Thermal Analysis of Flate Plate Collectors of Active Solar Stills

Rajeev Ranjan[1] Dharamveer Singh[2]
[1,2]R D Engineering College, Ghaziabad, India

Abstract— Solar distillation is the process of getting potable water by harnessing solar energy with the help of solar still which imitates the natural hydrological cycle with the difference that cycle is closed. Potable water is one of the basic requirements for the survival of organisms on the planet earth, However, water has been contaminated badly due to rapid industrialization, fast growth in agriculture and population all over the world. There is going to be lack of potable water in years to come if this problem is not addressed properly as reported by many researchers. In this circumstance, exploitation of the solar energy for electricity generation and distillation could be better alternative to mitigate the imminent problem of shortage of energy and potable water to a greater extent. The basin type passive and active solar stills have been investigated in the current study on the basis of energy matrices, exergoeconomic parameter, enviroeconomic parameter, productivity and various efficiencies. Its main motive is to offer better solar distillation system to turn out potable water at competitive price. Apart from the conventional solar distillation systems, various other solar distillation systems coupled with (a) N-identical partially covered photovoltaic thermal (PVT) flat plate collectors (FPC), (b) partially covered PVT compound parabolic concentrator (CPC) collectors and (c) evacuated tubular collectors (ETC) have been studied in detail. The thermal model has been developed for the proposed system. The life cycle cost analysis of various basin type solar distillation systems has been carried out by incorporating the effect of energy payback period. Four different types of weather conditions viz. [a, b, c and d] type for each month of year have been considered for the exhaustive computation of yield, energy output and exergy gain at optimum number of collectors and mass flow rate followed by computation of exergoeconomic parameter, enviroeconomic parameter, productivity and various efficiencies. Generally, exergoeconomic parameter is computed as exergy loss per unit cost for systems like mechanical, thermal etc. as reported by several researchers. However it has been proposed to be computed as the exergy gain per unit cost because of the fact that nothing has to be paid against the input (solar energy) to solar system. Also same input cannot be provided to different solar distillation systems while making comparison. The comparison of various solar distillation systems has been carried out at 0.14 m water depth, optimum number of collectors and optimum mass flow rate for the composite climate condition of Ghaziabad U.P, India. The production cost of water in ₹/kg and production cost of electricity in ₹/kWh have also been computed. The performance analysis viz. hourly productivity and various efficiencies of solar distillation systems have been carried out at optimum number of collectors and mass flow rate by incorporating the effect of water depth for two different months (June (summer) and January (winter). It has been concluded that double slope ETC active solar distillation system gives the best performance on the basis of energy matrices and production cost of water. Further double slope PVT-FPC active solar distillation system has been found better than other systems under consideration on the basis of enviroeconomic parameter and annual productivity (exergy based); however, the value of exergoeconomic parameter and energy based annual productivity is highest for double slope ETC active solar distillation system. On the basis of average daily electrical efficiency and average daily overall thermal efficiency, double slope PVT-FPC active solar distillation system gives the best performance; however, double slope PVT-CPC active solar distillation system performs best on the basis of average daily exergy efficiency, overall exergy efficiency and productivity among all active solar distillation systems under consideration. Moreover, double slope ETC active solar distillation system has been found to perform best among all active solar distillation systems under consideration on the basis of average daily thermal efficiency. At last, proposed solar distillation systems has been carried out followed by conclusions and recommendations.

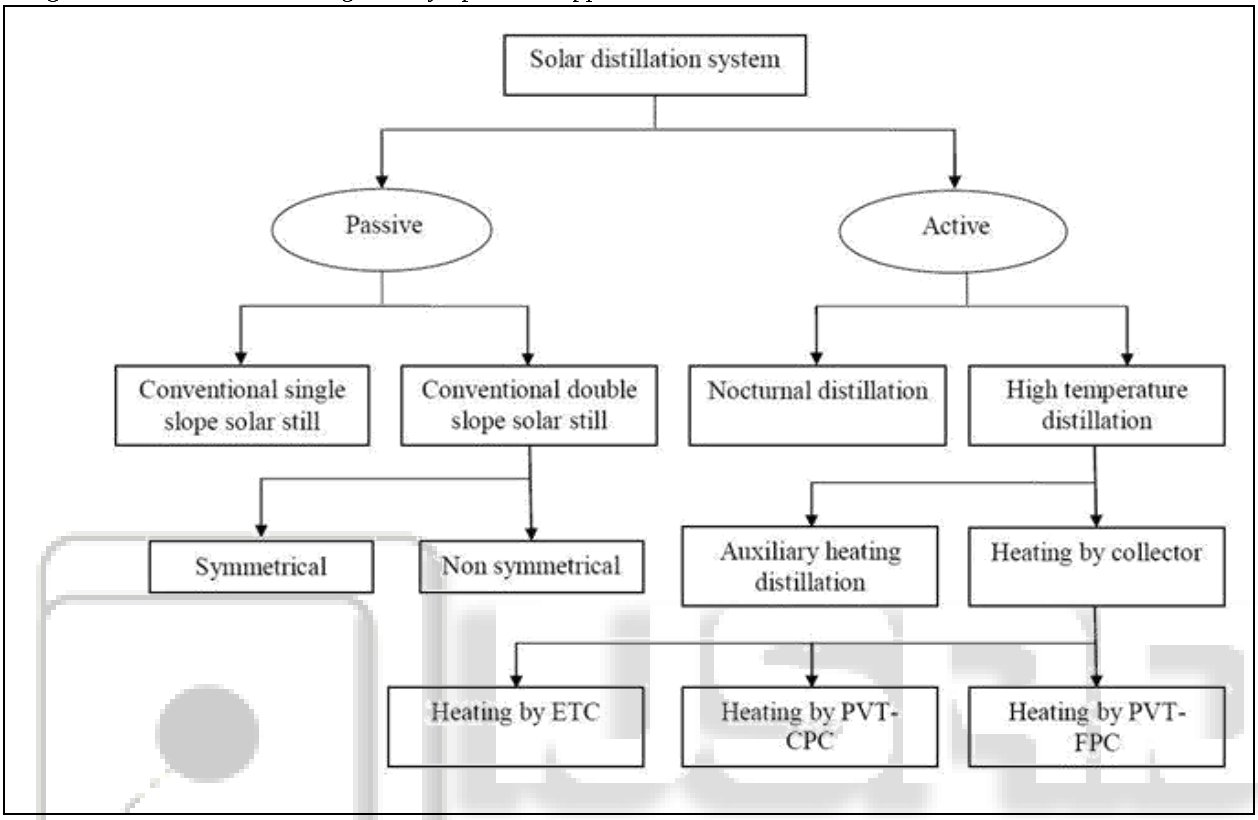
Keywords: Solar distillation, Flate Plate Collectors, Solar Stills

Nomenclatures:

T_a	Ambient temperature, °C
E_{out}	Annual energy output, kWh
$G_{ex\,annual}$	Annual exergy gain, kWh
E_{sol}	Annual solar energy, kWh
M_{ew}	Annual yield from solar distillation system, kg
A_b	Area of basin, m^2
A_{gE}	Area of east glass cover, m^2
A_g	Area of glass cover, m^2
A_{gW}	Area of west glass cover, m^2
T_{cN}	Average solar cell temperature, °C
T_c	Temperature of solar cell, °C
$I_b(t)$	Beam radiation, W/m^2
b_a	Breadth of aperture, m
b_r	Breadth of receiver, m
$F_{CR,i,n}$	Capital recovery factor
a	Clear days (blue sky)
d	Cloudy days (fully)
F	Collector efficiency factor, dimensionless
CPC	Compound parabolic concentrator collector
h_{cwg}	Convective heat transfer coefficient from water to inner surface of glass cover, W/m^2-K

I. INTRODUCTION

Drinkable water is one of the essential component for the existence of living beings on the planet earth. Water consumed by them is responsible for functioning of body cells. Hence reduction in daily water intake may affect the efficiency of body cell activity which results in chronic dehydration. The mass of water in human body is 75 % of its total mass. The salinity of most available water on the planet earth is up to 10000 ppm and that of sea water is in the range of 35000 to 45000 ppm. However the human being can consume water having salinity up to 1000 ppm as per World Health Organization (WHO). More than 70 percent of earth's surface is enclosed with water. Out of the existing water on earth surface, only less than 3 % is pure water. Further, more than 2 % water is locked up in the ice caps and glaciers and less than 1 % is available for the use of human being. The location and comparative proportions of existing water



II. BASIC PRINCIPLE OF SOLAR DISTILLATION

Solar distillation technology uses solar radiation as the source of heat energy to obtain potable water with the help of device known as solar still. It is based on the principle of greenhouse effect and evaporation/condensation of water. The schematic diagram of conventional single slope passive solar still shown in Fig. 2. It is a box type structure made up of fiber reinforced plastic (FRP), galvanized iron sheet (GI), wood or concrete covered with some insulation to prevent the heat loss from bottom and side walls. The box is covered with glass cover which is inclined with the horizontal surface to facilitate the trickling down of water condensed on the inner surface. The condensed water at the inner surface of glass moves down due to the component of gravitational force acting along the glass cover. The bottom surface of box is blackened from inside to absorb almost all radiation falling on it. This blackened (painted black) surface is generally known as basin liner.

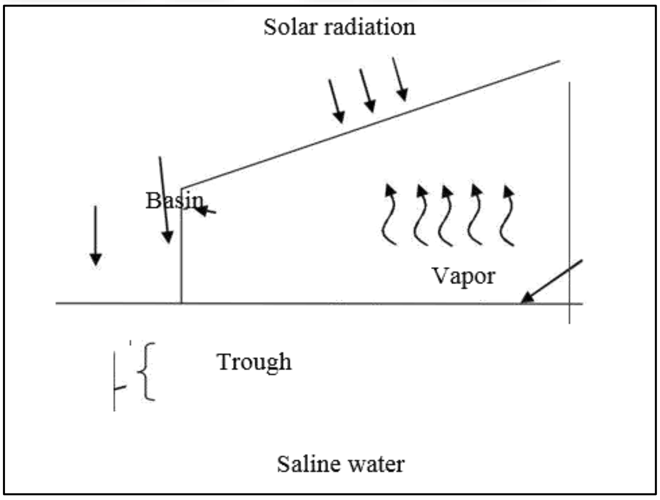


Fig. 1.6: Conventional single slope passive solar still (south oriented)

The major portion of solar radiation falling on the surface of glass cover is transmitted to water mass in the basin after reflection and absorption by it. A small portion of solar radiation reaching the water surface is reflected back and absorbed by water mass and remaining portion is transmitted to basin liner where it is mostly absorbed. The attenuation of solar radiation in water mass depends on its depth and absorptivity. The temperature of basin liner increases which further transmits most of its heat to water mass by convection and a small portion of heat is lost to atmosphere by conduction. Hence temperature of water increases which creates a temperature difference between water and glass surface. Heat is transferred from water surface to glass cover by three modes namely evaporation, convection and radiation. The evaporated water undergoes film type condensation after releasing the latent heat at inner surface of glass cover. The condensed water trickled down the glass cover and it is collected in a trough fixed at lower end of glass cover. The collected water in the trough is allowed to flow to the jar through a pipe and

it is taken out for further use. Here, it should be noted that the distilled water obtained is not fit for direct use in drinking and cooking application as it lacks the minerals. However, it can be made suitable for these applications after adding the required minerals needed for human beings. The thermal energy received by glass cover through convection, radiation and latent heat is lost to the atmosphere by convection and radiation. The daily yield from single slope passive solar still may vary from 0.5 l/m^2 (winter) to 2.5 l/m^2 (summer). The overall thermal efficiency (ratio of energy output to energy input) of single slope passive solar still varies from 5 to 40 % throughout the year.

The advantages of solar distillation system/solar still over other desalination technologies are as follows.

- It contains no moving parts to run the system in passive mode.
- It is an easy and cost effective technology to provide potable water for domestic and commercial level.
- It requires only solar energy for its operation which is renewable and non-polluting.
- No skilled labor is required for its operation and maintenance.
- It is possible to manufacture and repair locally.
- It gives a sense of satisfaction in owning a trusted and easy to use water treatment plant.
- It is very useful for remote settlements where only saline water is available.
- It is self sustainable and it can also meet electricity requirement up to certain extent when operating in active mode integrated with photovoltaic (PV) module

However, a solar distillation system has some demerits also which sometimes may limit the use of technology for large scale production. It includes (a) dependency on weather for input energy, (b) requirement of large solar collection area for commercial use, (c) low interest ofproducer, (d) low efficiency, (e) comparatively higher initial investment, (f) need of frequent filling and flushing of solar still and (g) requirement of system to be robust as it is installed in open space.

The application of solar distillation technology includes (a) production of potable water as well as DC electric power for remote areas where electricity has not reached so far, (b) hospitals, (c) automobile garage, (d) workshops, (e) laboratories, (f) educational institutions and (g) cleaning of kitchen utensils and mechanical parts.

III. OBJECTIVES OF RESEARCH WORK

Energy and potable water are two basic requirements for the survival of living beings. Three-fourth of the earth’s surface is covered with water but only a small portion (less than 3 %) of available water is fresh and the rest is saline/brackish unsuitable for direct use by human beings. Moreover, hardly 1 % of the fresh water is within human reach. Two-third of the world population is likely to face shortage of water 2025 onwards (UN Report, 2004). According to an estimate, water-borne diseases might pose a threat to the life of over 76 million people by the year 2020 (Pacific Institute of Oakland, California). To work out this problem, an energy intensive desalination systems have been installed which is not eco-friendly. At present, harnessing solar energy for electricity generation and distillation can mitigate the imminent problem of shortage of energy and potable water in rural/remote areas to a great extent. Solar energy option is eco-friendly, economical and easily maintainable.

The proposed solar distillation systems namely basin type (single slope and double slope) solar stills integrated with a number (N) of identical photovoltaic thermal flat plate collectors/photovoltaic thermal compound parabolic concentrator water collectors/evacuated tubular collectors can fulfill the requirement of both potable water and electricity up to certain extent to the remote areas where drinking water and electricity is not available. Most of the researcher in the field of solar distillation aspires to boost up the distillate (yield) from the solar still and also to obtain higher electricity in some cases so that the requirement of electricity and water can be met in the remote areas.

In this research work; theoretical analysis of various solar distillation systems has been carried out. The solar distillation systems under consideration are basin type (single and doubleslope) passive solar stills, basin type solar stills integrated with a number (N) of identical partially covered photovoltaic thermal (PVT) flat plate collectors (FPC), basin type solar stills integrated with a number (N) of identical partially covered PVT compound parabolic concentrator (CPC) water collectors and basin type solar stills integrated with N identical evacuated tubular collector (ETC). Energy matrices; exergoeconomic parameter, enviroeconomic parameter, productivity and various efficiencies of passive and active solar distillation systems for same basin area have been computed for composite climatic condition of New Delhi and they have been compared. Four climatic conditions namely type a, type b, type c and type d have been considered for the exhaustive computation of various parameters. The life cycle cost analysis of basin type passive and active solar distillation systems has been carried out by incorporating the effect of energy payback time. They have also been compared on the basis of exergoeconomic parameter, enviroeconomic parameter and productivity. At last, the performance analysis of basin type passive and active solar distillation systems has been carried out by incorporating the effect of water depth to assess the optimum water depth on the basis of daily efficiencies and productivity. The main objectives of the research work carried out after the thorough review of literature can be stated as follows.

1) Energy matrices, production cost of water, exergoeconomic, enviroeconomic, productivity and various efficiencies analyses of single and double slope passive solar stills for the same basin area under similar climatic condition.
2) Energy matrices, production cost of water and electricity, exergoeconomic, enviroeconomic, productivity and various efficiencies analyses of single and double slope PVT-FPC active solar distillation systems for the same basin area under similar climatic
3) Energy matrices, production cost of water and electricity, exergoeconomic, enviroeconomic, productivity and various efficiencies analyses of single and double slope PVT-CPC active solar distillation systems for the same basin area under similar climatic condition.
4) Energy matrices, production cost of water and electricity, exergoeconomic, enviroeconomic, productivity and various efficiencies analyses of single and double slope ETC active solar distillation systems for the same basin area under similar climatic condition.
5) Comparative study of basin type passive and active solar distillation systems on the basis of energy matrices, production cost of water and electricity, exergoeconomic parameter, enviroeconomic parameter, productivity and various efficiencies for the same basin area under similar climatic condition.

IV. Organization of Present Thesis

The present thesis has been carefully planned into four chapters. The first chapter talks about the general outline of research work carried out. It incorporates introduction, distillation process, types of solar still, historical background and literature reviews. Further, material requirement of solar still, working principle of conventional solar still, modes of heat transfer in solar still, the advantage and disadvantage of solar distillation systems and objective of the research work have been discussed. The last part of this chapter deals with quality of water from solar still, performance parameters including climatic and design parameters and application of distilledwater of exergy for the same basin area under similar climatic conditions. Single and double slope passive solar stills have been considered for comparative study. Four climatic conditions namely type a, type b, type c and type d for each month of year have been considered for the exhaustive computation of various parameters. The various parameters include energy matrices, productivity, exergoeconomic parameter, enviroeconomic parameter, production cost of water, production cost of electricity and various efficiencies. The effect of energy matrices on life cycle cost analysis of single and double slope passive solar stills have been carried out by incorporating energy payback period.

The third chapter talks about the analysis of basin type solar stills integrated with a number (N) of identical partially covered photovoltaic thermal (PVT) flat plate collectors (FPC) for the same basin area under similar climatic condition. Two solar distillation systems namely single and double slope PVT-FPC active solar distillation systems have been considered for comparative study. Four climatic conditions namely type a, type b, type c and type d for each month of year have been considered for the exhaustive computation of various parameters. The various parameters include energy matrices, productivity, exergoeconomic parameter, enviroeconomic parameter, production cost of water, production cost of electricity and various efficiencies. This chapter has been well organized in three sections. The first section deals with the effect of energy matrices on the life cycle cost analysis of single and double slope PVT-FPC active solar distillation systems. The second section deals with the comparative study of single and double slope PVT-FPC active solar distillation systems on the basis of exergoeconomic parameter, enviroeconomic parameter and annual productivity. The third and last section deals with the performance analysis of single and double slope PVT-FPC active solar distillation systems by incorporating the effect of water depth.

The fourth chapter talks about the conclusions and recommendation. This chapter discusses the conclusions of analysis carried out for various solar distillation systems in chapters II and III. At last, recommendations have been made as a follow up to the present research work.

In the next chapter, analysis for single and double slope passive solar stills has been presented. The methodology to calculate the various parameters has been reported. The various parameters include energy matrices, exergoeconomic parameter, enviroeconomic parameter, productivity and different efficiencies. This chapter basically focuses on life cycle cost analysis of basin type passive solar stills by incorporating the effect of energy payback period.

V. Methodology

The following methodology has been adopted for annual exergy analysis of solar still.

1) Step I

The climatic data namely solar radiation on a horizontal surface, ambient air temperature and number of days for the weather conditions (a), (b), (c) and (d) has been taken from Indian

Metrological Department (IMD), Pune, India. Solar radiation for inclined surface at 30° north latitude has been calculated using Liu and Jordan formula with the help of MATLAB.

2) Step II

Single slope passive solar still is shown in Fig. 2.1a and double slope passive solar still is shown in Fig. 2.1b. Table 2.1a represents the specification of single and double slope passive solar stills. Table 2.1b represents the design parameter of single and double slope passive solar stills.

Following Tiwari and Ghosal (2005) and Dwivedi (2009), water temperature in the basin (T_w), glass temperature at inner surface ($T_{g,i}T_{giE}$and T_{giW}) and glass temperature at outer surface can be evaluated as follows.

$$T_w = \frac{\overline{f(t)}}{a^1}(1-e^{-a_1 t}) + T_{w0}e^{-a_1 t}$$

VI. Results and Discussion

The annual exergy of single slope and double slope passive solar stills have been found to be 108.48 kWh and 89.24

kWh respectively. The annual energy of single slope and double slope passive solar stills has been found to be 1159.43 kWh and 1037.19 kWh respectively. Single slope has been found to perform better than double slope passive solar still on the basis of exergy based EPBT, exergy based EPF; LCCE based on exergy as well as energy and exergoeconomic parameter. However, double slope performs better than single slope on the basis of EPBT based on energy, EPF based on energy and annual productivity.

All relevant equations and data for the solar intensity and ambient temperature for the composite climatic condition of Ghaziabad have been transported to MATLAB computational program in order to compute exergy, yield, energy, energy matrices, exergoeconomic parameter and annual productivity

VII. Conclusions

A comparative study of single slope passive solar still and double slope passive solar still has been done on the basis of energy matrices based on exergy, exergoeconomic parameter, productivity, and efficiencies for the same geometrical parameter and same climatic condition. On the basis of the study, the following conclusions have been drawn.

1) Annual exergy gain, annual energy output, thermal efficiency and exergy efficiency of single slope passive solar still is higher than double slope passive solar still for the same geometrical parameter and same climatic condition.
2) LCCE based on exergy as well as energy is better for single slope passive solar still than double slope passive solar still. Both EPBT and EPF based on exergy are better for single slope than double slope passive solar still for the same geometrical parameter and same climatic condition. However, EPBT and EPF based on energy are better for double slope than single slope passive solar still for the same geometrical parameter and same climatic condition.
3) Annual productivity of double slope passive solar still is higher than single slope passive solar still for the same geometrical parameter and same climatic condition. Also, annual productivity is more than 100 % for both single slope and double slope passive solar still which suggest that both systems are feasible.
4) The value of exergoeconomic parameter is better for single slope passive solar still than double slope passive solar still for the same geometrical parameter and same climatic condition.
5) The enviroeconomic parameter based on energy as well as exergy is better for single slope than double slope passive solar still for the same geometrical parameter and same climatic condition.

   In the next chapter, analysis for single and double slope solar stills integrated with N identical photovoltaic thermal (PVT) flat plate collector (FPC) has been carried out. The energy balance equations for various components of the system has been written and they have been simplified to express water temperature in terms of solar intensity, ambient temperature, heat transfer coefficients and some constants. Then, glass temperatures have been expressed in terms of water temperature and some constants. After evaluating water and glass temperature, hourly yield and hourly exergy have been evaluated followed by the evaluation of annual energy and annual exergy. Then, energy matrices, exergoeconomic parameter, enviroeconomic parameter and productivity have been evaluated for single slope and double slope PVT-FPC active solar distillation systems and they have been compared. At last, performance analysis of systems has been carried out by incorporating the effect of water depth.

References

[1] Abdel-Rehim, Z. S., Lasheen, A. (2007), Experimental and theoretical study of a solar desalination system located in Cairo, Egypt, Desalination, 217, pp. 52-64.
[2] Abu-Arabi, M. and Zurigat, Y., (2005), Year-round comparative study of three types of solar distillation units, Desalination 172, pp. 137–143.
[3] Aderibigbe, D.A., (1985), Optimal cover inclination for maximum yearly average productivity in roof type solar still, Private communication to A.I. Kudish
[4] Agrawal, S. and Tiwari, G.N., (2012), Exergoeconomic analysis of glazed hybrid photovoltaic thermal module air collector, Sol. Energy 86 (9), 2826–2838.
[5] Ahmed, S.T., (1988), Study of single effect solar still with an internal condenser, Int. J. Solar and Wind Tech., 5(6), p. 637
[6] Akinsete, V.A. and Duru, C.U., (1979), A cheap method of improving the performance of roof type solar still, Solar Energy, 23(3), P. 271
[7] Al-Hinai, H., Al-Nassr, M. S. and Jubran, B. A. (2002), Effect of climatic, design and operational parameters on the yield of a simple solar still, Energy Convers Manag 43, pp. 1639 –1650.
[8] Arslan M., (2012), Experimental investigation of still performance for different active solar still designs under closed cycle mode, Desalination, Volume 307, Pages 9-19.
[9] Ashcroft, H., (1950), The productivity of several machines under the care of one operator, Journal of the Royal Statistical Society (London), Series B, Vol. XII, pp. 145-151.
[10] Badran, A. A., (2001), Inverted trickle solar still: effect of heat recovery, Desalination 133, pp.167–173.
[11] Badran, A. A., Al-Hallaq, A. A., Eyal Salman, I. A. and Odat, M.Z., (2005), A solar still augmented with a flat-plate collector, Desalination 172, pp. 227-234.
[12] Badran, O. O. and Al-Tahaineh, H. A., (2004), The effect of coupling flat plate collector on the solar still productivity. Desalination 183, pp. 137-142.
[13] Benson, F., (1952), Further notes on the productivity of machines requiring attention at random intervals, Journal of the Royal Statistical Society, Series B, Vol. XIV, pp. 200-210.
[14] Bhargava, A.K., Garg, H.P. and Agarwal R. K.,(1991). Study of hybrid solar system- solar air heater combined with solar cell. Energy convers Mgmt 31(5), p. 471-479.

[15] Calise F, d‟Accadia M D, Piacentino A, (2014), A novel solar regeneration system integrating PVT (photovoltaic/thermal collectors) and SW (seawater) desalination: Dynamic simulation and economic assessment, Energy 67, 129-148.

[16] Caliskan, H., Dincer, I. and Hepbasli, A., (2012), Exergoeconomic, enviroeconomic and sustainability analyses of a novel air cooler, Energy and Buildings 55, 747–756.

[17] Cappelletti, G. M., (2002), An experiment with a plastic solar still, Desalination 142, pp. 221– 227