AN EXPERIMENTAL STUDY ON SINGLE BASIN SOLAR STILL AUGMENTED WITH EVACUATED TUBES

by

K.SAMPATHKUMAR, K.MAYILSAMY, S.SHANMUGAM and P.SENTHILKUMAR

The productivity of the solar still is determined by the temperature of water in the basin and the glass temperature. Various active methods have been adopted to increase the temperature of the basin, so as to improve the productivity of solar still. Most of the previous research works have been focusing on flat plate collector and concentrating collector. In this experimental study, a single slope solar still directly augmented with evacuated tubes was used to increase the daily productivity by reducing heat losses. Evacuated tubes were directly coupled to the lower side of the single slope solar still with an area of 1m^2. Black gravel is used to increase the productivity by means of reducing quantity of water in the basin. Extensive experiments were conducted to explore the performance of solar still in several modes namely still alone, still with black stones, still with evacuated tubes, and still with evacuated tubes and black gravel. The experimental setup was designed and installed at Solar Energy Park, Tamilnadu College of Engineering, Coimbatore (77˚E, 11˚N), Tamilnadu, India. These experiments were conducted using tap water as feed. It was found that, after augmentation of the evacuated tubes, the daily production rate has increased by 49.7 % and it increased by 59.48% with black stones. Economic analysis was also done and payback period of this experimental setup is 235 days.

Key Words: *augmentation, black gravel, evacuated tube, solar still*

1. Introduction

Water is a precious natural gift and is being polluted by human activities, urbanization and industrialization. The ground water is often over exploited to meet the increasing demand of the people. Less than 1% of earth's water is available for human consumption and more than 1.2 billion people still have no access to safe drinking water. Over 50% of the world population is estimated to be residing in urban areas, and almost 50% of mega cities having population over 10 million are heavily dependent on ground water, especially in the developing countries like India [1].

Most of the rural people still live in absolute poverty and often lack access to clean drinking water. Nearly half of the population is illiterate, not at all aware of the waterborne diseases affecting their health. Nearly 70% of the infectious diseases in India are waterborne. Indian villages are posed with problem of overexploitation of ground water due to increasing dependence on it as other fresh water resources are dwindling fast. Various desalination techniques are used to purify the water. Solar distillation is an easy and cost effective method to provide pure drinking water in rural areas without affecting the nature.

In general, solar distillation process is carried out both in passive and active modes. Normally passive solar still operates in low temperature and the daily productivity is comparatively low. Whereas, to increase the evaporation rate in an active mode the extra thermal energy is fed into the basin. To increase the productivity of solar still, the various active methods are being carried out by many researchers. Most of the works were based on the flat plate collector and concentrating collector. Rai et al. [2] have studied the single basin solar still coupled with flat plat collector and found that the daily production rate was increased by 24% when compared to the simple single basin solar still. Tiris et al. [3] found that the maximum yield of a simple solar still was 2.575l/m^2 day while it was 5.18 l/m^2 day when integrated with flat plate collector. Badran et al. [4] found that its production rate was increased by 231% but efficiency has decreased by about 2.5%. The solar still productivity has increased by 36% while coupling flat plat collector and Badran et al. [5] found that the productivity was proportional to the solar radiation. Sanjay Kumar et al. [6] found that an active solar still with water flow over the glass cover has given maximum yield of 7.5 l/day. Singh et al. [7] concluded that the annual yield was at its maximum when the condensing glass cover inclination was equal to the latitude of the place. Voropouls et al. [8, 9] have studied solar stills coupled with solar collectors and storage tank both experimentally and theoretically and found that the productivity doubled for 24 hours period. Also, they have designed a hybrid solar desalination and water heating system [10].

Tiwari et al. [11] analysed the active regenerative solar still and also they analysed the high temperature distillation system [12]. Yadav et al. studied the transient solution for solar still integrated with a tubular solar collector [13], flat plat solar collector in thermosiphon mode [15] and significant rise in the distillate output was found when the still is coupled with the collector [14]. Sodha et al. [16] experimentally studied that yield of a solar still can be increased by utilization of waste hot water for distillation. Singh et al., [17] analytically found that the efficiency of the system with a solar concentrator was higher than the one with a solar collector. Zeinab S. Abdel-Rehim et al., [18] designed the modified solar still coupled in a solar parabolic through focal pipe and simple heat exchanger which resulted in 18% increase in productivity. Gracia Rodriguez at al., [19)] studied the distillation system coupled to a solar parabolic through collector and found that annual energy production was about 23% greater for a north-south collector. Integration of solar still in a multi source, multi use environment was studied by Mathioulakis et al. [20]. A relatively high temperature solar distillation with shallow solar pond was studied by El-Sebaii et al. [21]. Velmurugan et al. [22] found a considerable increase in productivity by coupling mini solar pond with solar still. Vimal Dimri et al. [23] studied the active solar still with different condensing cover material and found that yield was directly related to thermal conductivity of the condensing materials; copper gave a greater yield compared to glass and plastic.

Various types of evacuated tubes and their thermal analysis were described by Tiwari.G.N. [24]. Morrison et al. [25] concluded from the studies on water in glass evacuated tube water heater that, it is most successful due to its simplicity and low manufacturing cost and also evacuated tube solar collectors had better performance than flat plate solar collectors, in particular for high temperature operations. Indra Budiharadjo et al. [26] experimentally and numerically investigated the natural circulation flow rate through single ended water in glass evacuated tubes mounted over a diffuse reflector. Morrison et al. [27] found that circumferential heat distribution was an important parameter influencing the flow structure. Budihardjo et al. [28] conducted experiments in water-in-glass evacuated tube solar water heater and found that a typical 30 tube evacuated tube array was found to be lower than a typical 2 panel flat plate array for domestic water heating. Louise Jivan Shah et al. [29] conducted test in all glass evacuated tubular collector and the results showed that, the collector with the shortest tube length yielded the highest efficiency and the optimal inlet flow rate was around 0.4 – 1.0 kg/min.

Solar thermal collectors can potentially gain energy through conduction, convection and radiation. Flat plate collector and the evacuated tube are gaining energy from radiation. However, the flat plate collector will lose energy through conduction. But in the case of evacuated tubes, there is virtually no energy loss from the vacuum. The cylindrical shapes of the evacuated tube enable them to positively track the sun throughout the day. Flat plat collector provides peak energy output only during the midday when the sun is perpendicular to the collector surface. The flat plate collectors are best for 10˚C - 50˚C temperature operations. Normally, the domestic water heater needs an average temperature of 60˚C. Evacuated tubes are best for an operating temperature of more than 50˚C [30]. To achieve a higher water temperature in the basin, evacuated tubes are augmented directly with the solar still. So far, no such attempts of experimental investigation are reported in the literature for the productivity enhancement in solar still.

The main objective of this work is to experimentally investigate the performance of the solar still augmented with evacuated tubes. To increase the productivity of the still, black gravels are used inside the basin so as to reduce the quantity of water. Even though the black gravels were used for the productivity enhancement by Nafey et al [31] and here the same is used for the proposed system uses black gravels along with evacuated tubes for enhancing the productivity.

2. Experimental setup and Instrumentation

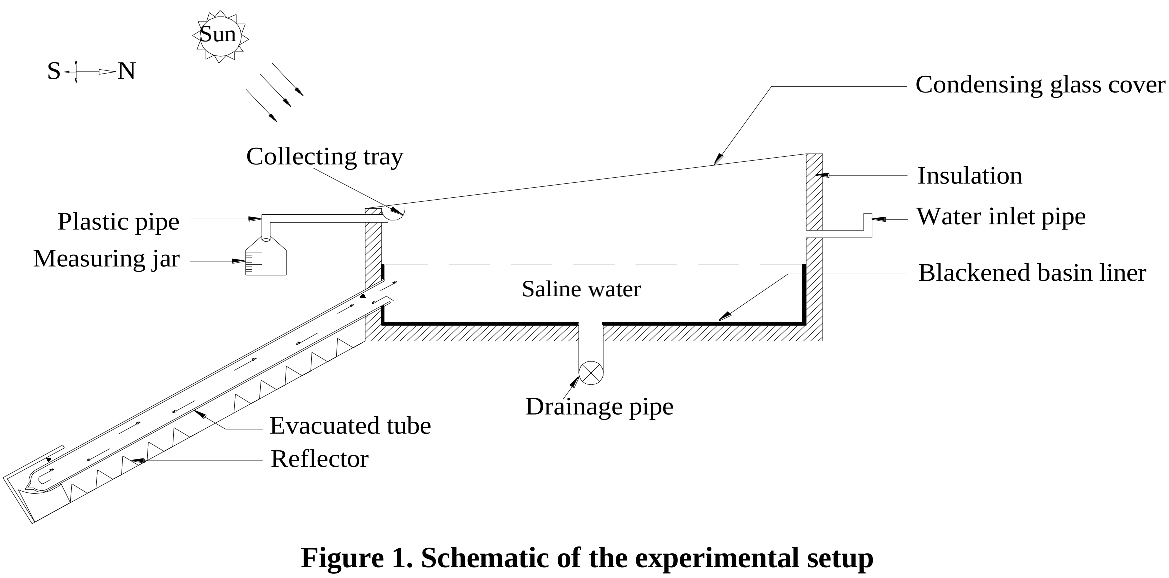

Figure 1. Schematic of the experimental setup

The experimental setup was designed and installed at Solar Energy Park, Tamilnadu College of Engineering, Coimbatore (77˚E, 11˚N), Tamilnadu, India. The major elements of the experimental setup are single basin solar still and evacuated tubes. The experimental setup used for the study is shown in fig.1. The still is made up of aluminium sheet of 100×100cm^2 areas and the same is also acting as a basin. The inner side of the aluminium plate acts as absorber plate and it is painted with black colour for a height of 10 cm at the bottom to absorb higher incident solar radiation. Remaining area in the aluminium plate acts as reflector so as to increase the effect of radiation in the solar still. Another box type outer structure of area 105×105cm^2 was designed and fabricated to hold the still. An insulation of 4cm thickness is provided at the bottom and sides to reduce the heat losses. Polyurethane foam (PUF) with the thermal conductivity of 0.024 W/m^{2}K is used for this purpose. The water in the basin is condensed by using an ordinary window glass of thickness of 0.4cm and it is fixed at an angle of 11˚with respect to horizontal axis (latitude of Coimbatore). The purified water condensed from the glass is collected by folding aluminium sheet in the lower side of the still in "U" shape. Further the "U" shaped collection tray is connected with rubber pipe to collect the purified in a measuring jar. A silicon rubber sealant is used to hold the glass intact with the still surface and to prevent the vapour leakages from the still. Holes are made in the upper side of the still for the inlet pipe and bottom side for the outlet pipe. The thermocouples inside the still are fixed by providing two other small holes in sides of the still.

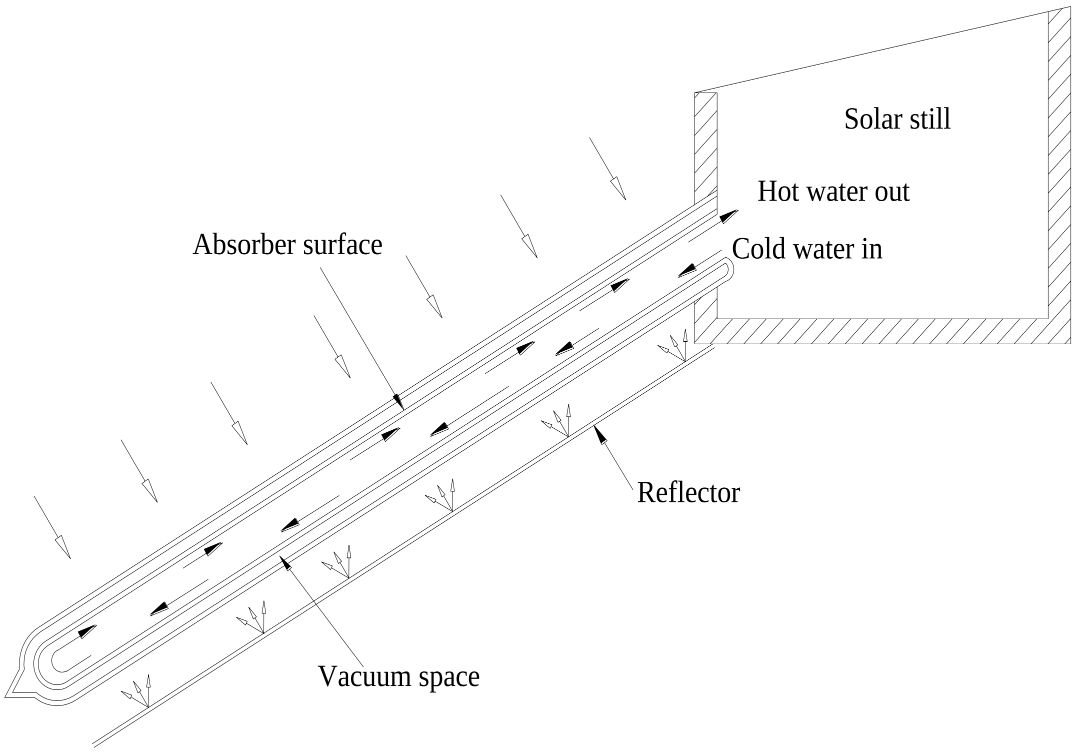

Figure 2. Arrangement of evacuated tube in solar still

The second major part of the experimental setup is the evacuated tubes. Arrangement of evacuated tube in solar still is shown in fig.2. Eight evacuated tubes are coupled by making 6 cm diameter hole in the lower side of the still. The evacuated tubes are placed on a metal frame and it is connected to the still stand at an angle of 45˚ with respect to the horizontal axis. Two reflector plates made up of aluminium in corrugated structure are used to increase the reflective radiation falling on evacuated tubes and it is fixed above the metal frame. Water in glass type evacuated tubes with a length of 15 cm, outer diameter of 5.8 cm, inner glass diameter of 4.7 cm and glass thickness of 0.16 cm are used for this study. Rubber gaskets are used to fix the evacuated tubes to the inner side of the basin. The angle of the evacuate tubes is maintained at 45˚ with respect to the horizontal surface so as to receive the maximum solar radiation. The bottom end of the evacuated tube is well supported with sponge materials in a separate metal structure of the frame. The vapour leakage from the still is prevented using silicon sealant. The selective surface absorber in the inner glass receives the solar radiation and it transfers it as heat energy to the water in the tube. The vacuum space in-between the two glasses reduces the heat losses. The water circulation flows naturally through the single ended tubes. Water in the evacuated tubes is heated by the solar radiation and the hot water rises to the still basin due to the density difference. The high temperature water entering the still basin gets mixed up with the low temperature water in the basin. This makes the low temperature water to flow back to the evacuated tubes and this process continues. The pictorial view of the solar still augmented with evacuated tubes is shown in fig.3.

Figure 3. Pictorial view of solar still augmented with evacuated tubes

The wind speed is measured using digital wind anemometer with the range of 0-15 m/s and accuracy of ±0.2 m/s. During the experimental investigation, the wind speed was in the range of 1-5 m/s. The temperature at various locations in the still was measured by "J" type thermocouples with the range of 0 ˚C – 700 ˚C and accuracy of ±1 ˚C. The intensity of solar radiation is measured using solarimeter with the range of 0-1200W/m^2 and accuracy of ±5 W/m^2. The solarimeter used for the study is manufactured by Central Electronics Limited (CEL), New Delhi, India. A plastic measuring jar of 1000 ml capacity with accuracy of ±5 ml is used for the collection of desalinated water.

3. Experimental procedure

The incident solar radiation is transmitted through an angled glass cover to the water in the basin. Thus the basin water gets heated up and evaporates. The evaporated water particles condense in the inside layer of the glass cover. This condensed water flows down the cover due to the slope provided and reaches the channels, where it is collected by the collection jar. At the beginning of the experiment, tap water is filled in the basin up to 5 cm height through the inlet pipe. The experiment is commenced after 24 hours of assembling the glass cover, so as to enable the setup to reach the steady state condition. For each experiment, the glass cover is cleaned in the morning to avoid the dust deposition over the outer layer of the glass. The extensive experiments were conducted on clear sunny days from May 2008 to March 2009. The readings were taken from 9AM in the morning till 5PM in the evening at hourly intervals. The variables measured in this experiment are water temperature (T_w), basin temperature (T_b), vapour temperature (T_v), inner glass temperature (T_{gi}), outer glass temperature (T_{go}), evacuated tube inlet temperature (T_{ei}) , evacuated tube outlet temperature (T_{eo}), ambient temperature (T_a), solar radiation on still ($I(t)_s$), solar radiation on evacuated tube ($I(t)_e$), wind speed (V) and productivity (P). The first set of experiment was started with simple solar still and black gravel is used for productivity enhancement. The second set of experiment was conducted by augmenting the evacuated tubes to the still. The black gravel is used for productivity enhancements as used in the first experimental setup.

4. Results and discussion

To increase the productivity of single basin solar still, evacuated tubes were directly coupled with the still. Further, to increase the productivity, black gravel was used to reduce the quantity of water in the basin and to increase the exposure area. Also the black gravel acted as energy storage medium and it releases the gained energy during off sunshine hours. The introduction of black gravel with evacuated tubes produced maximum output when compared to other experimental techniques. The performance affecting factors of the solar still were studied by recording various parameters.

4.1 Effect of solar radiation and ambient temperature

The solar still productivity is based on the influence of climatic conditions namely, intensity of solar radiation and ambient temperature prevailing in the testing location. Fig.3 shows the hourly variation of solar intensity and ambient temperature on 09.04.2009. The solar radiation gradually increases with time until 2 PM and reduced towards the evening. It reaches the maximum value of 1050 W/m^2. The ambient temperature was at its minimum of 29 ˚C during 9 AM and it has reached the maximum value of 35 ˚C during 1PM. The above two parameters were purely based on the local climatic conditions of the particular day.

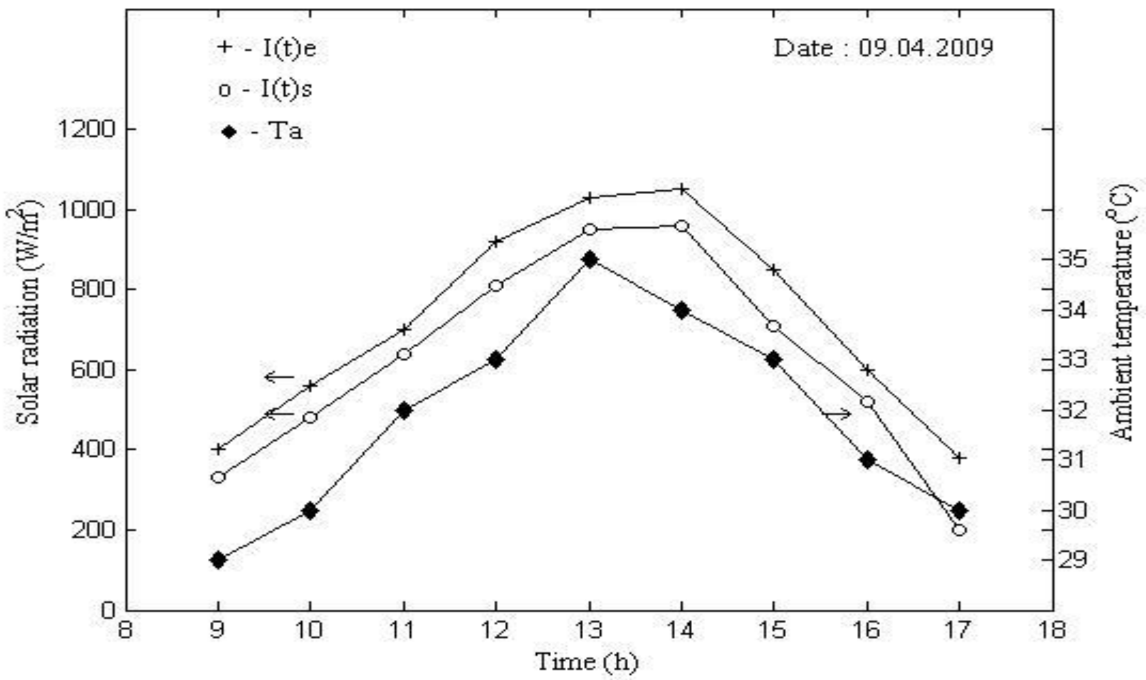

Figure 3. Variation of solar radiation and ambient temperature

4.2 Effect of augmenting evacuated tubes on still productivity

The effect of coupling evacuated tubes with a solar still is shown in fig.4. The basin water temperature is the main parameter, which affects the stills productivity. The evacuated tubes supply

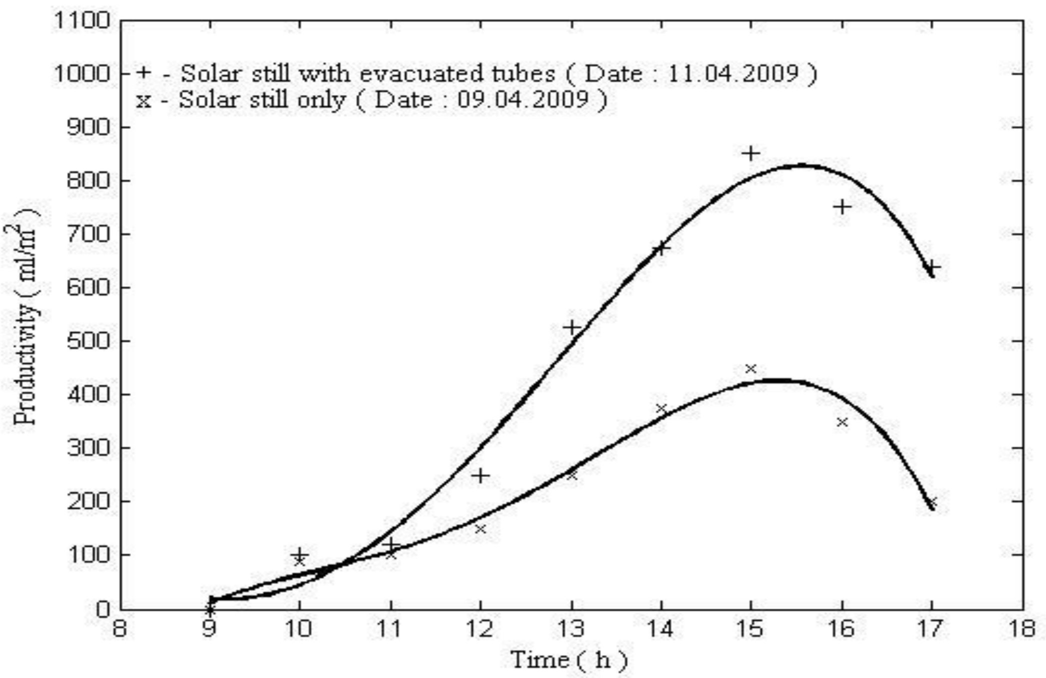

Figure 4. Effect of augmenting evacuated tubes on still productivity

additional heat energy to the water in the basin, in turn to increase the water temperature. The evacuated tubes were directly coupled with still to avoid various heat losses during the circulation of water to the still. Flow of water in the evacuated tubes takes place due to the difference in the density of water, where in water at lower temperature enters though bottom side of the tube and the water with high temperature leaves through upper side of the tube and mixes with water in still basin. Evacuated tubes have higher efficiency than the solar still. Increased water temperature in the basin and the temperature difference between the water and inner glass temperature increased the total output of the distillate. Average increase in the productivity after coupling evacuated tube to the still was 49.7%. The daily productivity of still with evacuated tubes was 3910 ml whereas it was only 1965 ml in the absence of it.

4.3 Effect of black gravel on still productivity

Black gravel was used mainly to reduce the quantity of water in the basin. Considerable impact on productivity is achieved by the introduction of black gravel coupled with evacuated tubes. The performance is sustained by filling the water up to the upper side outer diameter of the evacuated tubes. The productivity is increased by reducing the quantity of water and maintaining the same level.

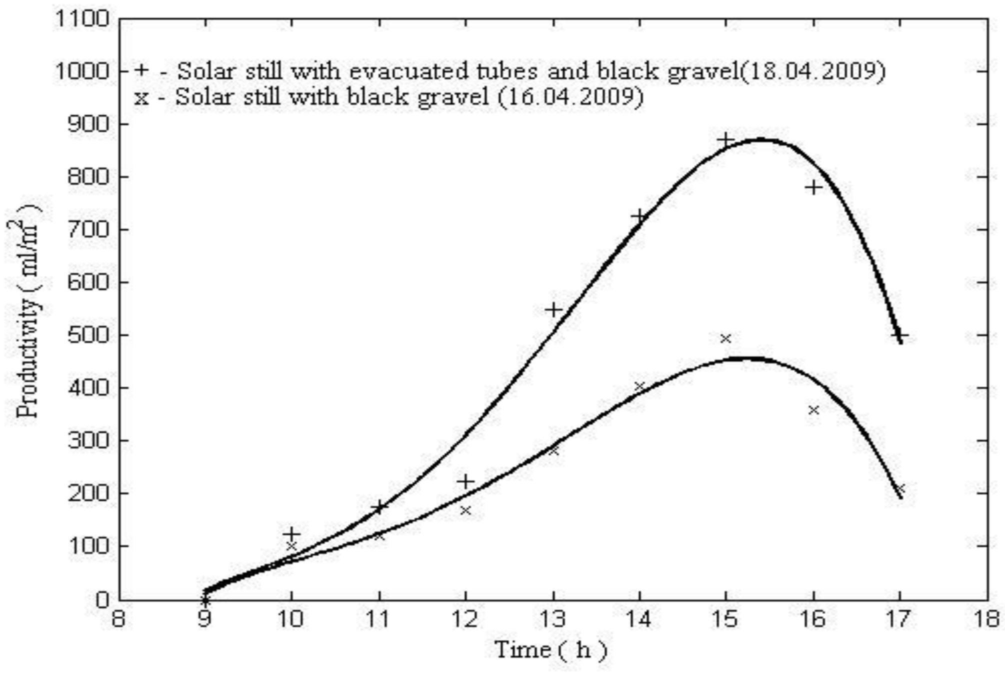

Figure 5. Effect of black gravel on still productivity

The black gravel also acts as an energy storage medium and increases the capillary action during evaporation. The effects of black gravel on simple solar still and black gravel with evacuated tube are shown in fig.5. The daily average productivity has increased by 8 % while using black gravel in simple solar still and by 59.48 % with the introduction of black gravel with evacuated tubes in the simple solar still.

4.4 Hourly variation of temperatures

The hourly variations in the temperatures recorded in the solar still coupled with evacuated tubes on April, 11, 2009 are shown in Fig.6. The complex process of measuring the temperature in the evacuated tube was performed based on the guidelines given by Indra Budiharadjo et al. [26]. A thermocouple was fixed to the lower side of the evacuated tube and it was taken as the inlet temperature. Three other thermocouples were fixed on the upper side of the evacuated tube and their average was taken as the outlet temperature. All the temperatures showed similar trends of increasing with the increases of solar radiation of respective during the day. It was found that the outlet evacuated tube temperature was the highest then followed by the inlet evacuated tube temperature, water temperature, vapour temperature, inside glass temperature, outside glass temperature and temperature. The productivity of the still is determined by the temperature difference between the water and the inside glass. Introduction of evacuated tubes increased the water temperature and in turn increased the productivity. The temperature of water was raised to a maximum of 84˚C during the study period and the average ambient temperature was 31.8˚C.

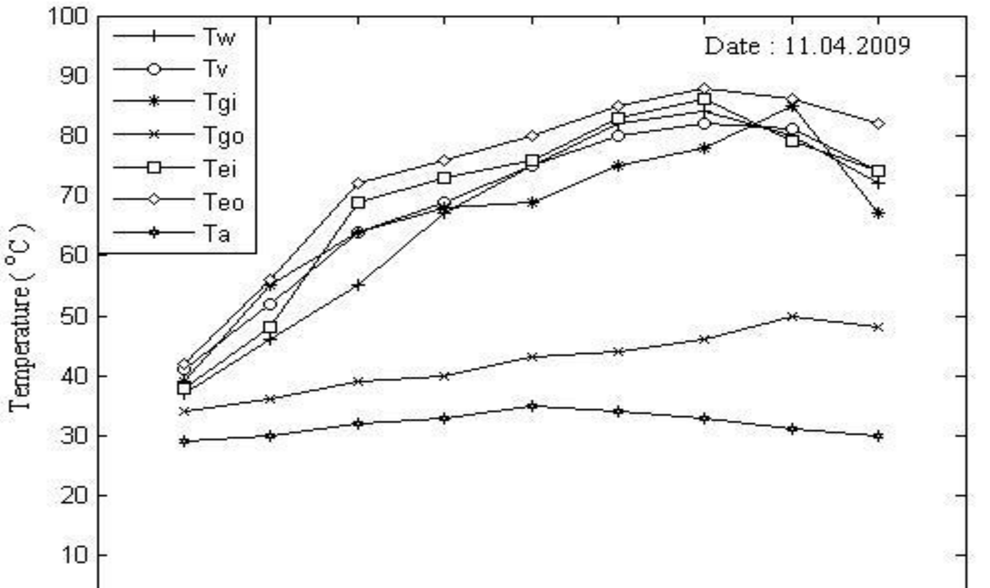

Figure 6. Hourly variations of different temperatures

The various active methods (flat plate collector, parabolic collector and solar pond) used for the productivity enhancement by various researchers and the present method (evacuated tubes) are illustrated in tab.1 in terms of percentage of increase in production.

Table 1. Percentage increase in production for various active methods

Sl.No.	Name of the authors	Type of active still	Increase in production (%)
1	Rai, S.N., Tiwari, G.N. [2]	Flat plate collector	24%
2	Badran O.O., Al-Tahainesh, H.A. [5]	Flat plate collector	36%
3	Zeinab S Abdel-Rehim, Ashraf Lasheen [18]	Parabolic collector	18%
4	Velmurgan, V., Srithar, K. [22]	Solar pond	27.6%
5	In this work	Evacuated tubes	49.7%

5. Economic analysis

The payback period of the solar still coupled with evacuated tubes depends on the fabrication cost, operating cost, maintenance cost, cost of feed water and the financial subsidy offered by government sectors.

1USD = INR. 47 (Assume)
Fabrication cost = Rs. 12000 ($ 212.76)
Operating cost = Rs. 5/day ($ 0.1)
Maintenance cost = Rs. 5/day ($ 0.1)
Cost of feed water = Rs. 1/day ($ 0.02)
Cost of distilled water = Rs. 12/l ($ 0.26)
Productivity of solar still = 5 l/ day
Cost of water produced/day = Rs. 60 ($ 1.28)
Subsidized cost given by government sectors is taken as 4%
Subsidized cost = Rs. 480 ($ 10.21)
Net profit = Cost of water produced – Operating cost – Maintenance cost – Cost of feed water
= Rs. 49 ($ 1.04)
Payback period = (Investment – Subsidized cost) / Net profit
Payback period = 11520/49 = 235 days

6. Conclusion

In this work, the solar still coupled with evacuated tubes was constructed and tested in outdoor conditions. Various experiments were carried out to enhance the productivity of the solar still. The performance of an ordinary still was compared with the still coupled with evacuated tubes. The effect of using black gravel was also studied for both the above said cases. It was found that the daily productivity has increased to 49.7 % by introducing the evacuated tubes and to 59.48 % by coupling evacuated tubes with gravel. Due to simplicity, low cost, less energy losses and high performance, the evacuated tubes were proved to be another option for high temperature distillation when compared to the flat plate collectors. The evacuated tubes were also efficient in the winter season. Annual yield will be more than other active methods like coupling of flat plat collector, parabolic collector etc. The inference of the economic analysis showed that the payback period of this system is 235 days.

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Authors' addresses:

K.Sampathkumar
Department of Mechanical Engineering
Tamilnadu College of Engineering
Coimbatore – 641 659, Tamilnadu, India

K.Mayilsamy
Department of Mechanical Engineering
Institute of Road and Transport Technology
Erode – 638 016, Tamilnadu, India

V.Shanmugam
Department of Mechanical Engineering
Tagore Institute of Engineering and Technology
Attur, Salem – 636 112, Tamilnadu, India

P.Senthilkumar
Department of Mechanical Engineering
KSR College of Engineering
Tiruchengode – 637 215, Tamilnadu, India

Corresponding author (K.Sampathkumar):
E-mail: ksktce@gmail.com