Performance Evaluation and Experimental Verification of a Novel Solar Water Desalination System

H. H. El-Ghetany
Solar Energy Department, National Research Centre, Dokki, 12622, Giza, Egypt

H. M. Elgohary
Engineering Sciences Department, Faculty of Petroleum & Mining Eng. Suez University, Suez, Egypt

Y. M. Mohammed
Engineering Sciences Department, Faculty of Petroleum & Mining Eng. Suez University, Suez, Egypt

Abstract – The aim of this work is to develop water desalination unit to produce desalinated water for remote and isolated communities that do not have the infrastructure of potable water networks. The desalination unit using the technology of single effect water distillation that will be thermally driven by solar energy. The studied system is experimentally verified under various weather conditions and studying the various factors that affect the performance of the system. The system condenser is designed to provide double effect of water condensation by using double heat exchanging surface. While the cooling effect is provided by the inlet cold saline water. The installed heat pipe evacuated tube solar collector obtained higher thermal performance and provided higher temperature compared with the flat plate collectors. It is found that the price index of the studied prototype is found to be 2.5 cent USD/ liter of distilled water and 75 cent USD / m^3 of drinking water which is positively competitive if it is applied in rural and isolated communities where national electrical grid is not available. From economic point of view, it is found that the payback period is less than one year if the daily production is distilled water, and it is up to seven years if the daily production is drinking water.

Index Terms: Experimental investigation; solar water desalination system; performance evaluation; distilled and potable water; system cost.

1. INTRODUCTION

Water desalination process is considered one of the water resources for freshwater supplies. The main driving force for water desalinated is the required energy either in its thermal form or in its electrical form. Desalination is the process of separating salt from saline water, which is a mixture of pure water and salt, in order to obtain fresh water. Using renewable energy sources in desalination processes instead of fossil fuels, a significant amount of pollution, greenhouse gas and global warming contribution can be avoided. Solar energy is a resource that is not only sustainable for energy consumption, it is indefinitely renewable. Several previous researches are done on the solar water distillation systems. Gang Xiao et al [1], presented a review on solar stills for brine desalination. They concluded that for supplying potable water in rural areas, it is suggested to install small and simple with a range between 20 to 200 kg/day. Solar stills can be combined with solar power systems, especially concentrated solar power (CSP) plants. More research studies focused on the improvement of the performance of the thermal storage assisted solar desalination technologies.

Ravishankar S. et al [2] presented a detailed technical review of several solar stills to enhance the produced fresh water yield and concluded that cooling the condenser surface by passing water or air as cooling medium over the glass surface, the yield of solar still increases. The optimized number of basins in the multi basin solar still is three and there was no remarkable increase in yield as the number of basins are increased. The yield and efficiency of the solar stills are improved by using of any other heat source such as solar collectors, electricity and other conventional sources. Finally using of sensible heat through flat plate collector, parabolic trough collector, parabolic dish collector, and solar pond leads to increase in inlet temperature of saline water for better evaporation and continuous usage of these leads to scaling effect on the inner surface of tubes as it uses saline water. For large scale of thermal distillation like Multi-stage flash distillation (MSF), Multi-effect distillation (MED) and Vapor compression (VC)—thermal (TVC) and mechanical (MVC), in order to improve the efficiency of these systems, the following recommendations can be achieved (Zarza E, Blanco [3], Al-Karaghouli, [4], and Zachary and Layman [5]).

1. Improvement of design configuration that affect the productivity of the distillation by more attention of the evaporator and condenser design to produce high productivity and quality.

2. In large systems, the concentrating solar collectors are highly recommended to be used to produce high thermal energy.
3. Using sensible heat storage system by coupling the solar distillation system by an external heat source like using concentrating solar collectors with thermal storage tank and heat exchanger.
4. Using latent heat storage system like molten salt storage tank as thermal storage, or corresponding PCM thermal storage.

The purpose of the current system is to produce fresh water from saline water. The water desalination process required energy to produce fresh water. The single effect distillation technology is used while solar energy is utilized to provide the system with the required thermal energy needed as shown in Fig. 1. The water desalination system consists mainly of two loops; Heat transfer fluid (HTF) loop and water loop respectively. The HTF (Heating oil 32) is chosen in the current system to carry the thermal energy from the heat pipe evacuated tube collector to the thermal oil storage tank. It has good heat transfer efficiency, high resistance to thermal cracking, excellent heat transfer properties, long life, and minimum maintenance costs.

Fig. 1 Solar water desalination system using evacuated tube collector

The HTF loop consists of (4) components; evacuated tube collector with storage tank, hot oil stainless steel coil immersed in thermal hot water storage tank acting as heat exchanger, backup electric heater as auxiliary heating sources, and hot oil circulating pump. The HTF is heated in the solar evacuated tube collector and the gained thermal energy is transferred to the hot water storage tank (100 liters) after passing the backup electric heater. The pumped HTF temperature increased in the evacuated tube collector up to 90 ºC and then it is heated in the hot oil auxiliary heater up to 200 ºC. A steam is produced from the top of the hot water storage tank and passed to the water-cooled condenser where a heat transfer process occurred between the steam and the cooling water and then the distilled water is produced. In order to return the hot oil back to the solar system, it should be cooled first, therefore it passes through a heat exchanger while the thermal energy in the hot oil is transferred to the incoming raw water (outlet from the condenser) to increase its temperature that decrease the time of evaporation and consequently increase the rate of condensation and finally, the outlet oil is pumped into the solar system through the hot oil circulating pump. The cold raw saline water (20 ºC to 25 ºC) is passed by gravity from the elevated storage tank to the condenser while it can be used to create a cooling surface to condense the coming vapor from the main storage tank. After the condensation process, the water gained thermal energy from the vapor which caused its temperature to increase. The water is then passed to the heat exchanger to gain the thermal energy from the returned hot oil. Heat is transferred and the water temperature is increased while the oil temperature is decreased. Evacuated tube heat pipe solar collectors (ETSCs) are one of the most innovative forms of solar thermal technology. ETSCs are very efficient and can achieve very high temperatures. Heat pipe evacuated tube collectors contain a copper heat pipe, which is attached to an absorber plate, inside a vacuum sealed solar tube. Inside the heat pipe is a small quantity of liquid, such as alcohol or purified water plus special additives. The vacuum enables the liquid to boil at lower temperatures than it would at normal atmospheric pressure. When sunlight falls on the surface of the absorber, the liquid in the heat tube quickly turns to hot vapor and rises to the top of the pipe. The fluid in the heat pipe condenses and flows back down the tube. This process continues, as long as the sun shines. Individual tubes can also be exchanged without emptying the entire system of it's fluid and should one tube break, there is little impact on the complete system. Heat pipe collectors must be mounted with a minimum tilt angle of around 25° in order to let the internal fluid of the heat pipe to return to the hot absorber

2. EXPERIMENTAL SET UP

The water desalination system consists of saline water elevated storage tank, condenser, heat exchanger, main hot water storage tank, heat pipe evacuated tube collector, oil circulating pump, back up electric heater, connecting tubes, measuring and control devices. The saline water elevated storage tank consists of elevated metal frame with 2 m height and base area of 0.80 m x 0.80 m. The raw materials of iron angles 5 cm x 5 cm x 6m length are purchased and based on the desired dimensions, after the cutting and welding process, the metal frame structure is made. To protect the metal structure from rust and corrosion, two layers of painting are made; the first one is the anti-corrosion painting (Primer) and the second one is the final finished layer painting. A Plastic saline water storage tank is purchased, prepared with the inlet and outlet opining and flow control devices are installed in the tank. After this preparation, the tank is fixed on the top level of the iron metal frame. An innovative double jacked with built-in spiral coil condenser is designed and manufactured. It is considered as the main part in the system as it produces the fresh distilled water yield. The steam outlet from the main hot water tank is flashed into the condenser where the condensation process is occurred. It consists of stainless-steel inner tank that receives the cold saline water from the elevated storage tank. The condensation cooling surface occurred through two sources; the first one from a copper spiral coil placed in the center of the inner storage tank where the cooling water is passed inside the coil and the steam is condensed outside the coil. The second cooling surface is observed by passing the cooling water in the annular space between the inner vessel and the second vessel creating a water jacket cooling surface. A thick layer with 10 cm glass wool insulation is placed outside the double jacket heat exchanger to minimize the heat losses to surrounding and finally a galvanized steel sheet covered the insulation layer to form the third vessel of the condenser. The raw materials are purchased and a rolling process is made to form the cylindrical shape and then by using the wielding process the inner vessel is formed. All the required desired inlet and outlet openings are made. The cooling coil is made from cupper tube which formed as spiral coil to increase the condensation surface area. In order to increase the rate of condensation, a well distribution of the inlet vapor is designed. A vapor distributor is manufactured and fixed in the upper part of the condenser while a condensed water accumulator is manufactured and fixed in the lower part of the condenser. Photographic view of the manufactured condenser are illustrated in Fig. 2. The heat exchanger with built-in spiral cupper coil is designed. It consists of stainless steel inner tank that receives the warm saline water outlet from the condenser and the hot oil outlet from the main hot water storage tank is passed through the spiral cupper coil where convective and conductive heat transfer mechanism is occurred. The raw materials are purchased and a rolling process is made to form the cylindrical shape and then by using the wielding process the inner vessel is formed. All the required desired inlet and outlet openings are made.

Fig. 2 Photographic views of the manufactured condenser

The coil is made from cupper tube which formed as spiral coil to increase the heat transfer surface area. A thick layer with 10 cm glass wool insulation is placed on the outer surface of the inner tank to minimize the heat losses to surrounding and finally a galvanized steel sheet covered the insulation layer to form the final shape of the heat exchanger as shown in Fig. 3. The main hot water tank is considered as the main part in the system to produce the water vapor to be condensed in the condenser. It consists of stainless-steel inner tank that receives the hot water outlet from the heat exchanger. The thermal energy occurred through a stainless steel spiral coil placed in the center of the inner storage tank that coming from the heat transfer fluid carrying thermal energy from the heat pipe evacuated tube solar collector and supplementary electric heater placed in a separate tank. All the required desired inlet and outlet openings are made. The cooling coil is made from stainless steel tube which formed as spiral coil to increase the heat transfer area.

Fig. 3 Photographic views of the manufactured heat exchanger

A thick layer with 10 cm glass wool insulation is placed outside the inner vessel of the hot water storage tank to minimize the heat losses to surrounding and finally a galvanized steel sheet covered the insulation layer to form the final shape of the storage tank as shown in Fig. 4. Evacuated tube solar collectors consist of a storage tank and 30 heat pipe tubes. The tubes have a vacuum between inner and outer layers of borosilicate, a toughened glass. Inside the tubes are sealed copper heat pipes containing a small amount of liquid which vaporizes and rises to the top of the heat pipes. The heat transfer fluid oil absorbs the heat of condensation at the top of the heat pipe and consequently its temperature is increased. The heat pipes perform a pivotal role in the operation of the solar systems. There are basically two sections that make a heat pipe; they are the "evaporator" and the "condenser. In basic terms, the operation of the heat pipe is to transfer efficiently the heat from the solar absorber to the collector manifold. As the entire heat pipe is under vacuum conditions it greatly lowers the boiling point of the working solution to around 25°C making heat pipes an effective method of solar fluid heating. The heating action works by a cycle of evaporation and condensation. The supplementary hot oil electric heater storage tank is connected between the outlet of the heat pipe solar collector and the main hot water storage tank as shown in Fig. 5.

Fig. 4 Photographic views of the manufactured hot water storage tank

Fig. 5 The supplementary hot oil electric heater storage tank

3. RESULTS AND DISCUSSIONS

Several experimental runs are made to experimentally investigate the system performance. The temperature distribution inside the main hot water storage tank is measured throughout the experiment day as shown in Fig. 6. The test run is started with the ordinary cold-water supply (25ºC) and its value is gradually increased due to exposure to conductive and convective heat transfer from the thermal energy provided either from solar system or from auxiliary electric energy It is found that the heating up period equal to 3.5 hours to reach the water temperature to 100ºC for vapor formation and the condensed water is produced.

Figure 6 represents the temperature variations and corresponding energy consumption in kWh throughout the experiment. While Fig. 7 shows the temperature variations and corresponding energy consumption in kWh for the whole day including the heating up period. It is found that the water temperature is increased until reach boiling the 3.5 hours heating up period, then the water vapor temperature is increased up to 126ºC by the end of the daytime. By continuing supplying the thermal energy from the auxiliary heating source with a remarkable reduction in ambient temperature during the night time that causes the water vapor temperature to slightly decrease up to 106 ºC at the end of the measured day. It is found also that the system consumed 67.2 kWh/day to provide steam. The thermal energy is the sum of the thermal energy coming from evacuated tube heat pipe solar collector and the auxiliary back up electric heater. The temperature variation of the condenser cooling water inlet and outlet temperatures is illustrated in Fig. 7. It is noticed that during the heating up period, where there is no steam generated, the inlet and outlet cooling water temperature is approximately the same value. When steam is generated and passed through the condenser, a significant temperature difference is obtained. While Fig. 8 shows the condenser cooling water inlet and outlet temperatures variations for the whole day including the heating up period. It is found that there is a remarkable temperature difference reduction due to the night losses to surrounding.

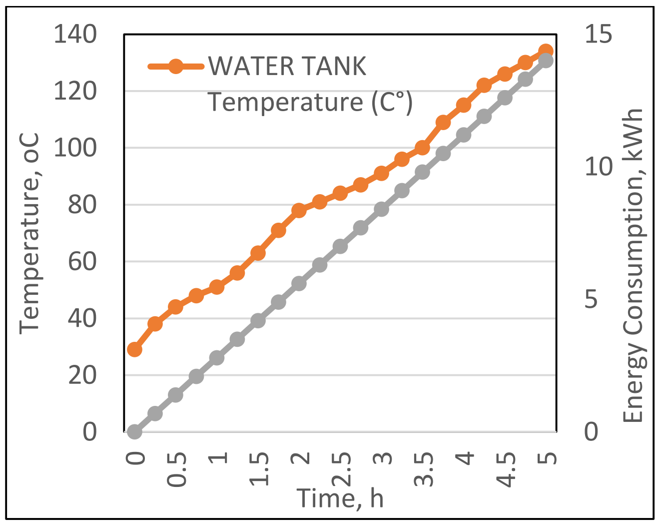

Fig. 6 Temperature distribution inside the main hot water storage tank and related energy consumption throughout the experiment daytime

The amount of the produced distilled water for one complete day including the 3.5 hours heating up period is illustrated in

Fig. 10. It is found that the system is capable to produce 5 m^3/day of the distilled water.

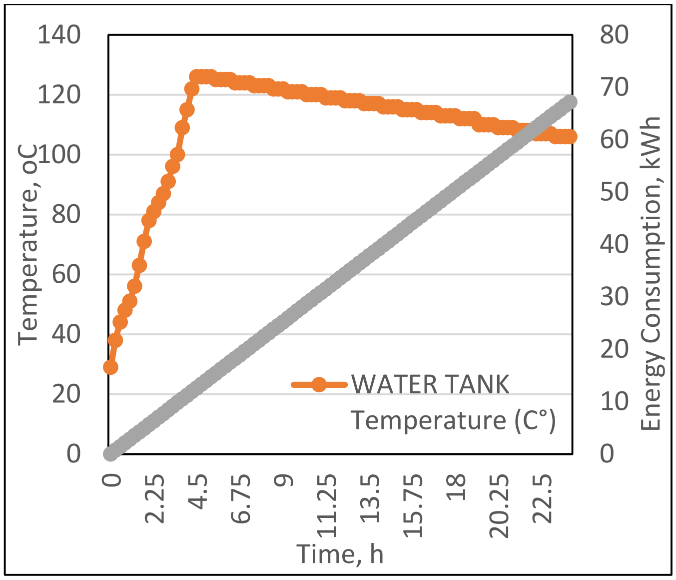

Fig. 7 Temperature distribution inside the main hot water storage tank and related energy consumption for complete one day

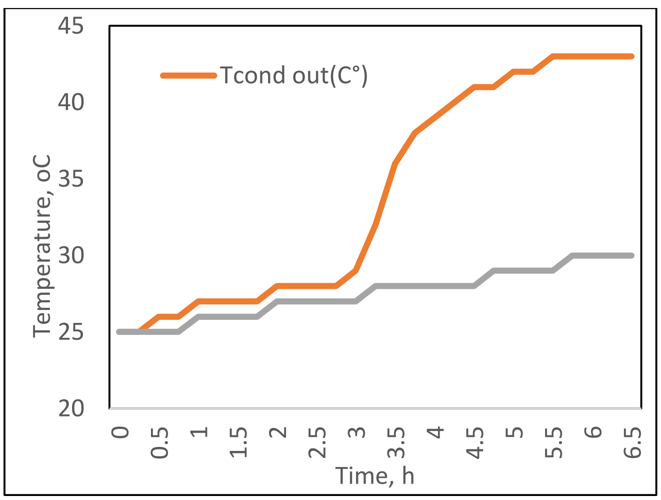

Fig. 8 Temperature variation of the condenser cooling water inlet and outlet temperatures throughout the experiment daytime

If the 3.5 hours heating up period is excluded, the amount of the produced distilled water for one complete day is found to be 6 m^3 /day of the distilled water as illustrated in Fig. 11. The amount of the produced distilled water for one complete day can be presented also versus the corresponding energy consumed in kWh as shown in Fig. 12. It is clear that in order to produce 6 m^3/day of distilled water, it will require 67.2 kWh consumed energy and Fig. 12 also gives a clear data for any amount of distilled water and its related required energy consumed.

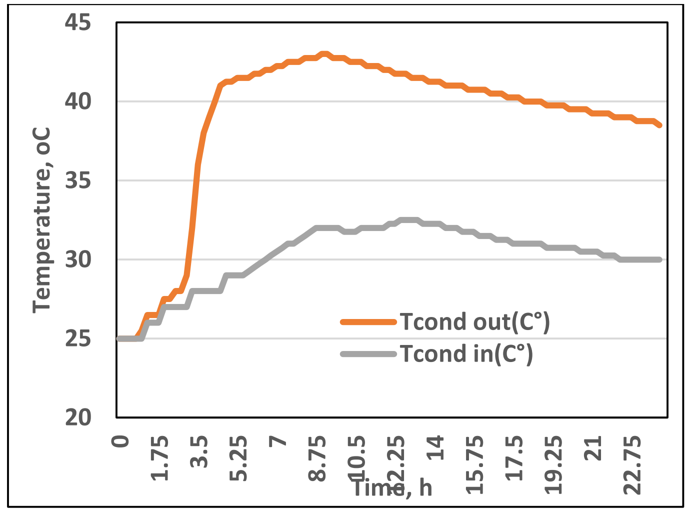

Fig. 9 Temperature variation of the condenser cooling water inlet and outlet temperatures for complete one day

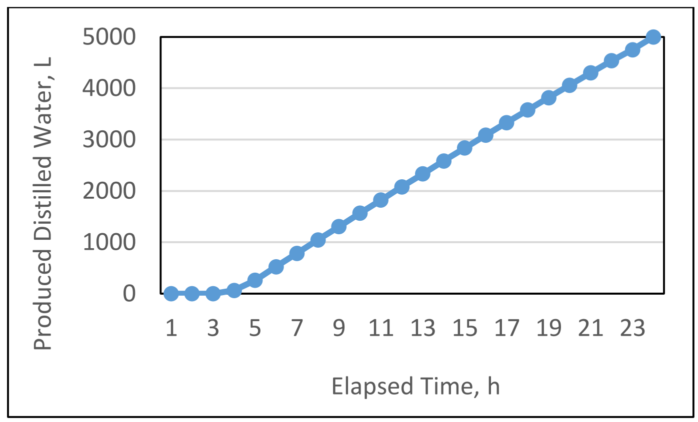

Fig. 10 Amount of the produced distilled water for one complete day including the 3.5 hours heating up period

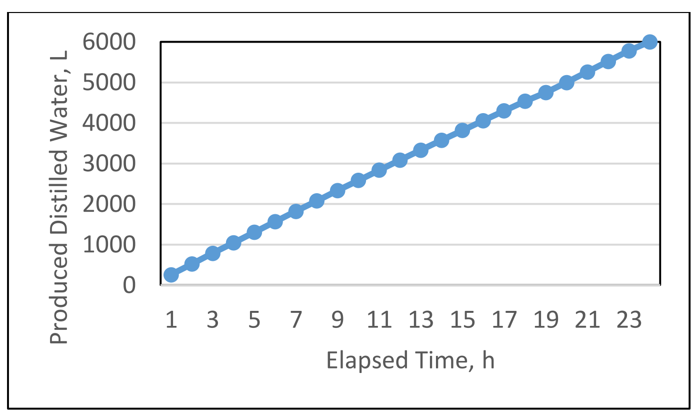

Fig. 11 Amount of the produced distilled water for one complete day excluding the 3.5 hours heating up period

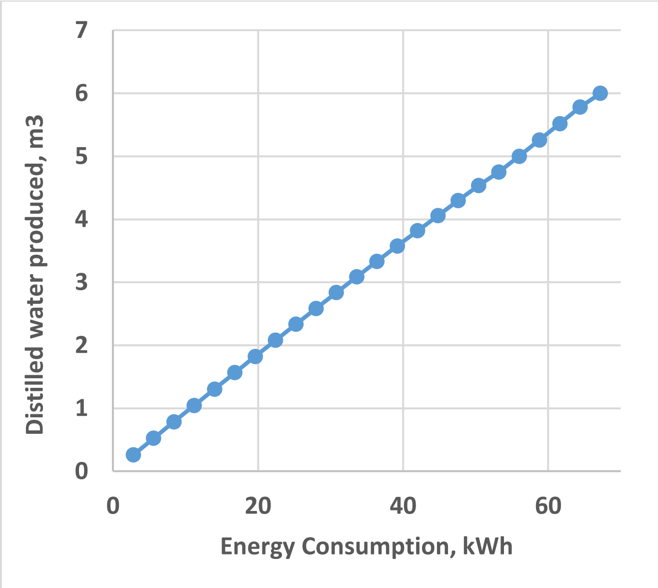

Fig. 12 Amount of the produced distilled water for one complete day versus the corresponding energy consumed in kWh

The amount of consumed energy per day for the current system utilized 26.4 kWh with solar energy and 40.8 kWh auxiliary heating system and can be represented in Fig. 13. It is clear that the solar fraction of the studied system is 39% which is reasonable if the system is working during day and night periods.

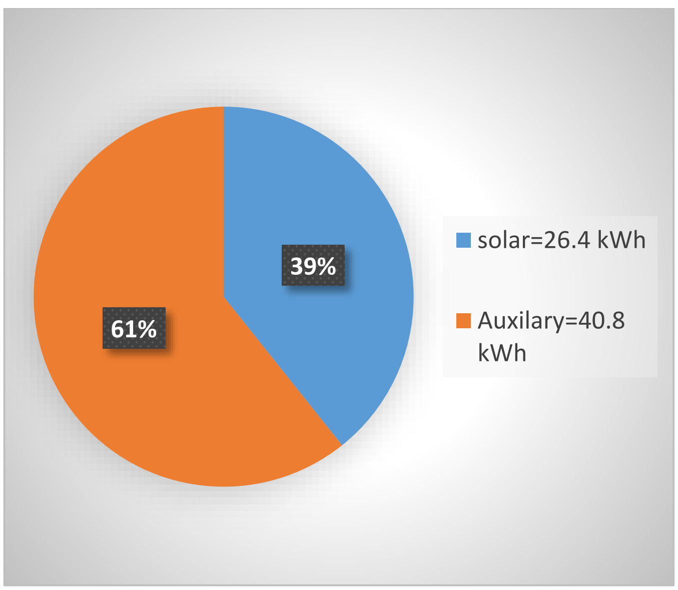

Fig. 13 Solar fraction as a solar energy sharing in the total required energy consumed

In order to investigate the system economy, a feasibility study is made for the studied system and all concerned parameters are included like initial cost and running cost. Two scenarios are presented. The first scenario is to deal with the system as the outlet product is only a distilled water. By considering the daily production of the distilled water is 6000 liters and the price of one liter equal 2.5 Cent USD with initial cost of USD 4,500, and taking into account annual cost of the operation and maintenance as 2% of the annual revenue, the outlet cash flow shown in Fig. 14 indicates that the payback period is less than one year.

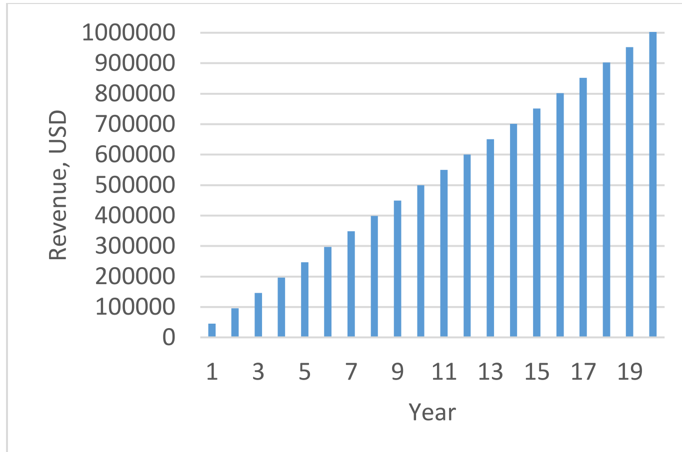

Fig. 14 Cash flow of the first scenario as the outlet product is only a distilled water

The second scenario is to deal with the system as the outlet product is only a drinking water. By considering the daily production of the distilled water is 6 m^3 and the price of one cubic meter of drinking water equal 50 Cent USD with initial cost of USD 4,500, and taking into account annual cost of the operation and maintenance as 2% of the annual revenue the outlet cash flow shown in Fig. 15 indicates that the payback period is up to 7 years.

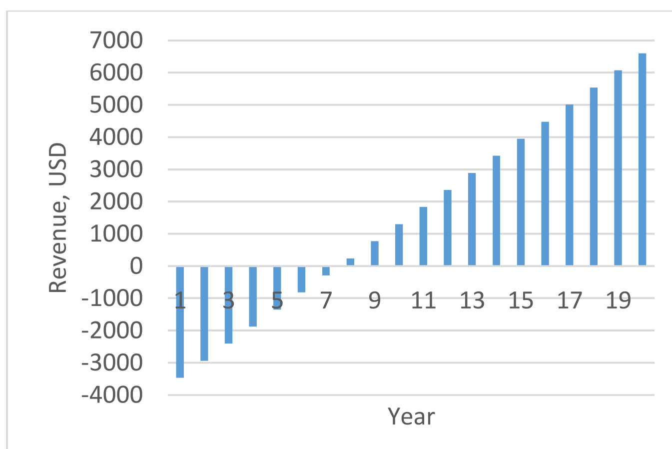

Fig. 15 Cash flow of the second scenario as the outlet product is only a drinking water

4. CONCLUSION

The desalination unit using the technology of solar single effect water distillation is experimentally verified under various weather conditions. The installed heat pipe evacuated tube solar collector obtained higher thermal performance and provided higher temperature compared with the flat plate collectors. It is found that the amount of the produced distilled water for one complete day is 6 m^3 /day of the distilled water which required consumed thermal energy estimated as 76.2 kWh. The amount of consumed energy per day for the current system utilized 26.4 kWh with solar energy and 40.8 kWh auxiliary heating which means that the solar fraction of the studied system is 39% which is reasonable if the system is working during day and night periods. It is found that the price index of the studied system is found to be 2.5 cent USD/ liter of distilled water and 50 cent USD / m^3 of drinking water which is positively competitive if it is applied in rural and isolated communities where national electrical grid is not available. From economic point of view, it is found that the payback period is less than one year if the daily production is distilled water, and it is up to seven years if the daily production is drinking water

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Author

Dr. Hamdy has an extensive experience in the field of mechanical engineering for 32 years either academically or professionally. Professionally, he is an electromechanical designer and reviewer for the pipe lines, storage tanks, heat exchanger, water treatment and solar energy systems of several projects. Academically, he is recognized both internationally and nationally in the area of solar energy applications. He is the author of more than 40 scientific research articles published in leading international journals and international and national conferences.