PERFORMANCE OPTIMIZATION OF AN INTEGRATED SOLAR DESALINATION SYSTEM

Joga Venkata Sandeep[1*], S Joshua Kumar[2], N Murali Krishna[3]

[1*,2,3]*Assistant Professor, M.V.G.R. College of Engineering, Vizianagaram, Andhra Pradesh-535005, India*

---***---

Abstract*-Desalination is a process which is used to convert the salt water or saline water into usable water using different techniques. The energy utilized by the desalination process to remove the impurities from the water is comparatively very more. So, instead of using non renewable resources like coal, petroleum products and natural gas we intend to use most abundant renewable energy on the earth that is solar energy. This paper focuses upon integrated solar desalination system using multi stage heat recovery processes. An experimental research conducted has been considered which is analyzed further by conducting theoretical validation to the performance parameters involved in this system. MATLAB is used to find out the amount of fresh water distilled per unit area and unit time, the total system efficiency and solar collecting efficiency are evaluated based on standard formulae. The maximum performance parameters which can be obtained are presented on both sunny day and cloudy day conditions.*

Key words: *Solar desalination, Heat Recovery, Fresh water distillation, Cost Analysis, Collector*

1. INTRODUCTION

Water is one of the most precious resource on earth's surface. There is always growing demand for the water utilization. Even though Earth's 75% area is covered by water 97% of the available water on the Earth's surface is salt water/ saline water which cannot be used for domestic purposes and drinking. Whereas the rest that is only 3% of water present on the Earth can be used for the domestic use and drinking purpose. Thus, in order to compensate the growing demand for water the requirement of water desalination plants or water purification system comes into picture. In many countries across the world this saline water which is available in plenty is being converted to usable water. This process of converting the available sea/ saline water into usable form is called desalination. Not only saline water the brackish water/ waste water is also being converted into usable form. Desalination is the process of removing unwanted substances and minerals from the water so that the water gets purified and is changed to usable form of water which can be used for drinking, domestic purposes and also can be used in the irrigation facilities. It is estimated that major portion of the available usable water is utilized for the purpose of irrigation. Thus, if the desalinated water can be used for irrigation means the demand for water can be compensated easily. It is estimated that by the year 2050 the availability of portable water gets decreased in 39 countries.

Sea water/ Saline water can be desalinated by different types of techniques. These techniques are majorly classified into 2 categories based upon the processes involved in the conversion of salt water to usable water. Those two categories are 1. Desalination using Thermal Energy and 2. Desalination using semi-permeable membrane. The thermal processes are divided into several other types based upon the process of thermal energy utilization in the process, they are stated as follows:

a) MSF (Multi Stage Flash)
b) MEB (Multiple Effect Boiling)
c) VC (Vapor Compression)
d) Freezing / Solar distillation

The processes which utilize membrane in order to desalinate the sea water /saline water are:

a) RO (Reverse Osmosis)
b) ED (Electro-dialysis)

The thermal energy desalination systems utilize heat energy in order to perform desalination process. This thermal energy/ heat source can be obtained by combustion of different hydrocarbon fuels like petroleum, diesel etc. As we know that the world is running out of non renewable sources like petrol, coal, natural gas etc. We need to replace these non-renewable sources of energy with renewable sources of energy like solar energy which is most abundantly available heat resource available on the earth, geo-thermal energy can also be utilized so as to extract heat from the underground and which can be utilized for desalination system. At, the current condition 1% of the world's population are using desalinated water for domestic and drinking purposes. It is merely estimated that by the year 2025 around 14% of world's population suffer with water scarcity problem. This water scarcity problem may occur due to depletion of natural water resources on the earth's surface that is releasing pollution into the water surfaces like rivers, lakes and ponds causing discomfort for aquatic eco system and encountering a problem of wasting the water as the polluted water cannot be used for any domestic purpose and even for irrigation. The ground water level is also getting gradually reducing day by day and we may finally reach a state where the ground water cannot be seen any further. Not, only decreasing of ground water level the ground water is also getting polluted by using harmful manmade fertilizers and pesticides for crops/ for the purpose of irrigation. This causes the ground water getting depleted by mixing of these fertilizers and making it unusable for any other purposes. In order to compensate the demands of water desalination system using solar energy comes into the main room as solar energy is free and abundant along with this is one of the most widely available renewable energy resource which can be generated easily and the utilization of solar energy doesn't create any type of pollution. The solar energy in the desalination system can be used either directly or indirectly.

In the direct method of solar energy desalination system the solar collector is coupled with a distilling system and the heat recovery that is heat absorption process from solar energy are carried out by utilizing this heat energy directly. Solar stills and many other different types of desalination systems using direct energy solar radiation are installed and implemented in wide range of areas in countries where the sun availability is plenty. The amount of usable water produced during the solar distillation using the direct method is directly proportional to the surface area of the collector and angle of incidence of solar radiation on the collector surface.

In indirect solar desalination/ distillation system there are two types of separate systems first one is a solar collection array which is mainly made up of photovoltaic/ thermal solar collectors, and there is in separate a plant for conventional solar desalination system. The amount of fresh/ usable water produced by the indirect method depends on the efficiency of the system. That is high efficient plants can produce more amount of usable water compared to less efficient plants. The cost per unit rate of fresh/usable water production will also depend upon the efficiency and the initial investment/capital of the solar distillation/desalination unit. Mostly the plants which produce usable water with less unit cost of production are more preferable compared to other systems.

.1.1 Literature Review:

The Analysis of the setup and the experimental results are taken from the paper "A novel integrated solar desalination system with multi-stage evaporation/heat recovery processes" by Zhen-hua Liu, Ren-Lin Hu, Xiu-juan Chen, Renewable Energy 64 (2014) 26e33 and other papers considered for analyzing the solution for the problem are:

It proposed an idea of solar desalination system. A setup is installed and experiments are conducted on it so as to observe the yield of fresh water at different time periods in a particular day. These experiments are conducted in both sunny day and cloudy day during the period of winter so that these results can be compared based upon the weather conditions on that particular day and these can also be compared based upon the intensity of solar radiation. It is observed that more amount of fresh water is obtained during sunny day when compared to that on cloudy day. The yield of fresh water in the experiments conducted during the sunny day is almost equal to twice that of yield of fresh water obtained during cloudy day. So, it can be noted that the system operation and the amount of yield of fresh water not only depend upon the intensity of solar radiation on that particular day, it also depends upon the atmospheric conditions like humidity or moisture in air and also on the operating conditions of the system. Thus, by taking this paper as a main reference theoretical analysis is carried out based upon the theoretical standard formulation methods and the obtained results are compared with the experimental values and are shown in this present paper.

"A new hybrid desalination system using wicks/solar still and evacuated solar water heater", by Z.M. Omara, Mohamed A. Eltawil, ElSayed A. ElNashar, Desalination 325 (2013) 56–64. This paper presents a new type of desalination system which is considered as a new hybrid desalination approach as this can work with evacuated solar water heater, jut Geo textile and solar still simultaneously. This evacuated solar water heater can be attached to the desalination stills so as to ensure complete supply of yield of fresh water continuously. Two identical portable solar wick and one basin solar stills were designed to evaluate the systems performance. Jut linen woven fabrics were stitched to the plane wick (lengthwise and crosswise) and integrated with solar still. The jut fabrics were used to reduce the rate of water flow to the appropriate rate. The following variables are studied: Single and double layers wick; plane wick, lengthwise and crosswise linen; feeding hot water during night. Theoretical analysis is verified through experiments carried in this paper.

"Thermal and economic analyses of solar desalination system with evacuated tube collectors", by Xiaohua Liu 1, Wenbo Chen, Ming Gu, Shengqiang Shen, Guojian Cao. In this paper the problems related to utilization of non renewable energy sources for desalination process are discussed and solar desalination process is highlighted. The thermal and economic analysis of solar desalination system along with evacuated tube are performed. The mathematical models based on mass and energy conservation are proposed in a brief way. The cost of constructing a evacuated tube, proportion of cost on each unit along with the unit cost of producing a unit of water are discussed.

"Performance analysis of an air-heated humidification, dehumidification, desalination plant powered by low grade waste heat", by W.F. He, L.N. Xu, D. Han, L. Gao. In this paper humidification, dehumidification and desalination systems are discussed, these systems are driven by air-heated systems by utilizing low grade heat energy. The performance analysis is made and the results are briefly discussed in the paper. Major advantages of utilizing low grade heat energy over the high grade energy are being stipulated in an innovative manner. This paper also gives the information regarding the Exergy analysis and the energy losses in these systems are demonstrated in an effective way. The change energy utilization rate of the desalination, humidification system with the change in value of pressure drop in heat exchanger is displayed.

2. SOLUTION METHODOLOGY

The theoretical results were obtained using the standard formulas. The Fresh water yield is obtained using computation of MATLAB and total efficiency of the system and the collecting efficiency are calculated using standard formulas

MATLAB is a computing platform, where numerical computing which can be done with the help of multi programming languages. This is a programming language belonging to 4^{th} generation that is a high level language which can be easily understood by machine and humans. This programming is developed by Math Works, the operations such as matrix manipulations that is multiplication, addition of matrices etc and functions and data can also be plotted easily, algorithms for different problems can be found out and implemented easily in MATLAB, the creation of user is that he can interfacing the programs only with different programming languages like C, C++, Fortran, Java and Python.

Efficiency of the total system can be given as the ratio of total amount of energy utilized for evaporating sea water into fresh water to the total amount of incident energy available on the solar collector.

Efficiency of the total system can given as:
η total = Total amount of energy utilized for evaporating sea water / Total amount of incident energy available on the solar collector

$\eta_{total} = Gm\ \Delta h / Acpc\ n\ Ir$

Here, Gm = Yield of fresh water per second

Δh = Difference of enthalpy between saturated steam and water
Acpc = Lighting area of CPC plate

n = Number of CPC plates in the system

Ir = Intensity of Solar radiation

The collecting efficiency is used to judge effectiveness of solar collectors. Collecting efficiency is given by ratio of amount of net energy absorbed by collecting unit to the total amount of incident energy available on the collector.

η collecting = Net energy absorbed by collector/ Total energy incident on collector

$\eta_{coll} = P / Acpc\ n\ Ir = \eta_{tot}/PR$

Where PR = Performance Ratio

The performance ratio is used as an indicator for evaluation of the desalination system performance.

Performance ratio (PR) = Total amount of energy utilized for the evaporation process/ Net energy absorbed by collecting system

$$PR = Gm\ \Delta h / P$$

Where Gm = Yield of fresh water per secondΔh = Difference of enthalpy between saturated steam and water

P = Net energy absorbed by collector

2.1 Theoretical value of PR:

The value of PR is usually more than 1 due to the process of heat recovery, if the PR value is more we can say that more amount of heat recovery happened from the system. Theoretical PR value is 2.2 and that can be evaluated as shown below:

Assume the power of collector each panel/unit is nearly equal and the amount latent-heat of vaporization of water which is recovering completely

The amount of power utilized for evaporation of sea water in every individual unit can be given as:

$$Qi = ø,$$

$$Qii = ø + Qi = 2ø$$

$$Qiii = ø + Qii = ø + 2ø = 3ø$$

$$Qiv = 2ø + Qiii = 2ø + 3ø = 5ø$$

Where Qi, Qii, Qiii and Qiv are the power used to evaporate sea water in unit1, unit2, unit3 and unit4 respectively

ø = Heat collecting power of one panel

Therefore, we can get the theoretical value of PR as:

$$PR = Qi + Qii + Qiii + Qiv / 5ø$$

$$PR = 11\ ø / 5\ ø = 2.2$$

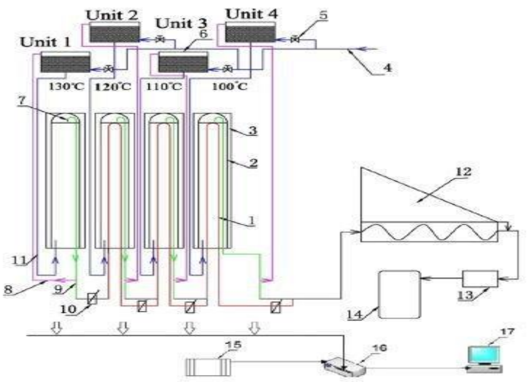
Thus from the value of PR it is observed that the system exhibits outstanding heat recovery

3. EXPERIMENT AND APPARATUS

In the integrated desalination system an experiment with multi stage heat recovery process is being conducted during sunny day and cloudy day at different intervals of time. The experimental procedure and setup is discussed as below:

This solar desalinating unit solar energy collection system, evaporation of seawater, process of heat recovery and process of condensation of freshwater are occurred within the same evacuated tubular solar collector so as to yield freshwater. This unit contains 4 linked collector units each unit has at least one solar desalination panel and saline water tank, mainly comprising a simplified CPC (Compound Parabolic Concentrator) and a another important unit that is a solar evacuated tube collecting unit.

The main source for desalination is solar energy and the partial source is latent heat of steam which is being passed into the system. The Unit I has a pressure regulating valve, one solar desalination panel and saline water tank. The process of heat recovery doesn't take place in the unit I, the amount of heat used for seawater evaporation is taken from the solar energy which is being absorbed by solar collecting tube. The Unit II and Unit III have the similar components containing a pressure regulating valve, one solar desalination panel and a saline water tank, a heat exchanger into which concentric copper tubes are mounted into the evacuated tube for heat the process of heat recovery. The last unit (Unit IV) consists of a pressure regulating valve, saline water tank and two parallel solar panels of desalination mounted with heat exchangers. As the mass of steam gradually accumulates when passing through these units, two panels are mounted in the last unit to provide more heat transfer area to recover heat effectively. For condensing the amount of steam generated in the last unit a cooling pool is arranged and the fresh water is collected into a cylinder.



1.concentric tube, 2.all-glass evacuated tube, 3.simplified CPC, 4. seawater supply inlet, 5. valve 6.seawater tank, 7. vapor-liquid separator, 8. pressure balance pipe, 9.steam outlet pipe, 10.pressure regulating valve, 11.seawater inlet pipe, 12. Cooling pool, 13. Cylinder, 14.freshwater tank, 15. solar radiation meter, 16. Agilent data-logger, 17.computer

Fig 1: A schematic diagram of a solar desalination system

3.1 The simplified CPC structure:

CPC can able to collect the solar radiation for a longer duration of time through out the day without having any tracking system/mechanism to track the sun. CPC is one of the highly efficient solar collector, the design and analysis of CPC is one of the most widely studied subject. Sayigh and Khonkar proposed a system in which tubular absorbing component that is an absorber is used and method is implemented in collection of radiation of solar intensity effectively. The tubular absorber is a solar tube which is made of all glass tube. It has 2 concentrically arranged glass tubes which are sealed with a space of annular vacuum at one end and a selective absorbing coating layer on the other surface that is on the vacuum side of the inner tube. First figure shows a CPC profile for standard all glass evacuated tube. Meanwhile, the upper parts of concentrator are amputated so as to form a truncated CPC.A simplified CPC that is obtained after the process of truncation and after cutting the involute out is shown in the below figure:

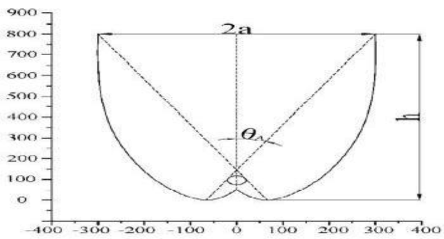


Fig 2: Standard CPC profile

3.2 Heat exchanger:

In this system a concentrically arranged tube heat exchanger is used to recover the generated heat from steam produced by evaporation of saline water. This concentric tube consists of 2 copper pipes which are welded at one end. One of the tube is placed concentrically into the glass tube so as to fill the annulus space between seawater supply and water tank. The amount of steam which came from the 1st unit enters through the inlet of the concentrically arranged tube and finally moves through the annular section of heat exchanger, then the steam which is arrived through the inlet junction of the inner tube can be placed at the upper position, and at the final state it is exited from the outlet end of the inner tube.

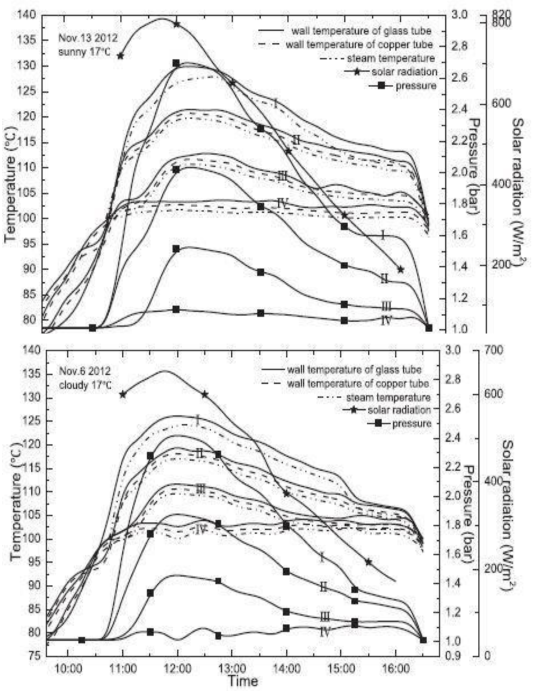
3.3 Experimental Procedure:

In this present desalination unit as explained the system consists of 4 units, now in the Unit I contains a pressure regulating valve, a seawater tank and a solar panel of desalination. The heat recovery process doesn't happen in the unit I, the amount of heat utilized for the process of evaporating the seawater is taken from the abundantly available solar energy. The Unit II and Unit III have the similar or almost same type of structure which contains a pressure regulating valve, a seawater tank and a solar panel of desalination and the heat exchanger used in this system which is made up of concentric copper tubes which is being mount into the an evacuated tube for process of heat recovery. The last unit (Unit IV)

Consists of CPC pressure profile regulating valve and two parallel solar collecting panels mounted with heat exchangers. As the mass of steam gradually accumulates when passing through these units, two panels are mounted in the last unit to provide more heat transfer area to recover heat effectively. A cooling pool is used at the end which can be used to condense the amount of generated steam in the last unit so that it could be collected in a cylinder. The temperature difference to be maintained between each consecutive units is 10 C and pressure maintained ranges between 2.5 bar to 1 bar.

4. RESULTS AND DISCUSSION

The experiment is conducted in sunny day as well as on cloudy day to observe the variation of temperature and pressure in the present system. The temperature difference between the neighboring units is about 8 – 9 C, the steam temperature is 4 – 5 C which is lower when compared to the wall temperature of inner glass tube and 2 – 3 C is lower when compared to the temperature of concentric tube in each unit. In this experiment the wall temperature of concentric tube is taken as fluid outlet temperature. The temperature and pressure variations observed on the sunny day and on cloudy day were almost similar, the steam temperature and pressure on the cloudy day is slightly less than that on sunny day. The maximum temperature of steam obtained on a sunny day in each of the four units is 122 C, 114 C, 107 C and 101 C respectively. The following figures show the temperatures/pressures of steam, the value of temperature of wall of an inner glass tubes and concentric tubes of the 4 units of the system on a sunny day and cloudy day.



Temperature and pressure values of each unit in a cloudy day.

Fig 3: Graphs showing variation of temperature &pressure

4.1 Fresh water yield:

The yield of freshwater per hour per sq meter of lighting area is calculated and values are plotted in a graph.

Here lighting area = (the Effective length of CPC) x (width of CPC). Here the value of lighting area is 2.64 m^2.

The maximum yield of fresh water is 1.26 kg/(h m^2) during sunny day and 0.7 kg/(h m^2) in a cloudy day. As, this experiment is conducted in the months of winter that is in October and November. So, it is predicted that the fresh water yield becomes at least twice during summer.

4.2 Total efficiency of the system:

Efficiency of the total system can be given as ratio of total energy utilized for evaporating saline water so as to convert it into fresh water and the total amount of energy getting incident on to a solar energy collecting unit.

The total efficiency of the system is calculated and plotted in the graph for 5 different days. The maximum experimental value of efficiency obtained in 0.9 in sunny days and exceeds 0.8 in cloudy days. This value can be further raised if more heat recovery occurs in the system.

4.3 Collecting efficiency:

The collecting efficiency is used to judge effectiveness of solar collectors. Collecting efficiency is given by ratio of net energy which is being absorbed by collector to total amount of incident energy on to a collecting unit.

5. THEORETICAL EVALUATION AND COMPARISON WITH EXPERIMENTAL RESULTS

5.1 Fresh water yield:

The major purpose of this system is to obtain the desired amount of fresh water by desalinating sea/saline water. From the experimental results maximum fresh water yield is 1.26 kg/(h m^2) during sunny day and 0.75 kg/(h m^2) in a cloudy day. The theoretical results are computed using MATLAB and the fresh water yield on sunny and cloudy day are obtained. The maximum yield of fresh water is 2.43 kg/(h m^2) during sunny day and 1.42 kg/(h m^2) on a cloudy day.

MATLAB Results:

```
m1 =

    2.2900    2.4332    2.1469    1.5744    1.1450    0.7156

>> m2

m2 =

    1.1450    1.4313    1.2881    1.0019    0.7156    0.5725
```

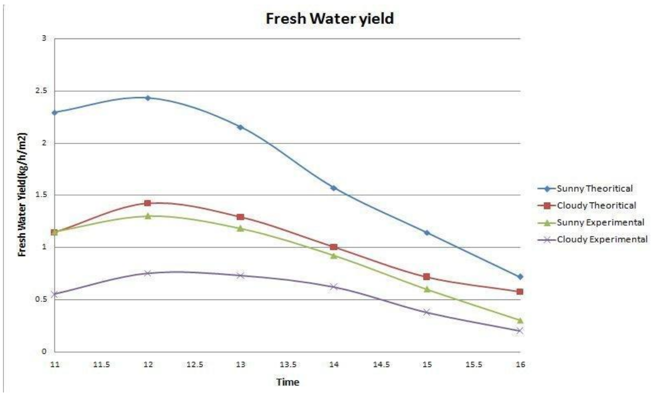


Fig 4: Graph representing fresh water yield for cloudy day and sunny day

5.2 Total efficiency of the system:

Efficiency of the total system can be given as ratio of total energy utilized for evaporating saline water so as to convert it into fresh water and the total amount of energy getting incident on to a solar energy collecting unit.

The maximum experimental value of efficiency obtained is 0.9 in sunny days and 0.8 in cloudy days. The maximum theoretical value of efficiency obtained is 0.925 in sunny days and 0.884 in cloudy days.

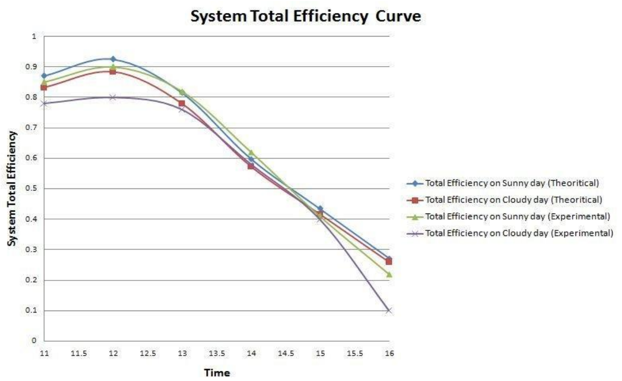


Fig 5: Graph showing total efficiency of the system

5.3 Collecting efficiency:

The collecting efficiency is used to judge effectiveness of solar collectors. Collecting efficiency is given by the ratio of net energy which is being absorbed by the collector unit to total amount of energy which is incident on collector.

The max value of η is 0.409 from experimental results and 0.426 in theoretical results.

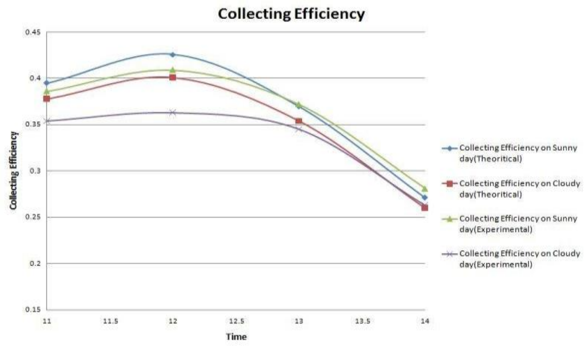


Fig 6: Graph representing collecting efficiency of the system

5.4 Economic Analysis:

The cost of evacuated tube collector:

TCeva = F c * A * Ccol = 0 .05 *2.64*19080= 2518.56 per evacuated tube

Here we have total of 5 evacuated tubes, so the total cost is 5*2518.56 = 12592.8

The cost of CPC = Ccpc * A = 2.64*1333= 3519.12 per CPC. So, for total of 5 CPC's cost is 5*3519.12= 17595.6

Cost of Heat Exchanger is given by

Base Cost = (Cost required to buy Materials so as to Construct Heat Exchanger)+ (Installation Cost of Heat Exchanger)

$TC_{Heat\ Exchanger}$ = (Base Cost) x

(A/P,10%,Life Cycle**)**

$TC_{Heat\ Exchanger}$ = 2200*66.65 * 0.1 = 13330

Total no of heat exchangers are 4 so =4*13330 = 53320

Cost of pressure regulating valve = 0.2*200*66.65= 2666

Total no of pressure regulating valves are 4 so =4*2666= 10644

Cost of remaining set up including sea water storage tanks = 9800

The land cost for setting up the equipment = The economic cost of land can be given as follows:

TCl= 0.02*1:1*A*Cland
=0.02*1.1*10*40000= 8800

So, the total cost of desalination system is Rs. 112752.4

Simple Payback period is 1.61 years

Life cycle cost is Rs. 147252.12/-

The energy saved is 1164.039 kWh per month

The amount of cost saved due to implementation of solar desalination system over electrically operated desalination system is Rs. 5820.19/- per month that is Rs. 69842.34/- per annum

6. CONCLUSION

A novel solar desalination integrated multiple stage heat recovery system is designed and analyzed by the comparison of theoretical and experimental results obtained in this paper. The system consists of 4 steam/ fresh water collecting units which are linked together. All the four units contain a one panel of solar collection and a saline water tank. The solar collecting/ desalination panel mainly comprises a simplified CPC that is a Compound Parabolic Concentrator and a solar evacuated tube collector. In the last three units, heat exchangers which are being made by using copper and these are mounted in concentrically with evacuated tubes for the process of heat recovery from hot steam in the system. The heat collecting and freshwater yielding performances of the whole system and each unit are investigated under different operating conditions. From experimental results obtained, the yield of freshwater in the solar collector is at a maximum value of 1.26 kg/h/m2 even though the experiments are carried out in the autumn or winter and the system total efficiency is near to the value 0.9. In theoretical results obtained the maximum fresh water yield is 2.43 kg/h/m2. That is an increase of 1.17 kg/h/m2 which shows an increase of 92.87% over the experimental results that is nearly twice the value of experimental fresh water yield. The maximum efficiency of the system in the theoretical results reached to about 0.925 which shows a slight variation with that of experimental value. The maximum collector efficiency in the experimental results is 0.409, whereas in theoretical results obtained the maximum collector efficiency reached to a value of 0.426. From economic analysis results obtained the total cost of the setup is Rs 112752.4/- which is not very high and can be implemented easily for domestic purposes. The payback period is 1.61 years which further more supports the system to get installed without any further alternatives. The annual cost savings are Rs 69842.34/-.

REFERENCES:

[1] Zhen-hua Liu, Ren-Lin Hu, Xiu-juan Chen, A novel integrated solar desalination system with multi-stage evaporation/heat recovery processes, Renewable Energy 64 (2014) 26e33

[2] Z.M. Omara, Mohamed A. Eltawil, ElSayed A. ElNashar, A new hybrid desalination system using wicks/solar still and evacuated solar water heater, Desalination 325 (2013) 56–64

[3] Xiaohua Liu 1, Wenbo Chen, Ming Gu, Shengqiang Shen, Guojian Cao, Thermal and economic analyses of solar desalination system with evacuated tube collectors, Solar Energy 93 (2013) 144–150

[4] W.F. He, L.N. Xu, D. Han, L. Gao, Performance analysis of an air-heated humidification– dehumidification desalination plant powered by low grade waste heat, Energy Conversion and Management 118 (2016) 12–20

[5] Ping-Yang Wang, Shuang-Fei Li, Zhen-Hua Liu, Collecting performance of an evacuated tubular solar high-temperature air heater with concentric tube heat exchanger, Energy Conversion and Management 106 (2015) 1166–1173