made of Acrylic Sheet is nearly the same. Hence, the replacement of the FRP walls with Acrylic Sheet was successful.
2. Heat input has increased due to transparent east, west and south walls and hence there was a significant increase in the yield and efficiency.
3. Water was collected from the south wall also as it is made transparent, hence, the yield of the still has improved.
4. Condensation on the south wall of the still has taken place, which shows that the condensation capacity of the still has improved.
5. Maximum yield is obtained at 14:00 h which came out to be 448 Ml in case of MDSBMSS and 452 Ml in case of MDSSS which is obtained at 13:00 h.
6. The project can be used in water stressed areas where the water contains a lot of impurity and the people lack the method to purify it. The project will be a great success in the remote areas having no ease of access to the electricity and the devices based on the electricity to purify water.
7. The amount of distillate has been found 3624 Ml/day in MDSBMSS on 10 September 2015 and 2400 Ml/day in MDSSS on 5 November 2015.

ABBREVIATIONS

I_{gse} Solar Radiation on the East Glass Surface (W/m^2)
I_{gsw} Solar Radiation on the West Glass Surface (W/m^2)
I_g Global Radiation (W/m^2)
I_d Diffused Radiation (W/m^2)
I_e Solar Radiation on the East Wall (W/m^2)
I_s Solar Radiation on the South Wall (W/m^2)
I_w Solar Radiation on the West Wall (W/m^2)

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