Performance Analysis of Vapour Adsorption Solar Still Integrated with Mini-solar Pond for Effluent Treatment

Dr. K. Srithar

Abstract—**Industrial effluent was evaporated in a single basin solar still and an Integrated vapour adsorption solar still separately. To preheat the saline water, a mini solar pond was integrated with these stills. Both the stills were operated with mini solar pond and tested individually. In single basin solar still, maximum productivity is obtained, when it is modified with sponge, pebbles and sand. The Vapour adsorption solar still was modified with sand, pebble and sponge to enhance their productivities. When mini solar pond, pebble, sponge and sand are used in Vapour adsorption solar still, maximum productivity was obtained. To settle the industrial effluent, a settling tank was also fabricated with five layers namely: tray for raw effluent, pebble layer, coal layer, sand layer and collection tray for settled effluent. Physical and chemical analyses were made for raw effluent, settled effluent and distilled water.**

Index Terms—**Effluent, Mini solar pond, Single Basin type, Vapour adsorption type solar still.**

I. Introduction

Freshwater is one of the Earth's most valuable renewable resources. Along with the supply of energy, access to freshwater is a fundamental need of all societies. Although water covers approximately 70% of the earth's surface, supplies of potable water are rapidly disappearing. This is because only 0.62% of the available water is in a form that can be traditionally treated for human consumption [1]. During the last century, these potable water sources from both surface and ground water resources have been increasingly depleted due to increases in worldwide population. One study [1] of water scarcity trends estimates that of the approximately 6.3 billion people living on earth (US Census, 2003), 400 million people now live in water scarce areas, and the number living in water stressed areas could grow to four billion by mid-century. The demand for potable water was increased by six-fold while the world's population increased into three-fold. To enhance the yield of the single basin solar still, continuously research works are carrying out. Badran et al. [2] integrated a conventional flat plate collector with a solar still to augment the production rate. They found that, the mass of distilled water production was increased by 52%, when the still was coupled with flat plate collector. Tiris et al. [3] integrated two flat plate collectors and a storage tank with single basin still for enhancing productivity of the still. They proved that, the average daily production of distilled water was 100% higher than a single basin solar still. A flat plate collector coupled with solar still [4], and flat plate collector with solar stills and hot water storage tank [5, 6] was designed by Voropoulos et al. Also they designed a hybrid solar desalination and water heating system [7] studied the effect. John Ward [8] designed a solar purifier, which consists of a plastic sheet and a glass window. They formed the plastic into an array of interconnected square cells which contain impure water. In their experimental set up there were no filters, no electronics, no moving parts and cleaning was also rarely needed. It was light weight, cheap strong, durable and can be used in any sunny location on earth. Helal and Malek [9] analysed a diesel solar-assisted MVC desalination system represents an optimal solution to provide small communities at remote areas with fresh water while generating enough power for the operators housing and plant operation with minimal impact on the environment. Antonio and Michel [10] have done a predictive model for an adsorption solar cooling system using the activated carbon and methanol pair and its numerical simulation. Wang et al. [11] have done a research on a combined adsorption heating and cooling system. The system consists of a heater, a water bath, and an activated carbon and methanol adsorption bed and ice box. This system has been tested with electric heating. The experiments show the potentials of the application of the solar powered hybrid water heater and refrigerator. Sumathy [12] have worked on the Experimental studies on a solar thermal water pump. The performance of a solar water pump which works on the basis of vapour generated by a flat-plate solar collector of exposed area 1 m^2 has been studied for three different discharge heads, namely 6, 8 and 10 m. Dai and Sumathy [13] investigated the heat and mass transfer in the adsorbent of a solar adsorption cooling system with glass tube insulation. The adsorber is a metal tube packed with activated carbon methanol pair surrounded by a vacuum tube glazing. Liu et al. [14] proposed a new adsorption refrigeration system, without refrigerant valves, and the problem of mass transfer resistance resulting in pressure drop along refrigerant passage in conventional systems when methanol or water is used as refrigerant can be absolutely solved. Anyanwu and Ogueke [15] proposed the thermodynamic design procedure for solid adsorption solar refrigeration is presented and applied to systems using activated carbon/methanol, activated carbon/ammonia and

Dr.K.Srithar, Associate professor, Thiagarajar college of Engineering, Madurai

zeolite/water adsorbent/adsorbate pairs. The results obtained showed that zeolite/water is the best pair for air conditioning application while activated carbon/ammonia is preferred for ice making, deep freezing and food preservation. Sumathy and Zhongfu [16] presented the description and operation of a solar-powered ice-maker with the solid adsorption pair of activated carbon and methanol. A domestic type of charcoal is chosen as the adsorbent, and a simple flat-plate collector with an exposed area of 0.92 m^2 is employed to produce ice of about 4-5kg/day. Anyanwu [17] studied and presented the basic principles and theories of solid adsorption solar refrigeration. The cycle performance thermodynamics is also reviewed, and the criteria for selection of adsorbent/adsorbent pairs are reported. The practically realized solar adsorption cooling systems were categorized by their adsorbate operating pressure ranges as low and high pressure systems. Hildbrand et al. Tahat [21] et al. produced a portable mini solar pond and analyzed the performance. Also they determined the effect of depth in various zones of solar pond and its water's salinity on store's temperature distribution both by experimentally and theoretically. Velmurugan et al. [22] conducted an experimental study in a single basin solar still integrating with a mini solar pond for enhancing the productivity of the still. An experimental and theoretical analysis for the same was done by Velmurugan and Srithar [23]. Also they [24] had reviewed the various applications of solar pond. The objective of this work is to effectively make use of solar stills for desalinating the industrial effluents. An ordinary basin type solar still and integrated vapour adsorption type solar still were tried individually. In the single basin stills, vapour adsorption still were integrated in the basin plate and in the vapour adsorption solar stills, basin plates are in the form of trays with two different depths. To get clarified pure saline water, first the raw effluent was passed through a settling tank. A solar pond was integrated individually with each still and the performances were compared. To enhance the productivity, in both stills, sand, pebbles and sponges were tried and their performances were also compared.

II. Experimental Setup

The schematic diagram of the experimental set up is shown in the Fig.1. It consists of a settling tank, a storage tank, a mini solar pond, a single basin solar still and a vapour adsorption solar still. The settling tank had five layers; tray for raw effluent, pebble layer, coal layer, sand layer and collection tray for settled effluent. Each tray was separated by wire meshes. A storage tank was placed in between mini solar pond and settling tank. The settled effluent was stored in the storage tank. From the storage tank the settled effluent was allowed to flow through the mini solar pond by using the flow control valve V1. The single basin solar still and stepped solar still were coupled to outlet of the mini solar pond. For controlling flow, from mini solar pond to single basin solar still, control valve, V2 was used. The valve V3 was used to control the settled effluent from the mini solar pond to the vapour adsorption solar still. To preheat the settled effluent in the mini solar pond, a swirled copper tube was used. Heat can be extracted from solar pond through two modes namely, batch mode and continuous mode. In this work, water is not sent through the mini solar pond continuously. For every half an hour, the hot water is taken from the mini solar pond and send to solar still. The same quantity of the water will supply to the solar pond. So, in this work batch mode of heat extraction was used. The solar pond was fabricated as truncated conical shape. The diameter at the top layer was 900 mm and the diameter at the bottom layer was 300 mm. The upper convective zone was at a height of 80 mm from the top surface. The total height of the pond is 300 m. Prasad et al. [24] estimated the thickness of lower convective layer of solar pond. Using the estimation, it was taken as 100 m. The intermediate zone or the non-convective zone was 120 mm from the top. The copper tube of 7 mm diameter was swirled as a coil structure in order to have more contact area with the hot salty water. The inlet of the copper coil was connected to the collecting tank, which was placed beneath the settling tank. The outlet of the mini solar pond is connected to the basin type still and vapour adsorption type solar still. The flow rate of effluent through the copper coil was being regulated by means of the valve V1. Thermocouples were placed in each zone to measure the temperature. An optimum salinity of 80 g/kg [23] was maintained in the solar still. A single sloped solar still consist of a wooden box having dimensions as 1.2×1.2 m2. Holes were provided for the distilled water output and for the effluent water input. The outer side of the wooden box was covered by the sheet metal, in order to protect it from solar radiation and rain. The basin of the still was made up of Galvanized Iron (GI) sheets, for its good conductivity and cheaper cost. The surface of the basin was coated with a matte black paint in order to absorb more incident energy from the sun. The dimensions of the basin were 1000×1000 mm2. The sides and the bottom of the basin were insulated by using sawdust. The condensing surface in the still was simply a glass cover. The glass of size 1100×1100 mm2 was used as the roof for the still. The distilled water was collected in the collection trough. The water condensed on the glass surface was collected into the trough by a piece of glass attached in the glass, right above the collection trough. The glass cover of still box was tilted with an angle of 10°. Leather sheet was used to prevent leakage from any gap between the glass covers and the still box. Poly Vinyl Chloride (PVC) tubes were used to discharge the distilled water from each unit to the bottles. The inlet water was fed into the still using flexible hoses.

The vapour adsorption still is made up with dimensions of the basin having area of 0.9 x 0.9 m2. It is fabricated of 2 mm thick GI sheet and coated with black paint to increase the adsorption. The basin is enclosed in the wooden box in the basin plate is vapour adsorption pipes containing activated carbon and ethanol which increases the evaporation rate. There are two concentric pipes, among them, the smaller one having brackish or saline water flow and is covered by larger pipe containing the mixture of activated carbon and ethanol. The gap of 0.2 m between the sides of the tray and the wooden box is filled with saw dust. This acts as insulation and prevents the side loss of heat through conduction. Other setup is similar to simple basin still. To measure the temperatures of basin plate, saline water, glass and three zones of mini solar pond, Copper Constantine thermocouples integrated with a temperature indicator and selector switch were used. Solar radiation was measured by a calibrated Kipp-Zonen pyranometer. A calibrated plastic beaker of 1 L capacity was used to measure the hourly yield. Vane type digital anemometer was used to measure the wind velocity. This experimental setup was designed, installed and tested at Thiagarajar College of Engineering, Madurai, Tamil Nadu, India. The average solar radiation intensity in Madurai was 600W/m2. The glasses of the both stills were facing towards south with an inclination of 10°, which is the latitude of Madurai, India.

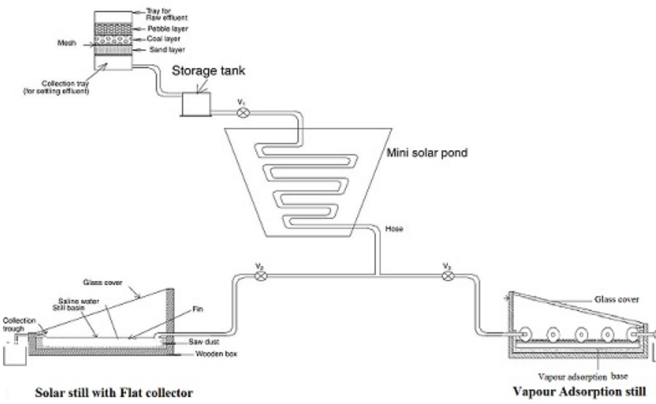

Fig.1 Experimental setup

III. EXPERIMENTAL PROCEDURE

The industrial raw effluent was poured into the raw effluent tray and it was allowed to pass through pebble, coal and sand layers. The pebble layer filters the large sized solid particles present in the effluent. The activated charcoal layer removes turbidity and bacteria present in the effluent. The sand layer filters the fine solid particles present in the effluent. The effluent was allowed to settle for at least two hours in the collection tray. This settled effluent was stored in a storage tank. From this storage tank, the effluent was passed through solar pond by a swirled copper tube. While passing through the copper tube, the effluent got preheated. The outlets of the copper tube were connected to the single basin solar still and vapour adsorption solar still by valves V2 and V3. To conduct the experiments in single basin solar still, valve V2 was opened and valve V3 was closed. The hot, settled effluent from the mini solar pond was filled in single basin solar still. In still, the effluent water got evaporated and condensed at the inner surface of the glass. The condensed water was gliding over the glass and collected at the collection trough. From the collection trough, the distilled water was collected in a beaker using flexible hoses. As water evaporated in the stills, its level will reduce in the stills. So, make up water was added in the stills by opening the valves V2 for every half an hour. Valve V3 was opened and valve V2 was closed during experimentation in vapour adsorption solar still. Experiments were carried out from 9 AM to 5 PM. The solar intensity, wind velocity, ambient temperature, yield and the temperatures of the various zones in mini solar pond were measured in hourly basis. The temperatures of the basin plate, glass and saline water of single basin solar still and vapour adsorption solar still were also measured. A mini solar pond, sponge, pebbles and sand were used to enhance the productivities of single basin and vapour adsorption solar still. In the following sections, the modifications the vapour adsorption still were explained.

A. Solar still coupled with Activated carbon and Methanol:

Introduction of Vapour adsorption material will enrich the sensible heat storage and thereby reduces the preheating time required for the saline water. In this work, 5 concentric pipes containing Activated carbon and methanol is used. Also mini solar pond was integrated with this still.

B. Solar still coupled with Activated carbon and Methanol with sponges:

To increase water exposure area, sponges were used in vapour adsorption solar still and integrated with mini solar pond. The exposure area increases due to the capillary action. This will increase the evaporative area as well as evaporation rate. The experiments were conducted at both the stills and readings were noted down. From the result of these experiments, it was observed that the productivity of vapour adsorption type still increased. This proved that the addition of sponges made increase in effect on the productivity of the still.

C. Solar still coupled with Activated carbon and Methanol with sponges and Pebbles:

In addition to Vapour adsorption setup pebbles were added to previous modification. It was observed that the productivity of still increased due to the higher volumetric heat capacity of the pebbles. This proved that the addition of sponges and pebbles made increase in effect on the productivity of the still.

D. Solar still coupled with Activated carbon and Methanol with sponges and sand:

As sand being as a sensible heat storage material, it was used in the gap between the concentric pipes. The productivity increases due to increase in sensible heat. Also the solar still was integrated with a mini solar pond. Other experimental procedures are similar to the previous section.

E. Maintenance of solar vapour adsorption still:

The major maintenance activity required to ensure that the vapour adsorption solar still continues to provide pure water output is cleaning. In either operation mode, the outer side of glass must be cleaned regularly to remove dust and any other contamination to allow maximum transmission of the sun's rays through the glass and into water. The maintaining of the water depth is important, it is maintained every 1 hour and it is also used to keep salt concentration. If the concentration of water increases, it decreases the evaporation rate. So it affects the productivity of pure water.

Fig.2. Modifications

IV. Physical and Chemical Treatment Analysis

Physical analysis (turbidity and total dissolved solids) and chemical analysis (pH, alkalinity, total hardness, Calcium, Magnesium, Potassium, Sodium, Iron, Manganese, Ammonia, Nitrate, Chloride, Fluoride, Sulphate, Phosphate, BOD and COD) were made at Tamilnadu water supply and drainage board, Tamilnadu, India. The various minerals present in raw effluent, settled effluent and distilled water were shown in the Fig. 2.

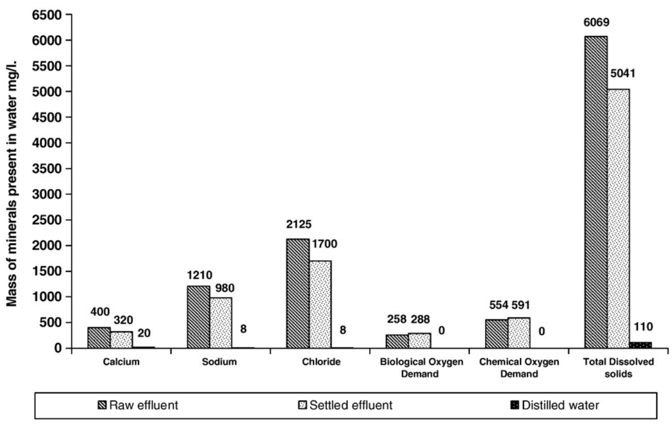

Fig. 3 Chemical analysis of raw effluent, settled effluent and distilled water

V. Results and Discussion

Vapour adsorption material, sponge, pebble, sand were used to enhance the productivities of the single basin and Integrated modified solar still. Performance of the both the stills were compared by integrating a solar pond. The improvement in productivity for modified solar stills.

A. *Effect of solar intensity due water-glass temperature:*

Solar intensity is the driving force for evaporating water from the basin to the glass in the still. Evaporation of water in the still depends on water-glass temperature difference also. When solar intensity increases, both productivity and water-glass temperature difference increase as shown in the Fig. 3 This graph was plotted for Vapour adsorption type solar still.

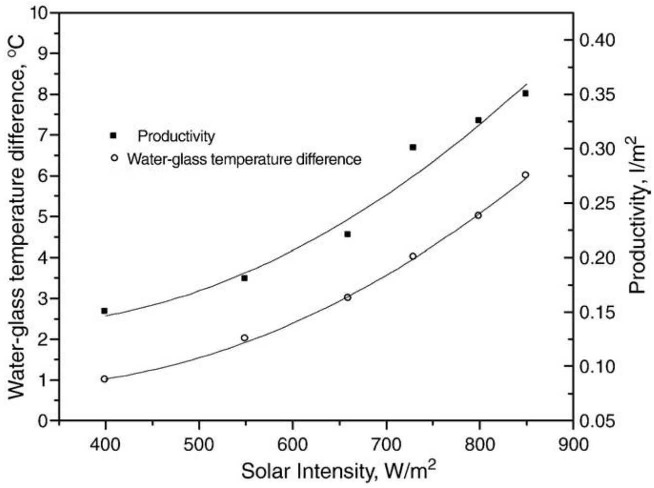

Fig.4 Effect of solar intensity on productivity and water-glass temperature difference

B. *Effect of solar radiation on productivity:*

For a constant value of wind velocity 1 m/s, data were taken from various days of experiments including all modifications. The variation of productivity with solar intensity is plotted in Fig. 4. It was found that productivity increased with solar intensity. When solar intensity increases, the saline water temperature increases. Thus the productivity increases.

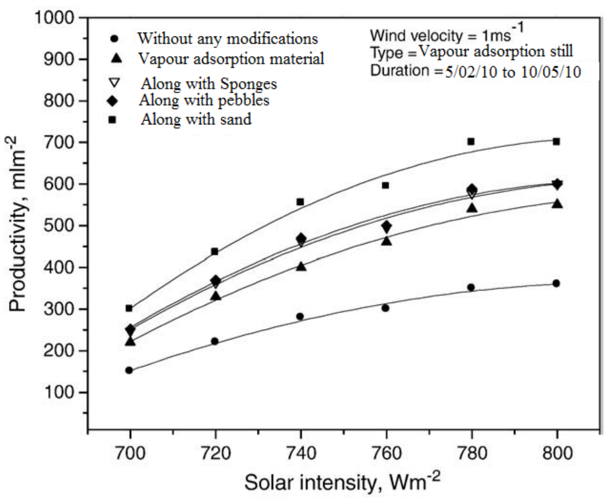

Fig. 5 Effect of solar intensity on productivity in Vapour adsorption solar still.

C. *Effect of Wind velocity on productivity:*

Fig. 5 shows the variation of wind velocity on productivity. Data were chosen from various days of experiments for a constant 700W/m2 solar intensity. Convective losses are directly proportional to wind velocity. Hence, wind velocity increases, the productivity decreases.

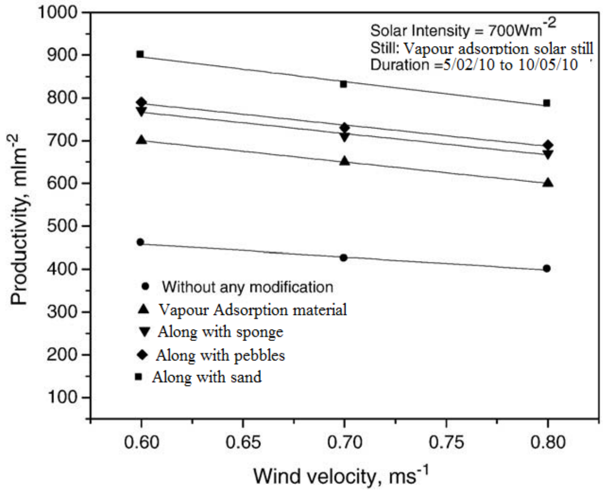

Fig.6 Effect of wind velocity on productivity in stepped solar still.

D. Solar still coupled with Activated carbon and Methanol:

Due to the presence of activated carbon and methanol inside the outer pipes, the water output increases when compared to conventional still. The overall efficiency vapour adsorption type still is 24.19% higher than conventional still.

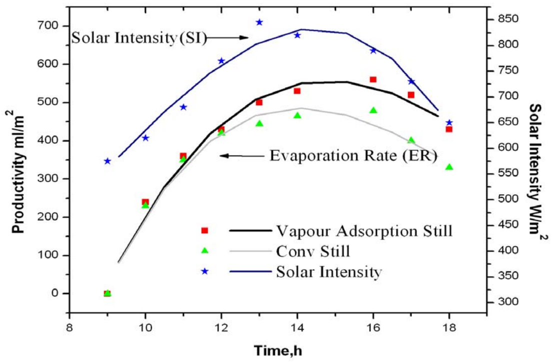

Fig. 7. Effect of evaporation rate using Activated carbon and methanol

E. Solar still coupled with Activated carbon and Methanol with sponges:

It is observed that due to the presence of activated carbon, methanol and sponge, the water output is increased to 27.41% in vapour adsorption type still due to the addition of sponge when compared to conventional still.

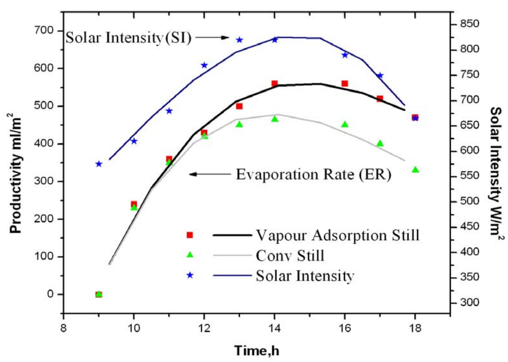

Fig 8. Effect of evaporation rate using Activated Carbon , Methanol and Sponge

F. Solar still coupled with Activated carbon and Methanol with sponges and Pebbles:

Due to the presence of activated carbon, methanol, sponge and pebbles, the overall water output is increased to 30.23% in vapour adsorption type still when compared to conventional still Because Volumetric heat storage of pebbles.

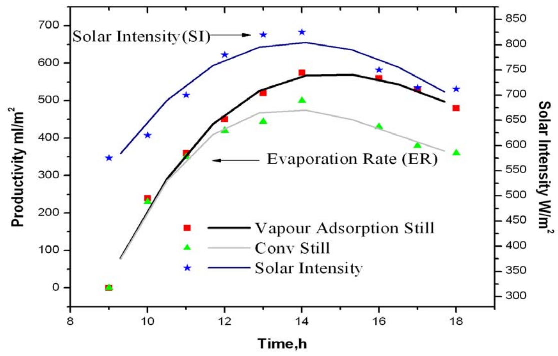

Fig 9. Effect of evaporation rate using Activated Carbon , Methanol and pebbles

G. Solar still coupled with Activated carbon and Methanol with sponges and sand:

It is observed that due to the presence of activated carbon, methanol, sponge and sand, the water output is increased in vapour adsorption type still when compared to conventional still. The overall productivity of the still is enhanced by 32.32 % by the use of vapour adsorption type basin by adding sand with sponge than simple basin.

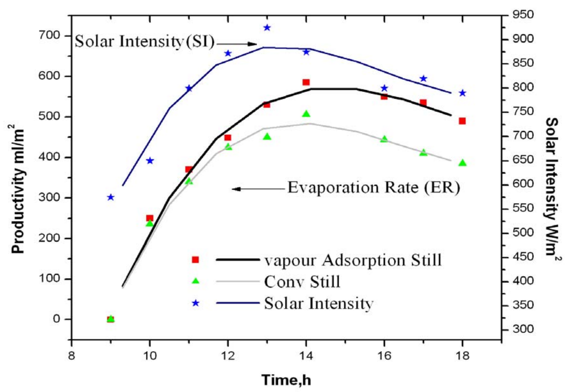

Fig. 10. Effect of evaporation rate using Activated Carbon, Methanol, Sponge and Sand

VI. Performance Comparison of Various Modifications

The following graphs shown below was the comparative illustration of the productivity of various modifications using Activated carbon, methanol, sponge, stone and sand per day. The bar chart shown below fig.10 was per day productivity of vapour adsorption type solar still for different materials.

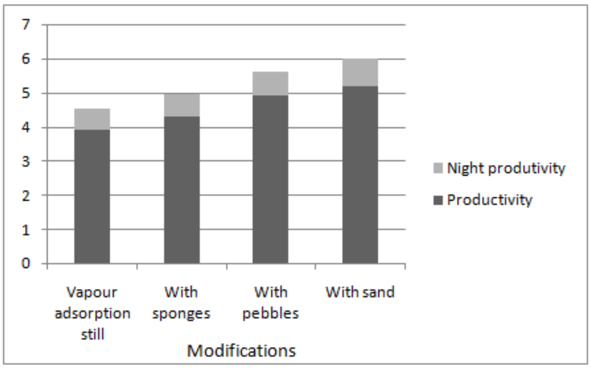

Fig. 11 Performance Comparison on Various modifications

VII. Conclusion

A Mini solar pond was used to store the solar thermal energy. The heat energy stored by the mini solar pond was used for preheating saline water in single basin solar still and vapour adsorption solar still. Experiments were carried out with different salinity in the mini solar pond. It was found that the optimum value of salinity in solar pond water was 80 g/kg.

Industrial effluent was used as raw water in the solar stills. For settling the effluent, an effluent settling tank was designed and fabricated. The performance of single basin solar still and vapour adsorption solar still were calculated. To enhance the productivity, the single basin solar still was modified with sponge, pebbles and sand. And the vapour adsorption solar still was modified with sand, pebble and sponge. Maximum productivity of 32.32% enhancement was obtained for vapour adsorption solar still was integrated with sand and sponge. It was found that the productivity increases with increase in solar intensity and water-glass temperature difference and decreases with increase in wind velocity. Economic analysis was made and payback period is calculated as 417 days.

References

[1] http://www.ceemeng.mit.edu/Stevens.pdf.
[2] Ali A. Badran, Ahmad A. Al-Hallaq, Imad A. Eyal Salman, Mohammad Z. Odat, A solar still augmented with a flat plate collector, Desalination 172 (2005) 227–234.
[3] C. Tiris, M. Tiris, Y. Erdalli, Sohmen, Experimental studies on a solar still coupled with a flat-plate collector and a single basin still, Energy Conversion and Management 39 (1998) 853–856.
[4] K. Voropoulos, E. Mathioulakis, V. Belessiotis, Experimental investigation of a solar still coupled with solar collectors, Desalination 138 (2001) 103–110.
[5] K. Voropoulos, E. Mathioulakis, V. Belessiotis, Solar stills coupled with solar collectors and storage tank-analytical simulation and experimental validation of energy behavior, Solar Energy 75 (2003) 199–205.
[6] K. Voropoulos, E. Mathioulakis, V. Belessiotis, Experimental investigation of the behavior of a solar still coupled with hot water storage tank, Desalination 156 (2003) 315–322.
[7] K. Voropoulos, E. Mathioulakis, V. Belessiotis, A hybrid solar desalination and water heating system, Desalination 164 (2004) 189–195.
[8] John Ward, A plastic solar water purifier with high output, Solar Energy 75(2003) 433-437. regeneration, Energy Conversion & Management 41 (2000) 1625±1647
[9] A.M.Helal and S.A.Al-Malek, Design of a solar-assisted mechanical vapor compression (MVC) desalination unit for remote areas in the UAE, Desalination 197 (2006) 273-300.
[10] Antonio Pralon Ferreira Leite and Michel Daguenet, Performance of a new solid adsorption ice maker with solar energy regeneration, Energy Conversion & Management 41 (2000) 1625±1647
[11] R.Z. Wang, Y.X. Xu, J.Y. Wu, M. Li, H.B. Shou, Research on a combined adsorption heating and cooling system, Applied Thermal Engineering 22 (2002) 603–617.
[12] K. Sumathy, Experimental studies on a solar thermal water pump, Applied Thermal Engineering 19 (1999) 449±459
[13] Y.J. Dai, K. Sumathy, Heat and mass transfer in the adsorbent of a solar adsorption cooling system with glass tube insulation, Energy 28 (2003) 1511–1527
[14] Y.L. Liu, R.Z. Wang, Z.Z. Xia, Experimental study on a continuous adsorption water chiller with novel design. International Journal of Refrigeration 28 (2005) 218–230.
[15] E.E. Anyanwu, N.V. Ogueke, Thermodynamic design procedure for solid adsorption solar refrigerator, Renewable Energy 30 (2005) 81–96
[16] K. Sumathy and Li zhongfu, Experiments with solar-powered adsorption ice-maker, Renewable Energy 16 (1999) 704-707
[17] E.E. Anyanwu, Review of solid adsorption solar refrigeration II: An overview of the principles and theory, Energy Conversion and Management 45 (2004) 1279–1295.
[18] Catherine Hildbrand, Philippe Dind, Michel Pons, Florian Buchter, A new solar powered adsorption refrigerator with high performance, Solar Energy 77 (2004) 311–318.
[19] R.Z. Wang, J.Y. Wu, Y.X. Xu, W. Wang, Performance researches and improvements on heat regenerative adsorption refrigerator and heat pump, Energy Conversion & Management 42 (2001) 233±249.
[20] Xiaolin Wang, Kim Choon Ng, Experimental investigation of an adsorption desalination plant using low-temperature waste heat, Applied Thermal Engineering 25 (2005) 2780–2789
[21] M.A. Tahat, Z.H. Kodah, S.D. Probert, H. Al-Tahaineh, Performance of portable mini solar pond, Applied Energy 66 (2000) 299–310.
[22] V. Velmurugan, K. Mugundhan, K. Srithar, Experimental studies on solar stills integrated with a mini solar pond, 3rd BSME-ASME International conference on Thermal Engineering, Dhaka, Bangladesh, 2006, in CD.
[23] V. Velmurugan, K. Srithar, Solar stills integrated with a mini solar pond – analytical simulation and experimental validation, Desalination 216 (2007) 232–241.
[24] V. Velmurugan, K. Srithar, Prospects and scopes of solar pond: a detailed review, Renewable and Sustainable Energy Review 12 (2008) 2253–2263.
[25] Ram Prasad, D.P. Rao, Estimation of the thickness of the lower convective layer of solar ponds, Renewable Energy 7 (1996) 401–407.