Performance analysis of single slope solar still integrated with refrigeration systems

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Abstract. The over misuse of existing new water supplies has become a major issue in numerous pieces of the world. Hence, recycling of water is necessary to meet the requirements of the growing population. Solar water purification is one of the viable technologies. This work is focused on the productivity enhancement of a single slope solar still by using two types of refrigeration system such as thermoelectric refrigeration system and vapour compression refrigeration system. In the modification of the existing solar still setup, the extra cooling was achieved by adding thermoelectric modules in the external condenser which is used for increasing the condensation area and thus the rate of evaporation. In the second set up, a vapour compression refrigeration system is coupled with the solar still in such a way that the evaporator coil of the refrigeration system is placed inside the external condenser for providing extra cooling effect and the condenser of the refrigeration system is placed in the basin of solar still for enhancing evaporation rate of the basin water. The results show that these modifications enhanced the performance and productivity of the solar still. The enhancement in the productivity of the passive solar still using thermoelectric refrigeration system was found to be 45.77% more and for solar still with external condenser integrated with vapor compression refrigeration system was found to be 167.7% more as compared with the solar still alone.

1. Introduction
Seas and oceans add up to about 97% of the water on Earth which is saline, remaining 2% of the water is frozen in ice sheets as glaciers, a simple 1% of the water is accessible for the life of plants and other creatures. The over misuse of existing new water supplies is turning into an issue in numerous pieces of the world. Because of increasing population and human activities the water is getting depleted and polluted. Desalination of saline water would be one of the viable solutions for the water scarcity [1]. Desalination of water using solar energy is being done naturally throughout the year in the Earth’s atmosphere and it is directly used for the drinking purpose [2].

Solar still is used for solar distillation, which is a process of distilling pure water from saline water by using solar energy. Solar still can be classified as passive and active. Conventional (Simple) solar still are passive solar still and solar stills with additional equipment like preheater, additional condenser, for enhancing the performance are active solar still. Malik et al. [3] was published a review paper on various factors affecting for the improvement of productivity in passive solar distillation. Later, Tiwari [4] had worked on active solar distillation. The evaporation rate within the solar still depends upon the temperature distinction between glass cover and the glass cover. In order to enhance the yield of the distilled water, it is desirable to have the basin temperature as high as possible and the glass cover temperature as low as possible [5]. This was the motivation for the present research work.
on to enhance the productivity of the solar still by increasing the temperature difference between the condensation and evaporation of the solar still.

The main objective of this work is to maximize the rate of evaporation of the saline water inside the basin and the rate of condensation of the vapour at the inner surface of the glass cover [6]. H.E.S. Fath recommended that for enhancing the productivity of solar still, the basin temperature, evaporation and condensation surface area should be maximised and glass temperature, heat losses through side walls should be minimised. Active solar still has any one of the following: solar collectors [7-14] or water heater or waste heat recovery for preheating the basin of solar still, the use of internal and external condensers for enhancing the rate of condensation or applying vacuum (partial) inside the solar still to enhance the evaporation processes, and cooling the glass cover for decreasing the glass cover temperature hence the temperature gradient between the glass and the basin water increases eventually increasing the rate of evaporation.

Murugavel et al. [13] proposed different methods of improving the productivity experimentally on single basin passive type solar still. Inclination and the direction of inclination of the cover depend on latitude of the location. Results showed that a solar still with glass cover plate of 3 mm thickness gives 16.5% more production than the glass cover of 6 mm thickness. Experiments with deep basin reveal that the productivity of the still decreases with an increase in depth of water during daylight. Monowe et al. [17] put forward a new design of a portable thermal–electrical solar still with an external reflecting booster and an outside condenser. H.N. Singh et al. [20] suggested the monthly performance of passive and active solar stills for different Indian climatic conditions. From different water depth, the annual yield is at its maximum when the condensing glass cover inclination is equal to the latitude of the place. Badran [19] optimized thickness of the solar still glass cover. The efficiency of the conventional passive solar still is very low and hence, improvement in its design is the need of the hour. But only few works has been reported on increasing the condensation rate by using refrigeration systems like vapour refrigeration system [5] and thermoelectric refrigeration [22].

In this work, main focus on increasing temperature gradient between the condenser and evaporator part and that leads to the productivity of solar still was increased by increasing the condensation rate by means of thermoelectric refrigeration and increasing the condensation area by attaching the external condenser having thermoelectric module. Incorporation of external condenser resulted in the condensation of evaporates partially on the glass cover and external condenser.

2. Working Principle

2.1. Conventional Solar Still (CSS)
Simple solar still (Figure 1.) consist of a basin, glass cover, base liner etc. The incident solar radiation is transmitted through the glass cover of the solar still after partial reflection and absorption. The transmitted radiation is further reflected and absorbed by the basin water and finally reaches the blackened surface of the basin where it gets mostly absorbed. After absorption of solar radiation by the blackened surface, most of the thermal energy is absorbed by the water mass, and the rest, which is very small, is lost to the atmosphere through bottom insulation. Thus, the water gets heated and move upward due to convection and buoyancy. And eventually it reached the inner surface of the glass cover. The heat loss from the evaporate through radiation, convection and evaporation, occurs between the water and glass cover. The evaporated water gets condensed on the inner surface of the glass cover after releasing the latent heat of condensation. This condensed water trickles into the distillate output under the effect of gravity [22].
2.2. Thermoelectric refrigeration
Early 19th century scientists, Thomas Johann Seebeck and Jean Charles Athanase Peltier, first discovered the phenomena that are the basis for today’s thermoelectric industry. Seebeck found that if a temperature gradient exists across the junction of two dissimilar conductors, electric current would flow. Peltier, on other hand, learned that passing current through two dissimilar electrical conductors, caused heat to be either emitted or absorbed at the junction of the materials. Usually thermoelectric module consists of P-type and N-type semiconductors. Figure 2. shows the schematic diagram of thermoelectric module.

The main advantage of thermoelectric refrigeration is that, it has no moving parts; hence it has long life and noise free. Most of the thermoelectric modules are compact and simple in construction. Thermoelectric refrigeration has low cooling capacity. In thermoelectric refrigeration, no refrigerant is used and hence there is no leakage. Thermoelectric module required less DC voltage is, so it can be connected with PV panels directly.

2.2.1. Vapour Compression Refrigeration System. Refrigeration and air conditioning is used for cooling products or a building environment. The refrigeration or air conditioning system (R) transfers heat from a cooler low-energy reservoir to a warmer high-energy reservoir at the expense of energy. The vapour compression cycle is used for refrigeration in preference to gas cycles; making use of the latent heat enables a far larger quantity of heat to be extracted for a given refrigerant mass flow rate.
This makes the equipment as compact as possible. A simple vapour compression refrigeration system consists of a compressor, condenser, an expansion valve and an evaporator as shown in Figure 3. The low temperature, low pressure vapour at state 2 is compressed by a compressor to high temperature and pressure vapour at state 3. This vapour is condensed in the condenser at constant pressure to state 4 and then passed through the expansion valve where, the vapour is throttled down to a low pressure liquid and passed on to an evaporator, where it absorbs heat from the surroundings from the circulating fluid (being refrigerated) and vapourizes back into low pressure vapour at state 2. This cycle then repeats.

2.3. Single Slope Solar Still with External Condenser having Thermoelectric Modules

The saline water from the solar still evaporates by absorbing solar insolation and the resulted vapour is partially transported to the inner glass surface due to the convection current formed in the space between the water surface and glass cover. The other part of the vapour moves to the external condenser chamber due to the pressure difference between the small evaporator volume and the larger condenser chamber volume and due to the comparatively low temperature created in the condenser chamber with the use of thermoelectric module. Figure 4. shows the schematic design of Single slope solar still with external condenser having thermoelectric modules. The diffused vapour at the condenser chamber gets condensed, propped up by the thermoelectric module and the distillate was collected from both the solar still side and the condenser chamber side. Figure 5. shows configuration of the thermoelectric modules with side walls of external condenser. Fins and fans were used to increase the heat disposal rate at the hot side thermoelectric modules. Figure 6. shows actual thermoelectric module.

2.4. Single Slope Solar Still with External Condenser Integrated with Vapour Compression Refrigeration System

The saline water from the solar still evaporates by absorbing solar insolation and the heat liberated by the condenser of refrigeration system, which is immersed in the basin of the solar still. The resultant vapour is partially transported to the inner glass surface due to the convection current formed in the space between the water surface and glass cover. The other part of the vapour moves to the external condenser chamber due to the pressure difference between the small evaporator volume and the larger
condenser chamber volume and due to the comparatively low temperature created in the condenser chamber with the use of cooling effect of vapour compression refrigeration system (i.e., evaporator of refrigeration system placed inside the external condenser of the solar still). The schematic design of single slope solar still with external condenser integrated with vapour compression refrigeration system is shown in Figure 7. The diffused vapour to the condenser chamber gets condensed with the help of cooling effect of vapour compression refrigeration system and the distillate was collected from both the solar still side and the condenser chamber side. Thus, coupling the solar still with the vapour compression refrigeration cycle will have following significant advantages:

**Figure 4.** Schematic design of Single slope solar still with external condenser having thermoelectric modules.

**Figure 5.** Thermoelectric module assembly

**Figure 6.** Thermoelectric Peltier sensor Module

The evaporator of the refrigeration unit is used to extract the latent heat of the evaporation from the water vapour in the solar still. The heat rejected in the condenser of the refrigeration unit which is dipped inside the basin of the solar still is utilized for heating the feed saline water. Both these factors lead to an increase in the rate of the condensation and hence the fresh water produced.
Figure 7. Schematic design of Single slope solar still with external condenser integrated with vapour compression refrigeration system

Table 1. Thermoelectric Module Specifications

| Specification          | Value         |
|------------------------|---------------|
| Maximum cooling capacity | 80 W          |
| Input Current           | 8.5 A         |
| Input Voltage           | 15 V          |
| Thickness               | 2 mm          |
| Dimensions              | 40 × 40 × 44 mm |

2.5. Design of Solar Stills

2.5.1. Passive Solar Still. Passive single slope solar still with basin area of 0.6 m × 0.4 m was fabricated using GI sheet. Basin was painted with black plaint as basin liner for increasing the absorption rate of the basin. A 3 mm thick glass cover with 12° inclinations was fixed at top of the vertical walls of the solar still. Side walls of the still were fabricated using plywood and 3 mm thick thermocol was used to minimise the heat loss from the solar still. The vacuum sealing was done with silicon. J-type thermocouples were installed having a range of 0°C to 350°C. The details of solar still is given below

Table 2. Solar still Specifications

| Specification                | Value         |
|------------------------------|---------------|
| Length of still absorber basin | 0.6 m         |
| Breadth of still absorber basin | 0.4 m        |
| Inclination of glass cover   | 120 (latitude of Calicut) |
| Glass cover thickness        | 3 mm          |
| Depth of water in the basin  | 2.5 cm        |

3. Results and Discussion

Experiments were conducted at the solar energy centre, NIT Calicut during April, 2014 on the days when the average solar radiation was almost equal (similar pattern of global radiation variation) excluding the cloudy days. The experiments were conducted on solar still alone, solar still with
external condenser having thermoelectric modules and solar still with external condenser integrated with vapour compression refrigeration system. For all the experiments, a basin water depth of 2.5 cm was maintained. The average data of 5 days from 9.00 am to 5.00 pm was taken. The distilled water was collected from the solar still side and the condenser chamber side separately. The thermoelectric module and cooling fans was powered using DC power supplier and compressor of the vapour compression refrigeration system was powered by AC supply. A comparative study of the cumulative yield over the day in different experiment setups at constant water depths is discussed.

3.1 Hourly variation of yield with respect to time
The variation of yield with respect to time with solar still alone, still coupled with thermoelectric module and still coupled to the refrigeration system is shown in Figure 10. The hourly collection of yield started from 9 am and reached the maximum at 2.00 pm and then decreased for all three setups. When the experiment was done with solar still alone, the maximum yield was found to be 90 ml., for the solar still coupled with thermoelectric module, the maximum yield was 125 ml. and for solar still coupled to the refrigeration system, the maximum yield was found to be 225 ml and is the highest among the three different modes of operation.

At 9.00 am, the solar still integrated with vapour compression refrigeration system gave a yield of 15 ml from the condenser side, which was due to the additional heat liberated from condenser of refrigeration system immersed in the basin. It is clear from the results that the hourly yield of the distilled water was always maximum for solar still integrated with vapour compression refrigeration system as compared to the other modes of operation.

![Figure 10. The hourly production rate of passive solar still and modified solar still.](image)

3.2 Comparison of hourly yield collected from solar side and condenser side
Figure 11. shows the comparison between hourly yield of distilled water from solar still side and the condenser side for solar still with external condenser having thermoelectric module. The hourly yield of distilled water from both solar still side and condenser side increased as solar insolation increases and reaches a maximum at the noon and reduces at evening. In early hours, the yield from solar still was found to be more as compared to the condenser side. This may be due to the fact that in early hours the space between the basin and glass cover was less saturated, so the evaporation and condensation rate of water is proportional and hence the mass of water drawn to the external condenser was less. But towards the noon, the evaporation rate was much more than the condensation rate of solar still. So the space between the basin and glass cover got saturated, eventually the vapour
pressure increased and the water vapour moved to the external condenser chamber due to the comparatively low temperature created in the condenser chamber with the use of thermoelectric module. In the afternoon, the yield rate in the solar still side increased slightly than the condenser side. This was because the low temperature of the glass cover (condensation surface of solar still) increased the condensation rate.

![Figure 11. Comparison of hourly yield collected from solar side and condenser side of solar still with external condenser having thermoelectric modules.](image1)

In the second case; solar still with external condenser integrated with vapour compression refrigeration system, the hourly yield of distilled water from the condenser side was always much more than the solar still side as shown in Figure 12. This might be due the extra cooling effect of the refrigeration system. In this case, the evaporator coil which was placed inside the external condenser was in direct contact with evaporates of the solar still, so quick cooling of the condenser is possible. But in the first case, cold side of the thermoelectric modules was in contact with the surface of the external condenser. The surface of the condenser had to be cooled first and then the space inside the condenser had to be cooled which would obviously take time for cooling. The production rate in this setup is much more due to the fact that extra heat energy is used to heat the basin water of the solar still. In this case also the water yield from both solar still side and condenser side increased as solar insolation increased and reached a maximum at the noon and reduced at evening.

![Figure 12. Comparison of hourly yield collected from solar side and condenser side of solar still with external condenser integrated with vapour compression refrigeration system](image2)
3.3. Variation of productivity for different modes

Figure 13 shows the variation in daily productivity for all the three different modes. The daily productivity from the solar still alone is 378 ml, solar still with external condenser having thermoelectric module is 551 ml, and the maximum productivity obtained with solar still with external condenser integrated with vapour compression refrigeration system is 1012 ml. From the experiments, there was an enhancement in productivity of 45.77% when the modification of solar still done with thermoelectric refrigeration. For solar still with external condenser integrated with vapour compression refrigeration system, the productivity enhancement was 167.7% than the solar still alone. So, this setup gave the best productivity among the two-refrigeration system at the tested conditions.

Figure 14. shows the variation of yield of the solar still with respect to the time and solar radiation. The hourly yield for all three setup is directly proportional to the incident solar radiation. The production of hourly yield was highest when the solar radiation is extreme and it decreased with the intensity of solar radiation. But yield rate in the afternoon session was much more for all the three setups than the morning session; this is because at morning the basin water at atmospheric temperature and the incident solar energy is used for the sensible heating of the basin water. In afternoon the basin water was already hot so the incident water is used for the evaporation process.

![Figure 13. Variation in productivity for different modes](image_url)

![Figure 14. Variation of yield with respect to time and solar insolation](image_url)
4. Conclusions
The current solar energy distillation plants are relatively inexpensive, especially useful where there is a need for small plant exists. However, there is still much room for innovation and improvement. It is well known that solar distillation exhibits a considerable economic advantage over other salt water processes, because of cost free energy and reduced operating costs.

The operation of a solar distillation system coupled with refrigeration systems have been investigated experimentally. Comparison of the output for different setups was studied. Experiments are conducted at constant water depths of 2.5 cm. It is observed that solar still is highly efficient when it was coupled with vapour refrigeration system as compared the thermoelectric refrigeration system for the climatic condition of Calicut. Solar still with external condenser integrated with vapour compression refrigeration system gives the maximum daily yield of 1012ml. The daily productivity in the solar still alone was 378 ml where as in the case of solar still with external condenser having thermoelectric module was 551 ml.

Enhancement in productivity of passive solar still by using thermoelectric refrigeration system was 45.77%. For solar still with external condenser integrated with vapour compression refrigeration system, the productivity enhancement was 167.7% compared with the solar still alone. So this setup gives the best productivity among the two refrigeration system. The hourly yield for all three setup is directly proportional to the incident solar radiation. The production of hourly yield is highest when the solar radiation is extreme and it decreases with the intensity of solar radiation.

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