Development of desalination unit using solar still coupled with evacuated tubes for domestic use in rural areas

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Potable water and energy are two main priorities of mankind. The rural communities, especially of developing and under-developed countries are facing acute shortage of both. A sustainable, domestic water desalination process for rural India to meet the demand for potable water is the need of the hour and solar thermal desalination proves to be a promising alternative. In this article, experimental studies of single-slope, single-basin solar still integrated with evacuated tubes in natural mode (coupled system) are carried out for the climatic conditions of Bangalore (12.96°N, 77.56°E), Karnataka, India. For solar still basin area of 0.51 m^2, the distillate yields obtained from the coupled system for water depths of 0.06, 0.04 and 0.02 m are 3.289, 4.652 and 5.534 kg respectively, from 7:00 h to 19:00 h. The variation of instantaneous energy efficiency for the coupled system is found to be in the range 0.33–73.18% between 9:00 and 17:00 h for water depth of 0.02 m, which decreases with increase in water depth in the solar still. Chemical analysis of inlet water sample and outlet distillate was carried out and compared with Indian drinking water standards, IS-10500:2012. It is observed that the values for chemical composition of distillate are well below the limits of drinking water standards. The total cost of the developed coupled system was estimated to be Rs 6980 (US$ 1 = Rs 60.25 as on 15 April 2014). This eco-friendly system does not depend on any conventional source of energy for its operation and is easy to build and maintain.

Keywords: Chemical analysis, coupled system, distillate yield, energy efficiency, solar thermal desalination.

NEED for potable water is presently the biggest challenge faced by most of the developing countries. Three-fourths of the Earth's surface is covered with water, 97% of this is saline and only 3% is freshwater. Of this 3% of freshwater, 2.5% is in the form of polar ice and glaciers, and only 0.5% is currently available for the needs of living beings on this planet[1]. The depletion of freshwater is because of various reasons like population growth, changes in the lifestyle of people, untimely rains and increase for industrial needs[2]. Other reasons contributing to this may be the dumping of industrial and domestic sewage to freshwater bodies like lakes and rivers, and global warming is in a way related to all these factors. Due to non-availability of potable water, people especially in rural areas are forced to consume polluted or contaminated water, which in turn will lead to waterborne diseases and sometimes may even cause death.

In India, the rural population consists of more than 700 million, residing in 1.42 million habitations. Approximately 37.7 million Indians are affected by waterborne diseases, 1.5 million children die of diarrhoea, 73 million working days are lost annually due to the waterborne diseases and the economic burden is estimated to be US$ 600 million a year[3]. Rural India mainly depends on groundwater for its drinking needs. Chemical contamination due to the presence of fluoride, chloride, nitrate, iron and arsenic in drinking water is a serious concern. Figure 1

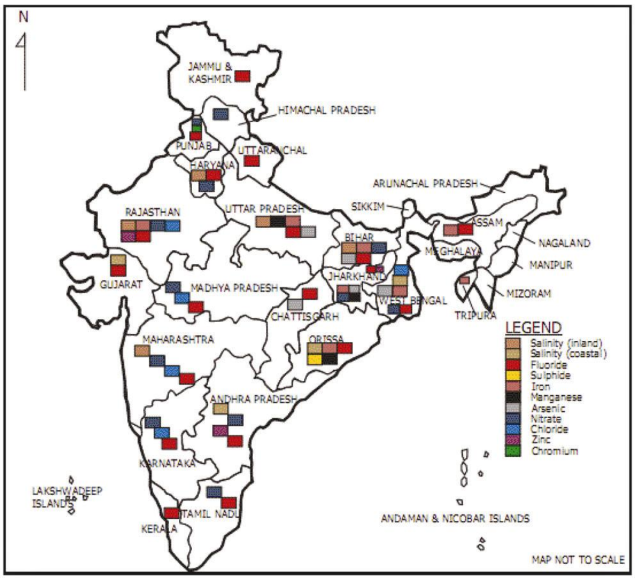

Figure 1. Map of India showing major groundwater contaminants in various states[4].

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Table 1. Habitations of Karnataka affected by excess chemical contamination, 2013–14 (ref. 5)

	No. of habitations affected by excess of					
District	Fluoride	Chloride	Nitrate	Iron	Alkalinity	Total no. of habitations affected
Bagalkot	12	34	21	9	0	76
Bangalore (R)	2	0	1	0	0	3
Bangalore (U)	1	0	1	22	0	24
Belgaum	12	31	21	307	44	415
Bellary	1105	3	617	9	0	1734
Bidar	5	0	2	6	0	13
Bijapur	1005	288	1059	1778	1	4131
Chamraj Nagar	0	0	1	74	0	75
Chikballapur	658	0	169	8	0	835
Chikmagalur	1	0	0	1	0	2
Chitradurga	0	0	0	0	0	0
Dakshina Kannada	1	8	6	301	0	316
Davanagere	605	37	621	182	0	1445
Dharwad	6	23	13	62	32	136
Gadag	506	34	27	0	14	581
Gulbarga	213	1	132	0	0	346
Hassan	46	3	29	444	0	522
Haveri	1	119	0	16	0	136
Kodagu	0	0	0	0	0	0
Kolar	165	0	62	3	0	230
Koppal	285	4	50	33	0	372
Mandya	134	0	878	71	1	1084
Mysore	6	0	12	26	0	44
Raichur	150	27	21	5	0	203
Ramnagara	90	0	42	350	0	482
Shimoga	10	1	16	67	0	94
Tumkur	2112	27	1069	1674	14	4896
Udupi	0	0	0	0	0	0
Uttara Kannada	0	135	0	601	1	737
Yadgir	373	4	329	0	0	706
Total no. of habitations affected	7504	779	5199	6049	107	19,638

The value '0' indicates that no record is found for selected contaminant.

shows major groundwater contaminants in various states of India[4]. About 66 million Indians are facing threat due to excess fluoride and 10 million due to excess arsenic in groundwater[3]. Presence of fluoride, chloride, nitrate and iron in groundwater is a common problem in Karnataka, one of the southern states of India. For the financial year 2013–14, Table 1 shows the habitations in particular districts of Karnataka[5] which are affected by excess fluoride, chloride, nitrate, iron and alkalinity in various drinking water sources like deep tube wells, open wells and rivers. Table 1 also shows that the number of habitations affected by excess of fluoride, chloride, nitrates, iron and alkalinity in Karnataka are 7504, 779, 5199, 6049 and 107 respectively.

Desalination of the brackish/contaminated water can help countries meet the rising demand for potable water. Desalination in simple terms means removal of salt and other minerals from the sea/contaminated water to make it fit for drinking or for industrial use. On the one hand, common desalination processes like reverse osmosis (RO), multi stage flash (MSF), electro dialysis, multiple effect (ME) and vapour compression (VC) are considered costly for domestic water purification and on the other, these processes usually run on conventional sources (fossil fuels), which in turn leads to global warming[6]. Production of 4.745 billion m^3 of potable water per year requires 0.13 billion tonnes of oil/year (ref. 7). Hence, this demands for a sustainable desalination process which is affordable, simple and useful in meeting the domestic–rural potable water needs.

Figure 2 shows that the annual average direct solar radiation[8] in most parts of India ranges from 4 to 6 $kWh/m^2/day$. Solar energy, which is abundantly available in the country, can be used as a source to run the desalination process. One of the oldest and simplest desalination apparatus is the solar still and it can serve as a small-scale domestic water supply unit[9]. Solar thermal energy is used to evaporate the brackish water present in the basin of the solar still and these vapours are condensed and collected. This collected water is fit for drinking. Even now in rural/remote areas, the conventional solar still is preferred because it is eco-friendly, simple in design and low operating and maintenance cost.

Antwi *et al.*[10] conducted a study in Bongo district of Ghana, where a solar still was used to treat the local bore well water with initial fluoride concentration of 20.6 mg/l. The fluoride content in the outlet water from the solar still was found to be 0.7 mg/l. Khanna *et al.*[11] conducted a case study of Chui village, Nagaur District, Rajasthan. The average values of total dissolved solids, total hardness and fluoride for three water samples collected from Chui village were recorded to be 2943.3, 1588.3 and 3.05 ppm respectively. It was concluded that the solar still can be used to provide potable water for the remote areas of Rajasthan. Tiwari and Tiwari[12] conducted experiments for five different depths of water ranging from 0.04 to 0.18 m and studied the effect of water depth on heat transfer coefficients in a single-basin passive solar still. To increase the output, Velmurugan *et al.*[13] designed a solar still with fin and the increase in productivity for a solar still with wick, sponge and fin was observed to be 29.6%, 15.3% and 45.5% respectively, compared to the conventional solar still. Ansari *et al.*[14] and El-Sebaii *et al.*[15] carried out studies to store the heat in a passive solar still using heat storage materials – phase change materials (PCM). They dealt with mathematical models like balance of energy equations for both the solar still as well as the PCM. The choice of the PCM, effect of PCM on power of charge/discharge and influence of heat storage on yield of the system were also studied.

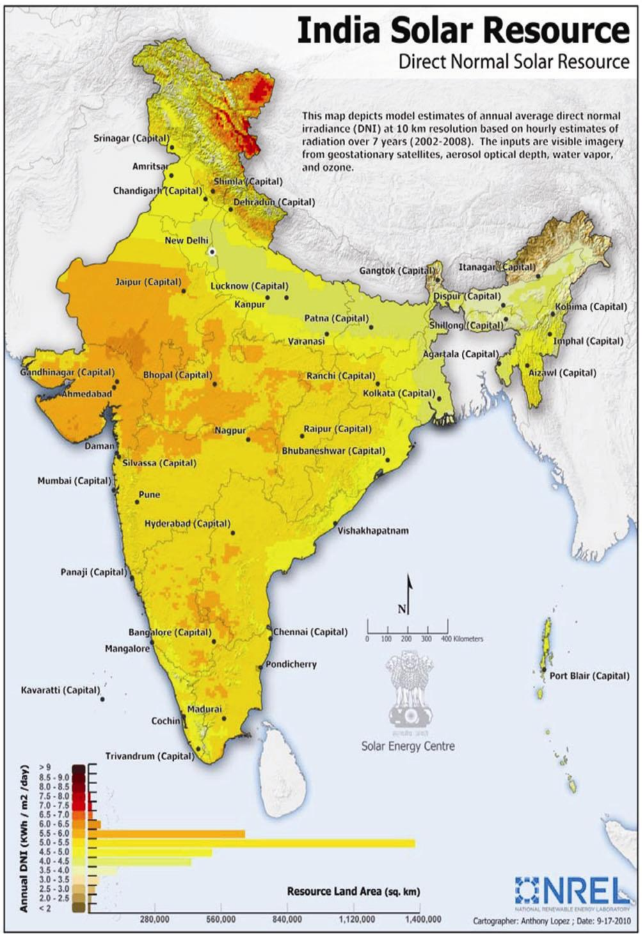

Figure 2. Map of India showing annual average direct solar radiation[8].

Low productivity is the major problem associated with passive solar stills. Hence active solar stills are used to enhance the evaporation rate of water, which in turn helps in enhancing the output of the solar still. Thermal analysis of active solar still was carried out by Tiwari *et al.*[16], where the solar still was coupled to the collector panel through a tube-in-tube heat exchanger. It was observed that instantaneous thermal efficiency was inversely proportional to the collector area. Voropoulos *et al.*[17] investigated a solar still coupled with solar collector and a hot water storage tank. Two advantages of this system are high yield compared to conventional solar still and hot water could be supplied from the storage tank. A hybrid photovoltaic/thermal (PV/T) active solar still was designed by Shiv Kumar and Tiwari[18] by coupling the conventional solar still to a flat plate collector and its performance was studied. Solar PV was used to drive a DC pump to circulate the water between the solar still and collector and maximum daily yield of 7.22 kg was obtained at water depth of 0.05 m for this hybrid system. Studies have also been carried out on solar still coupled to evacuated tube collector (ETC). Sampathkumar and Senthilkumar[19] conducted an experimental study on solar still coupled to an ETC. The main reason for using ETC is to supply hot water to the solar still. It was found that the yield of the system doubled compared to the conventional passive still. Omara *et al.*[20] coupled conventional still to ETC and compared its performance with conventional still and solar still using different types of wicks to enhance the productivity. Heat from ETC was transferred to the basin water through a heat exchanger. The productivity of double-layered square wick was found to be higher compared to conventional and plain wick still. Singh *et al.*[21] performed thermal analysis of solar still coupled to vacuum tubes directly without any heat exchanger between them. The temperature of water in the solar still was found to increase due to thermo-syphon process. Effect of different water depths (0.03 and 0.05 m) on yield, energy and exergy efficiencies was estimated. The daily maximum yield for the combination of 10 vacuum tubes with water depth of 0.03 m was found to be 3.8 kg/m^2. Several researchers[22–29] have reviewed the work on solar still and carried out various experiments to improve its efficiency.

Integrating evacuated tubes to the solar still proves to a better option compared to flat plate collector due to various reasons – simplicity, lower heat losses, less expensive, easily available and high performance. Several studies on integration of solar still with flat plate collector and vacuum tubes using heat exchangers have been carried out compared to the system where a solar still is coupled with evacuated tubes in natural mode. Hence, the current study intends to:

(1) Design, develop and experimentally study the performance of coupled system (single-slope single-basin solar still integrated with evacuated tubes) for the climatic conditions of Bangalore, Karnataka, India. In this set-up the evacuated tubes are connected in natural mode, i.e. they are directly connected to the solar still without any heat exchangers.

(2) Study the effect of various water depths (0.06, 0.04, 0.02 m) in the solar still on yield and on instantaneous energy efficiency of this coupled system.

(3) Study various temperatures, solar intensity and wind velocity profiles for typical days and for different water depths in the solar still.

(4) Check the feasibility of this system in getting rid of excess chemical contaminants in the water. Chemical compositions of initial and final water sample are analysed and compared with Indian drinking water specifications, IS-10500:2012.

(5) Carry out cost estimation of the developed coupled system.

Materials and method

Experimental set-up

The experiments were carried out in the premises of B.M.S. College of Engineering, Bangalore, which lies at 12.96°N lat. and 77.56°E long., during the period from January to April 2014 from 7:00 to 19:00 h.

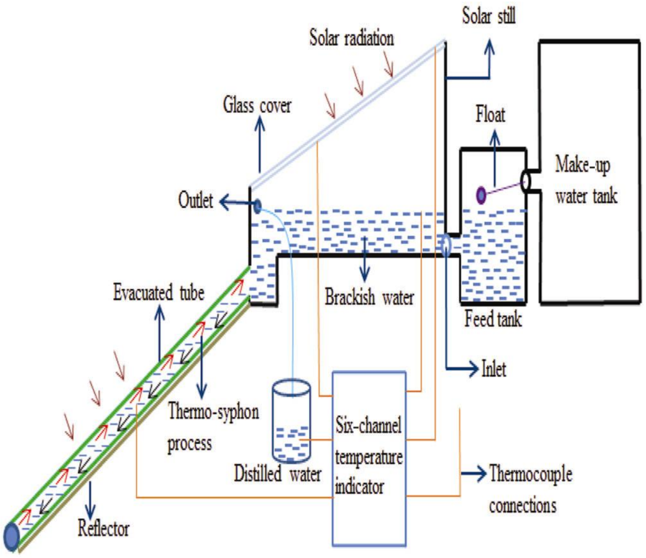

Figure 3. Schematic diagram of the experimental set-up.

The schematic diagram and specifications of the coupled system are shown in Figure 3 and Table 2 respectively. The set-up consists of the solar still and evacuated tubes. Single-slope single-basin solar still is made up of galvanized iron sheet (GI) and insulated using nitrile rubber so that no heat is lost from the basin to the atmosphere. Solar still consists of one inlet, two outlets (one on each side of the set-up) and an opening for insertion of thermocouples. Black powder coating of the still is done to increase its absorptivity of solar radiations. A frame to fix the window glass on the still using rubber beading is fabricated. Inclined water collecting channels are designed on all the sides of the frame to ensure that every drop comes out as soon as it drips down into the channel. Finally the gaps are sealed using Red RTV high temperature sustaining silicon sealant to prevent vapour leakage. The whole basin is made airtight. Evacuated tubes are fixed to the basin using rubber gaskets and mounted over a diffuse reflector made of aluminium sheet. Two water tanks, feed tank – which is connected to the inlet of the system and make-up tank – which helps supply water to the feed tank are used in the experiment. Three holes at depths of 0.02, 0.04 and 0.06 m are made on the feed tank, which is placed at the height equal to that of the still and a float bulb is fixed into these holes to maintain constant depth (at which the experiments are carried out) and continuous flow of water into the system. To collect the distillate, jars are placed at the end of hose pipes connected to the outlets of the still. The angle of inclination of both glass cover and evacuated tube collector is equal to

Table 2. Specifications of the coupled system

Solar still	
Material and thickness	Galvanized iron sheet/0.002 m
Inner basin area	0.51 m^2
High side and low side	0.290 and 0.174 m
Glass cover	
Thickness	0.004 m
Inclination	13° to the basin
Insulation	
Material	Nitrile rubber
Thickness	0.025 m
Evacuated tube	
No. of tubes	10
Length	1.5 m
Inner and outer diameter	0.037 and 0.047 m
Centre to centre spacing between two adjacent tubes	0.095 m
Inclination	13° to the horizontal
Aperture area of evacuated tube collector	1.353 m^2
Others	
Aluminium reflector	1.6 × 1.03 × 0.001 m
Feed and make-up tanks	20 litres each

Table 3. Instruments used in the experiments

Parameter	Instrument	Type/make	Range	Resolution
Temperature	Thermocouple with six-channel digital temperature indicator	K-type (Cr–Al)	0–200°C	1°C
Wind velocity	Anemometer	Lutron, AM-4201	0.4–30 m/s	0.1 m/s
Distillate yield	Measuring cylinders	Borosil	0–250 ml	2 ml
			0–1000 ml	10 ml
Solar radiation	Data are collected from the weather station set-up at the B.M.S. College of Engineering campus where the experiments were carried out			

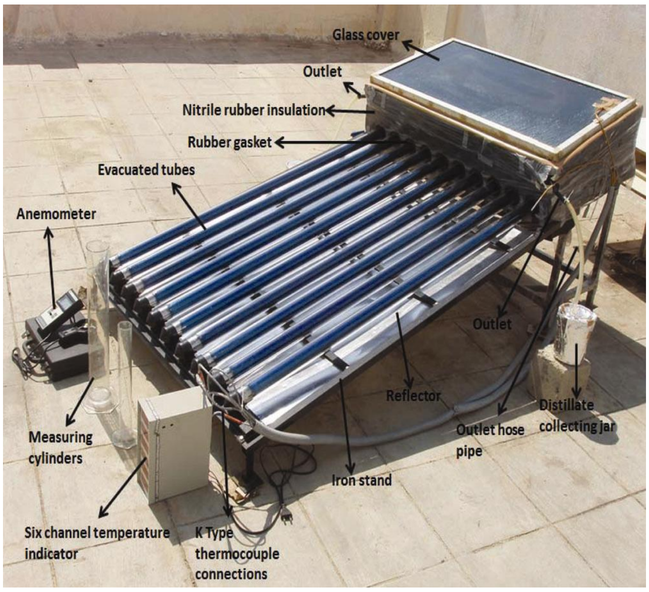

Figure 4. Photograph of developed experimental set-up with various instruments.

the latitude of the Bangalore location and the whole set-up is mounted facing south on an iron stand. A photograph of the experimental set-up is shown in Figure 4.

Table 3 shows the instruments used for measuring various parameters of the coupled system. Calibrated K-type (Cr–Al) thermocouples are used to measure various temperature of the system, like ambient temperature, outer glass surface temperature, inner glass surface temperature, water temperature in evacuated tube, water temperature in solar still and outlet distillate temperature. Wind velocity over the glass surface is measured using an anemometer, amount of distillate collected is measured using measuring cylinders and data on solar radiation are taken from the weather station set-up in the same campus where the experiments are carried out.

Operating principle and procedure

Operation of the solar still is similar to the natural hydrological cycle of evaporation and condensation. Solar radiations strike the glass cover, penetrate into the still and heat up the water present in the basin. Due to difference in the volatility, pure water evaporates and condenses on the inner surface of the glass cover, eventually leaving back the salts and chemical contaminants. The water drips down the glass into the channel and is collected in the jar. This collected water is free from excess chemical contamination and is fit for drinking.

Initially, the basin of the still and vacuum tubes are filled with water sample (which is tested for its chemical composition) from the feed tank through the inlet. Required depth and continuous flow of water from feed tank into the still are maintained using a float bulb. The evacuated tube consists of two concentric borosilicate tubes. The space between the inner and outer tubes is evacuated. The inner tube is filled with water and has a selective coating to absorb the solar radiations. Water in the inner tubes gets heated, moves up to the basin and cold water from the basin comes down into the tube. Due to this thermo-syphon process, the water in the basin gets heated and this increases the evaporation rate of water in it. Main advantage of coupling the evacuated tubes to the still is that the evacuated tubes have zero convection losses and does not require a tracking system to trace the sun. Experiments with three different depths (0.02, 0.04, 0.06 m) have been performed to find the optimum depth yielding the maximum distillate. Further, the feasibility of this system in getting rid of excess chemical contamination of the water sample is checked. The chemical contamination of both the initial and final sample is compared with the Indian standards (IS-10500:2012). The experiments are carried out from 7:00 to 19:00 h and various parameters like temperature, wind velocity, solar radiation and distillate yield are recorded hourly. The glass cover and the outer tube surface are cleaned daily to ensure that the parameters are not affected by dust.

Instrumental error and calibration

Before recording the temperature data, the thermocouples were calibrated by comparing their values with known values of temperature. According to the manufacturer's guidelines, the thermocouples are bound to have accuracy of 1% but errors up to 4% were observed during calibration. So, the measured and recorded temperature data are expected to have error up to 4%. The accuracy of the anemometer is ± 2% and tolerance values for distillate measuring cylinders of 250 and 1000 ml are ± 1 and ± 3 ml respectively. For simplicity, the error bars are not considered in plotting the recorded data.

Instantaneous energy efficiency

The instantaneous energy efficiency[21] of the coupled system is obtained using

$$\eta_{\mathrm{c}} = \frac{h_{\mathrm{e}} A_{\mathrm{b}} (T_{\mathrm{w}} - T_{\mathrm{gi}})}{I(t) A_{\mathrm{b}} + I_1(t) A_1},$$

where h_e is the evaporative heat transfer coefficient from water to glass surface (W/m^{2}K), A_b the basin area of the solar still (m^2), T_w the temperature of water in the solar still (°C), T_{gi} the inner surface temperature of glass cover (°C), $I(t)$ the solar radiation over the glass cover of the solar still (W/m^2), $I_1(t)$ the solar radiation over the evacuated tube collector (W/m^2), and A_1 is the aperture area of evacuated tube solar collector (m^2).

The amount of solar radiation over the glass cover surface of the solar still and over the evacuated tube collector is considered to be same. Hence, eq. (1) can be written as

$$\eta_{\mathrm{c}} = \frac{h_{\mathrm{e}} A_{\mathrm{b}} (T_{\mathrm{w}} - T_{\mathrm{gi}})}{I_{\mathrm{s}}(t)(A_{\mathrm{b}} + A_1)}, \tag{2}$$

where $I_s(t)$ is the solar radiation over the coupled system (W/m^2). Further h_e (refs 21, 30) in eq. (2) is determined using

$$h_{\mathrm{e}} = 16.273 \times 10^{-3} \times h_{\mathrm{wc}} \times \frac{P_{\mathrm{w}} - P_{\mathrm{gi}}}{T_{\mathrm{w}} - T_{\mathrm{gi}}}, \tag{3}$$

where h_{wc} is the convective heat transfer coefficient from water to glass surface (W/m^{2}K), P_w the saturated vapour pressure at water surface in the solar still (N/m^2) and P_{gi} is the saturated vapour pressure on the inner surface of glass cover (N/m^2). The expressions for P_w, P_{gi} (refs 12 and 21) and h_{wc} (refs 12, 21 and 30) are obtained using equations

$$P_{\mathrm{w}} = \exp\left[25.317 - \frac{5144}{(T_{\mathrm{w}} + 273)}\right], \tag{4}$$

$$P_{\mathrm{gi}} = \exp\left[25.317 - \frac{5144}{(\mathrm{T}_{\mathrm{gi}} + 273)}\right], \tag{5}$$

$$h_{\mathrm{wc}} = 0.884\left[(T_{\mathrm{w}} - T_{\mathrm{gi}}) + \frac{(P_{\mathrm{w}} - P_{\mathrm{gi}})(T_{\mathrm{w}} + 273)}{268.9 \times 10^3 - P_{\mathrm{w}}}\right]^{1/3}. \tag{6}$$

Equations (1)–(6) are used to determine the instantaneous energy efficiency for the coupled system on typical days for various depths of water in the solar still. These equations are specifically used for the condition of glass cover open to the solar radiations where both the glass cover and evacuated tubes act as heat collectors.

Results and discussion

Experiments were carried out from January to April 2014 and the results for various parameters recorded for some typical days in the mentioned period are given here. The hourly variation of various parameters like solar radiation, ambient temperature, outer surface temperature of glass cover, inner surface temperature of glass cover, temperature of water in evacuated tube, temperature of water in solar still and outlet distillate temperature for the experiments carried out for different depths of water in solar still, i.e. 0.06, 0.04 and 0.02 m are shown in Figure 5 *a–c* respectively, for typical days in March 2014.

Figure 5 *a* shows the parameters for the experiment carried on 23 March 2014 for water depth of 0.06 m in solar still of the coupled system. It can be observed that the maximum solar radiation of 908 W/m^2 is reached at 12:00 h. The maximum ambient temperature of 37°C and outer surface glass temperature of 69°C are observed at 15:00 h. Maximum inner surface glass temperature, water temperature in evacuated tube, water temperature in solar still, outlet distillate temperature of 78°C, 80°C, 81°C and 49°C respectively, are observed at 16:00 h. The various parameters for the experiment conducted on 24 March 2014 for water depth of 0.04 m in solar still are shown in Figure 5 *b*. At 12:00 h, the maximum solar radiation of 935 W/m^2 is recorded. The ambient temperature lies in the range 28–37°C. Maximum inner surface glass temperature, water temperature in evacuated tube and outlet distillate temperature of 85°C, 88°C and 53°C respectively, are observed at 16:00 h. The temperature of the outer surface of the glass cover (74°C) and water temperature in the solar still (88°C) are recorded maximum and the same at 15:00 and 16:00 h. Experiment for 0.02 m depth of water in the solar still was also carried out on 25 March 2014 and the parameters recorded are shown in Figure 5 *c*. The maximum solar radiation for the day is equal to 944 W/m^2 at 12:00 h. Most of the temperature parameters like ambient temperature, outer surface temperature of glass, inner surface temperature of glass, temperature of water in evacuated tube and temperature of water in solar still were recorded maximum at 15:00 h as 37°C, 76°C, 86°C, 89°C and 89°C respectively. The maximum outlet distillate temperature of 52°C is obtained at 16:00 h.

The hourly wind velocity over glass surface of solar still was also noted for all the typical days on which the experiments were performed. Wind profile is shown in

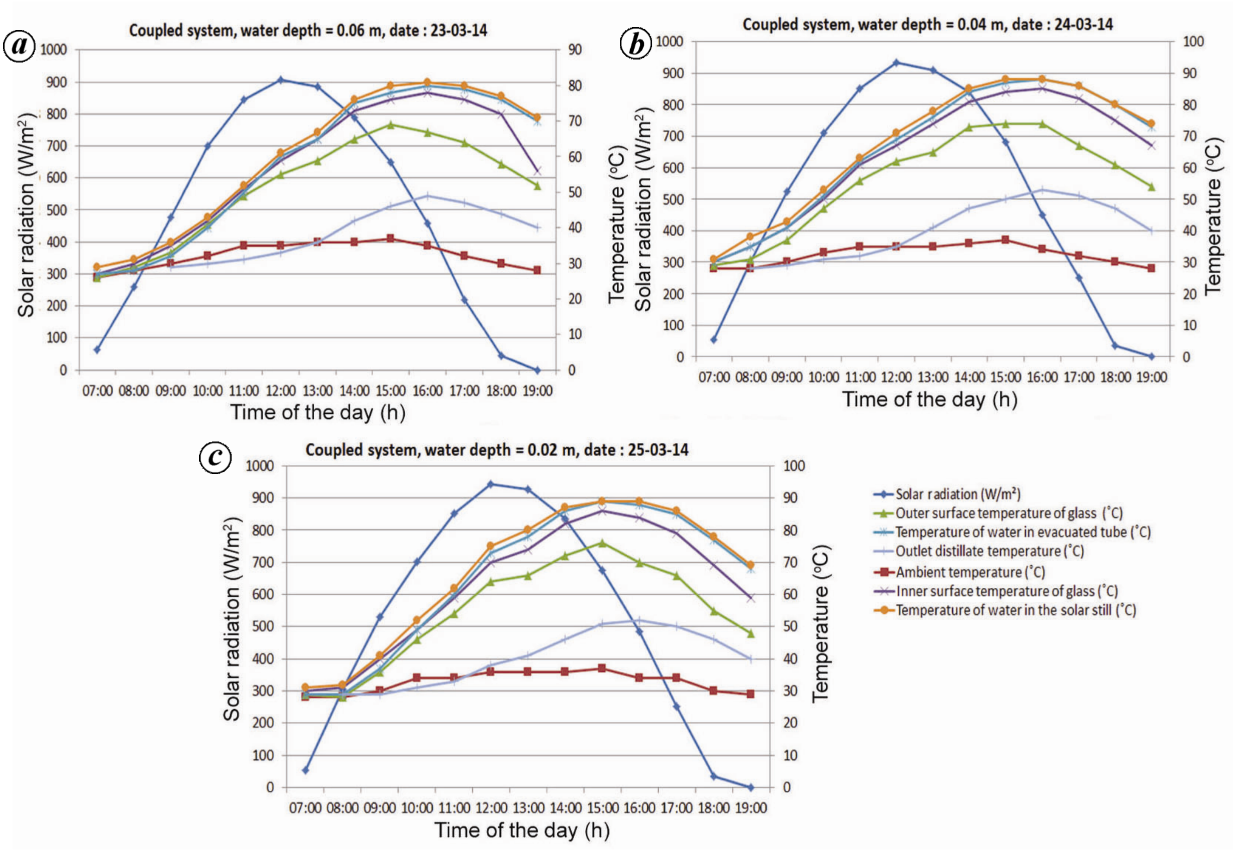

Figure 5. Hourly variation of solar radiation and various temperatures for water depth of (***a***) 0.06 m, (***b***) 0.04 m and (***c***) 0.02 m in solar still on 23, 24 and 25 March 2014 respectively, for Bangalore location.

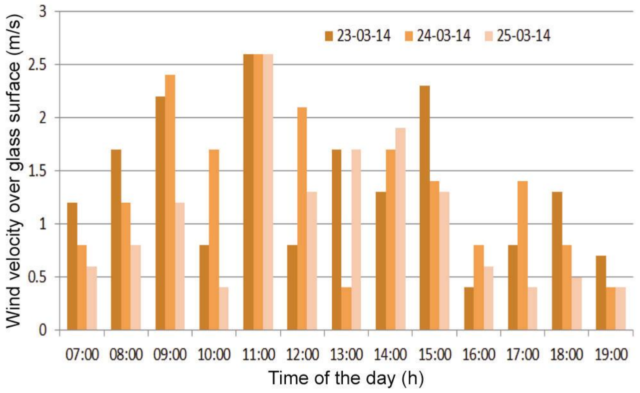

Figure 6. Hourly variation of wind velocity over glass surface of solar still for typical days.

Figure 6. The water vapour in the solar still give away latent heat of condensation to the glass cover and get condensed on it. As the glass cover is exposed to atmosphere, some amount of heat is dissipated to the surroundings. The wind flowing over the glass cover carries away the heat and cools it. The temperature of glass cover is an important parameter on condensation rate of vapours. Omara *et al.*[20] have pointed out that the dependency of distillate yields on solar radiation is more than the wind velocity. El-Sebaii[31] studied the effect of wind speed on distillate yield for the condition where outer surface and inner surface temperature of glass cover are not equal. It was found that for the mentioned condition, wind velocity had less impact on distillate yield. Hence effect of wind on distillate is considered to be low. And as far as depth of water is considered, wind has no impact on it if water mass in the coupled system is between 0 and 100 kg (ref. 31). The coupled system always has water mass less than 100 kg and so there is no impact by wind on water depth. The wind velocity on the surface of the glass cover ranged from 0.4 to 2.6 m/s on the typical days of experiments.

The distillate yield varied for different water depths. Figure 7 shows the hourly yield for different depths, where m_w is distillate yield of the system (ml/h). The yields obtained for water depth of 0.06, 0.04 and 0.02 m in the coupled system from 7:00 to 19:00 h are 3.289, 4.652 and 5.534 kg respectively, for time period from 7:00 to 19:00 h. The maximum distillate yield of 5.534 kg is obtained for water depth of 0.02 m. The maximum hourly output obtained for depth of 0.06 m is 0.598 kg between 16:00 and 17:00 h and for depths of 0.04 and 0.02 m it is 0.710 and 0.874 kg respectively, between 15:00 and 16:00 h.

Depth of water in the solar still has a major impact on heat transfer coefficients from basin water to glass cover and distillate yield of the coupled system. Tripathi and Tiwari[32] studied the effect of different water depths on yield of an active solar desalination system in terms of convective heat transfer coefficient and evaporative heat transfer coefficient from basin water to glass surface. The study concluded that internal convective heat transfer coefficient and evaporative heat transfer coefficient increases with decrease in depth of water in the solar still because of the increase in basin water temperature, which in turn will increase the distillate yield. Figure 8 shows the hourly variation of convective heat transfer coefficient (h_{wc}) and evaporative heat transfer coefficient (h_e) for various water depths in the coupled system. The figure clearly indicates that the average values of both h_{wc} and h_e are higher for lower water depths. So it can be concluded that heat transfer coefficients are maximum for 0.02 m water depth compared to 0.04 and 0.06 m in coupled system. The quantity ($T_w - T_{gi}$) is the difference between basin water temperature and glass cover inner surface temperature. From Figure 5 *a–c*, it can be observed that the average ($T_w - T_{gi}$) for water depth of 0.02 m is 4.54°C and comparatively a reduction of about 22.03% and 25.42% is observed for water depth of 0.04 and 0.06 m respectively. Hence, due to the higher basin water temperature and higher heat transfer coefficients for 0.02 m water depth, the distillate yield is more compared to other water depth values in the coupled system. Repeated experiments were performed on the coupled system for three months (January–April 2014) on three different water depths, i.e. 0.06, 0.04 and 0.02 m. For all the experiments the distillate yield was observed to be maximum for water depth of 0.02 m and decreased with increase in water depth. The average reduction in distillate yield/day for water depths of 0.06 and 0.04 m compared to 0.02 m for these three months of experimentation was observed to be in the range of 40–42% and 14–17% respectively, for good sunny day. The results given in this article are some of the typical days in the mentioned study period.

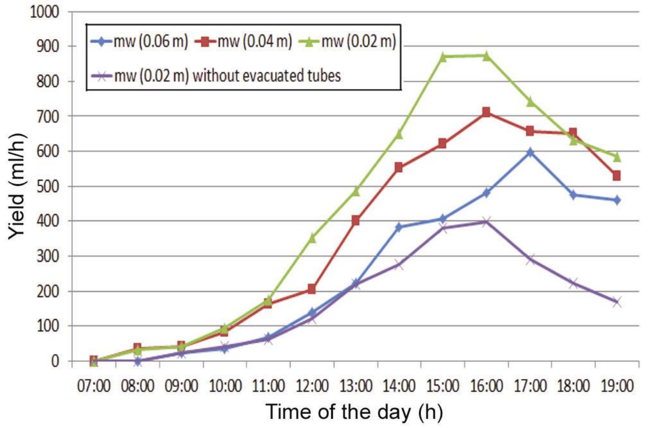

Figure 7. Hourly variation of yield with water depth in the solar still of coupled system.

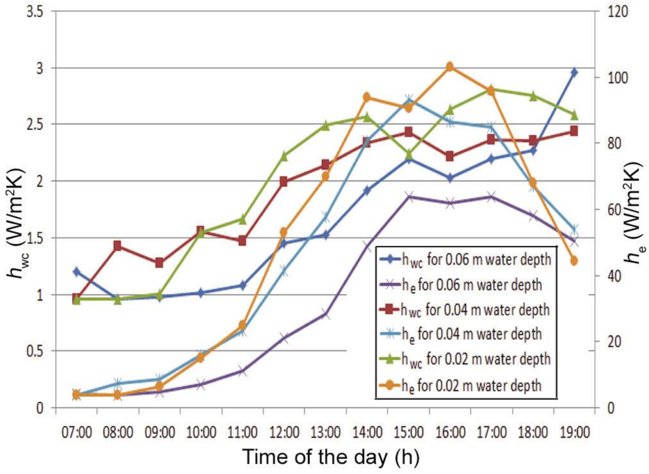

Figure 8. Hourly variation of h_{wc} and h_e with depth of water in coupled system for typical days.

Considering all the temperature profiles of the experiments, the maximum temperature of water in the evacuated tubes as well as in solar still of coupled system was observed in the 0.02 m water depth experiment and the temperature was found to decrease with increase in water depth. One can observe from Figures 5 *a–c* and 7 that there is a time gap between the maximum solar radiation measured and the maximum yield obtained. This is due to time lag between evaporation, condensation and heat storage effect of water. The distillate output increases at night with increase in water depth because the water in the solar still stores the heat and remains hot enough for long hours. The recording of the parameters was terminated for the day at 19:00 h, but an average distillate of about 1.5 kg was observed after 19:00 h. This is because water stores some amount of heat during the day which is used at night and temperature of the glass cover reduces after 19:00 h. Both wind velocity and solar intensity play an important role in variation of ambient temperatures. Water temperatures in evacuated tube and solar still are directly proportional to the solar intensity. Usually all the temperatures and distillate yield begin to decrease from 16:00 or 17:00 h because of the reduction in solar radiation. The distillate yield initially increases, reaches a peak and starts to decrease with time.

Figure 7 shows the curve for distillate yield obtained for an experiment performed on 26 March 2014, maintaining the water depth of 0.02 m in the still without coupling it with evacuated tubes. The experiment was carried out by converting the coupled system into a passive solar still by uncoupling the evacuated tubes and plugging the holes with a stopper/cork. Care was taken to ensure that the holes do not leak. The total solar radiation from 7:00 to 19:00 h on a typical day is observed to be 6694 W/m^2.

Wind velocity over the glass cover and ambient temperature are found to be in the range 0.6–1.7 m/s and 28°C to 37°C respectively. Even though the depth of water is maintained at 0.02 m, the average reduction in distillate yield obtained for the still without evacuated tubes when compared to coupled system is found to be 60.2%. Evacuated tubes supply additional heat energy to the basin water. Hence, coupled system has an advantage over conventional passive solar still.

The hourly variation of instantaneous energy efficiencies on typical days for different water depths during sunshine hours is shown in Figure 9. The instantaneous energy efficiency of the coupled system is found to be in the range 0.33–73.18%, 0.89–37% and 0.27–31.72% between 9:00 and 17:00 h for water depths of 0.02, 0.04 and 0.06 m respectively. High energy efficiency per hour is found for lower water depth of 0.02 m and it decreases with increase in water depth. At 18:00 h, during sunset, the energy efficiencies are found to be higher and the curves for all the three water depths tend to cross hundred per cent. This is due to the sudden decrease in solar radiation, which drastically reduces the value of the denominator in eq. (2). It is noticed in eq. (2) that the instantaneous energy efficiency is inversely proportional to the amount of solar radiation over the coupled system. Hence, decrease in solar radiation will result in increase in energy efficiency[19]. However, significant drop in distillate yield is not noticed because of the time lag between evaporation and condensation. In the morning, the energy efficiency is lower because of the increase in heat flow to the water compared to heat of evaporation in the still. Similar trend of energy efficiency curves has been observed by Singh *et al.*[21] and Hongfei[33].

In Figure 9, the energy efficiency curve drops down at some points. For water depth of 0.06 m in the coupled system, the efficiency drops at 8:00 and 10:00 h. Similarly for water depth of 0.04 m, efficiency drops at 9:00 h and for depth of 0.02 m, it drops at 9:00 and 15:00 h. For instance, at 15:00 h and for water depth of 0.02 m, the energy efficiency drops by 4.3%. This is because of the drop in the values of h_e and h_{wc} (Figure 8). The values of heat transfer coefficients reduce because of the decrease in the value of $(T_w - T_{gi})$. Also, for 0.02 m water depth, at 15:00 h the value of T_{gi} is maximum (Figure 5 *c*). Hence the curve for energy efficiency drops.

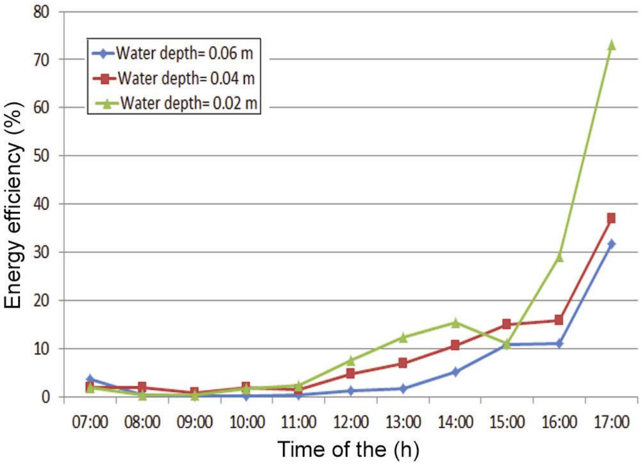

Figure 9. Variation of instantaneous energy efficiency with time water depth in the coupled system.

Chemical analysis of water samples

Synthetic sample is prepared by mixing known amount of fluoride in hard water and chemical analysis of water samples is carried out. The chemical composition of both inlet water sample and outlet distilled water is tested using standard methods according to the American Public Health Association (APHA) and American Water Works Association (AWWA). The results are shown in Table 4. The values obtained for chemical composition of both the inlet and outlet water samples are compared with the Indian standard drinking water specifications (IS 10500:2012). These tabulated results prove that the outlet water from this desalination system is fit for drinking and the system is successful in reducing the chemical contaminants of inlet water sample. The feasibility of the system to get rid of excess chemical contaminants like fluoride, calcium and magnesium is thus proved. The system is also successful in reducing total dissolved solids, hardness, electrical conductivity and alkalinity present in inlet water sample. The distillate obtained from the system contains chemical parameters within the limits of drinking water standards.

Costing of the coupled system

The cost break-up of various materials used for fabrication of the coupled system, including the fabrication cost is shown in Table 5. The total cost of the coupled system developed is estimated to be Rs 6980 or US$ 115.8 (with conversion factor US$ 1 = Rs 60.25; as on 15 April 2014). The cost of the coupled system may still reduce if production is increased. The system is designed in such a way that it can be easily fabricated by the locals, which in turn generates rural employment.

Conclusion and future work

In the present work, a coupled system is developed by integrating a single-slope single-basin solar still with evacuated tubes in natural mode, i.e. without any heat exchangers between the tubes and the solar still. The coupled system is fabricated and tested for climate conditions of Bangalore.

Table 4. Comparison of chemical composition of water before and after purification with acceptable limits

Parameter	Inlet water sample	Acceptable limit according to IS:10500:2012	Outlet water sample
pH	6.9	6.5–8.5	7
TDS (mg/l)	597	500	10.62
Electrical conductivity (μS/cm)	1253	–	23.7
Total alkalinity (as $CaCO_3$; mg/l)	500	200	52
Total hardness (as $CaCO_3$ and $MgCO_3$; mg/l)	632	200	84
Fluoride (F; mg/l)	12.3	1	< 0.01
Chloride (Cl; mg/l)	151.97	250	< 0.01
Nitrate (NO_3; mg/l)	13.6	45	0.674
Sodium (Na; mg/l)	1.2	200	< 0.01
Calcium (Ca; mg/l)	117.04	75	11.21
Magnesium (Mg; mg/l)	82.62	30	13.61
Calcium hardness (as $CaCO_3$; mg/l)	292	–	28
Magnesium hardness (as $MgCO_3$; mg/l)	340	–	56
Potassium (K; mg/l)	0.2	–	< 0.01
Inference	Unfit for drinking	_	Fit for drinking

Table 5. Cost break-up of various materials used in the fabrication of coupled system (January 2014)

Component	Quantity	Cost (INR)
GI sheet	20 kg	1200
Glass cover	1	450
Evacuated tubes	10	1250
Aluminium reflector	1	190
Water tanks	2	300
Nitrile rubber (0.025 m thick)	1 m^2	550
Iron stand	15 kg	750
Powder coating (black)	–	400
Miscellaneous (adhesive tape, silicon sealant, hose pipes, collars, float bulb, rubber gaskets)	–	890
Fabrication cost	–	1000
Total		6980

Based on the various experiments conducted and the above discussions, the following conclusions are drawn:

(1) Thermo-syphon process helps increase the temperature of water in the basin of the solar still. Hence, it can be concluded that integrating evacuated tubes with solar still increases the water temperature and distillate yield.

(2) The maximum distillate yield obtained for basin area of 0.51 m^2 is 5.534 kg for water depth of 0.02 m for the time period 7:00–19:00 h. The yield decreases as the depth of water in the coupled system increases. The reduction in distillate yield of the coupled system for water depth of 0.06 and 0.04 m compared to 0.02 m is 40.56% and 15.93% respectively. The average reduction in distillate yield obtained for the still without evacuated tubes when compared to coupled system is found to be 60.2%.

(3) The maximum hourly energy efficiency of 73.18% for the coupled system is observed for lower water depth of 0.02 m and the energy efficiency decreases with increase in water depth in the coupled still. Similarly, the internal heat transfer coefficients are higher for lower water depths.

(4) The developed system is successful in reducing the excess chemical contamination of inlet water sample. The chemical composition of distillate obtained satisfies the drinking water standards. The cost of the developed coupled system is estimated to be Rs 6980.

To get 8–12 litres of potable water, two units of developed coupled system can be used or the basin area of the solar still in the coupled system should be increased. Usually in rural areas, water for bathing is heated by burning wood, twigs, leaves or cow dung, which leads to emission of carbon dioxide or/and carbon monoxide to the atmosphere. At 19:00 h, the temperature of the basin water is observed to be quite high, i.e. in the range 69–78°C. This water can be drained from the solar still and stored in the insulated tanks so that it can be used for domestic purposes like cooking and bathing, which in turn help reduce the carbon emissions to the atmosphere. This eco-friendly system does not depend on any conventional source of energy for its operation and proves to be a promising alternative for meeting the domestic potable water needs in the rural areas. The system can be easily built by the locals and is easy to maintain.

This work on coupled system is just a beginning and the results are only a starting point to improve the system. Future work will be specifically targeted to increase the distillate yield of the developed system using linear sponge and thermal storage beds made of pebbles and granite stones in the solar still. Further, the effect of air over the glass surface (forced convection using a fan) on distillate yield will also be studied.

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