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Study of the Performance of the Inverted Solar Still Integrated with a Refrigeration Cycle

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Abstract

In this paper, an experimental study of an inverted solar still integrated with a refrigeration cycle at different water depth and feed saline water temperature is presented. Experiments were conducted under the climatic conditions of Muscat, Sultanate of Oman during the month of July. When the temperature of the feed saline water was 35 ºC, it was observed that the daily yield obtained were 6670, 4940 and 3930 ml/day at water depths 8, 6 and 4 cm, respectively. On the other hand, when the temperature of the feed saline water was 30 ºC, it was observed that the daily yielded distilled water obtained were 9500, 10080 and 6400 ml/day at water depths 8, 6 and 4 cm, respectively. In terms of the productivity of the solar stills, the results of this work were compared with that of documented literature. It was found that higher daily yield of fresh water was achieved in case of the refrigerated inverted solar still as compared to the conventional inverted solar still. Moreover, the daily production of the refrigerated inverted solar still was found to be increased by increasing the water depth in comparison to the conventional inverted solar still where the inverse behavior was reported.

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Keywords: Inverted solar still; waste heat; condenser of a refrigerator; evaporator of a refrigerator; water depth; Oman;

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1. Introduction

Oman lies in high solar insolation band and the huge solar energy potential can be used to convert saline water to fresh water. This produced fresh water can be used by small communities that live in remote areas in Oman, which are suffering from a scarcity of fresh water. The most practical and simple way to accomplish solar desalination is by using solar stills. The original solar still (i.e., basin-type solar still) is just an air tight area in which evaporation of feed saline water and condensation of its vapor take place simultaneously in the same unit. It consists of a basin that is covered by two transparent sloping covers, symmetrical at the centre of the basin (e.g., glass cover). The interior of the still contains seawater and air. The operation of the still is very simple. The incident solar radiation is transmitted through the transparent glass cover to the water and heats it. When the seawater is heated, it starts to evaporate and the formed vapour is mixed with the air above the water surface. On meeting the inside of the glass ceiling of the still, the humid air is re-cooled and some of the vapour condenses on the glass. If the glass cover is tilted, the formed condensation drops will start running down the cover by gravitational forces, and may then be collected at the side of the still [1]. The distillate output of a solar still depends, extremely, on water-to-cover temperature differential. As temperature differential is more, as the output is greater as well. However, the solar still output in terms of distilled water productivity is still very limited. This requirement of high output of distilled water of solar stills has presented a challenge for researchers around the world who directed their efforts to develop solar stills that are more advanced [2]. A number of initiatives have been triggered to look for some methods to enhance the still yield from the same collection area. According to Zaki et al. [3], the methods of improving the productivity of the solar stills include increasing the brine temperature, improving distillate collection process, injecting black dye in the seawater, reducing the heat conduction through basin walls and top cover, enhancing the evaporation process, or decreasing the condensation surface temperature.

On the basis of various modifications and mode of operations introduced in simple solar stills, these solar distillation systems are classified as passive and active type solar stills [4-9]. In active type of solar stills, an extra-thermal energy by external mode is fed into the basin of the solar still for faster evaporation (e.g., additional condensers or collectors). If no such external mode is used then that type of solar still is known as passive solar still. Therefore, in passive type still either simple modification has been done inside the still or some materials have been used in basin along with saline water [9]. Passive methods include the use of dye or charcoal to increase the solar absorptivity of water [4,10-12], applying good insulation [5], lowering the water depth in the basin to lower its thermal capacity [5,12], ensuring vapor tightness, and using reflective side wall [12]. According to Abu-Arabi et al. [4], active type of solar stills include the use of solar collectors or waste heat to heat the basin water, the use of internal and external condensers or applying vacuum inside the solar still to enhance the evaporation/condensation processes, and cooling the glass cover to increase the temperature difference between the glass and the water in the basin and hence increase the rate of evaporation. According to Singh and Tiwari [6], the work on passive solar distillation was reviewed by Malik et al. [13] and further review was carried out by Tiwari [14], which also includes work on active solar distillation. Further, Tiwari et al. [15] carried out a study on the present status of research work on both passive and active solar distillation systems.

Dunkle [16] found that the mass transfer rate within the solar still depends upon the water and the glass cover temperature difference. In order to enhance the yield of the distilled water, it is desirable to have the basin temperature as high as possible and the cover temperature as low as possible. This temperature difference is very important as it controls the rare of evaporation from the basin and the rate of condensation on the glass cover. This motivated the research for the methods to enhance the still productivity by increasing such temperature difference. The main objective of these methods is to maximize the evaporation of the saline water inside the basin and the condensation of the vapour in the inner surface of the cover. According to Tiwari et al. [17], this can be achieved either by increasing the water temperature or by decreasing the glass cover (condensing cover) temperature or by having both conditions at the same time. To increase the temperature difference between the saline water surface and the transparent cover, many researchers studied the effect of coupling the solar still to a flat plate solar collector [3,18,19). The results indicated the performance of the still could improve significantly. However, this was associated with increasing the system cost. Another way to increase the temperature difference is by adding a condenser to the still, which will increase the still performance because of the increasing of the heat sink capacity [20-22]. Other researches in the open literature investigated different designs and techniques to use the latent heat of condensation to preheat the feed water, instead just to dissipate to the environment. For example, many investigators suggested work on a double-effect solar still and compare the obtained results with that of a single-effect solar still. In this case, the latent heat of vaporization lost to the ambient through the condoning cover in a single-effect solar still can be reused in the heating of water in the basin above the condensing cover in a double-effect solar still, and this would lead to an improvement in the still efficiency system. Work on a double-effect solar still was carried out by Sodha et al. [23,24] and Tiwari et al. [25].

An improvement was achieved by using an inverted absorber solar concentrator that is integrated with the basin type solar still. An inverted absorber solar still is an improved design of a single slope solar still with a curved reflector under the basin. This arrangement helps in more heating of the basin of a solar still from both sides (i.e., top and bottom surfaces) directly and indirectly. Norton et al. [26] in a study investigating possible rural applications for the compound parabolic concentrator (CPU), proposed the incorporation of a basin type still with an inverted absorber line-axis asymmetric CPC. Such systems were also fabricated and characterised experimentally in a northern Indian climate [27]. Suneja et al. [28] conducted a study of an inverted absorber solar distillation unit, a double effect still was also used to improve the still output. In this case, the latent heat of vaporization, in the lower vessel, was reused to heat the water body in the upper vessel. The performance evaluation of an inverted absorber solar still was also presented by Tiwari and Suneja [29]. They derived analytical expressions for water temperature, condensing cover temperature, hourly yield and thermal efficiency in terms of design and climatic parameters. Suneje and Tiwari [30] carried out an analysis of a triple basin inverted absorber solar still. They found that the inverted absorber triple basin solar still gives a substantially higher yield than a double basin and a single basin inverted absorber solar still. In the Sultanate of Oman, Abdul-Wahab et al. [31] presented an experimental based study of an inverted solar still conducted at Sultan Qaboos University, in Muscat. For the same area, Dev et al. [32] presented an experimental study of inverted absorber solar still and single slope solar still at different water depths and total dissolved solids for the climatic condition of Oman.

In this work, an inverted solar still in combination with a refrigeration cycle was fabricated and tested. The condenser of the refrigeration cycle was placed inside the solar still that contains the feed. The waste heat from condenser was used as an additional energy input to heat the feed. On the other hand, the evaporator of the refrigeration cycle was used in order to remove rapidly the heat from the condensing surface that dissipates from water condensation. This was achieved by transporting the mixture of air-vapor just under the cover of the still to the evaporator of the refrigeration cycle. This resulted in the creation of flow between the cover of the still and the surface of the feed saline water. Therefore, the created water vapor over the surface of the saline water that moved towards up, was expected to come in contact with the inside cold surface of the cover and they condensed to form the product distilled water.

2. Description of experimental set up

A schematic diagram and photograph of the experimental set up of the refrigerated inverted solar still is shown in Figs. 1 and 2, respectively. This experimental set up is installed at Sultan Qaboos University (SQU), Oman. The refrigerated inverted solar still consists of two main parts: an inverted solar still with a perforated cover and a refrigeration cycle. The inverted solar still part is fabricated by using a galvanized iron sheet of 5/16 inches thickness. The size of the solar still is 400 mm length and 200 mm width. The whole assembly of the inverted solar still is positioned inside an enclosure. This enclosure is made of glass of 5/16 inches thickness. The size of the enclosure is 1000 mm length and 1000 mm width. The left and right sides of the enclosures is insulated by a 5 cm thick of Styrofoam and the top of the enclosure were the cooling system implemented. The basin is colored black in order to absorb solar radiation. In addition, mirrors are placed under the basin (i.e., under glass enclosure) to heat also the basin from its bottom surface. These mirrors will concentrate the solar radiation onto the lower surface of the metallic basin which thereafter transfers heat to the feed saline water.

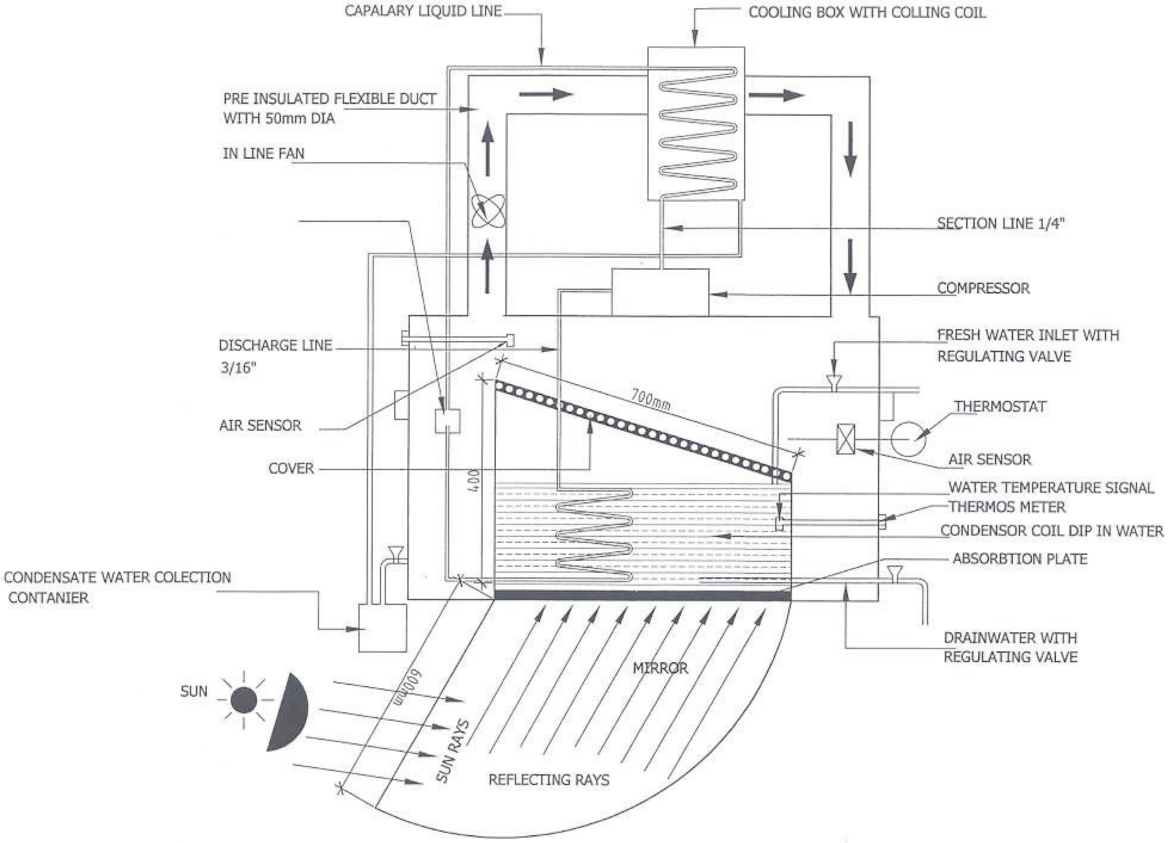


Fig. 1. Schematic diagram of the refrigerated inverted solar still

Fig. 2. Photographs of the refrigerated inverted solar still taken

In order to maintain the condensing glass cover at very low temperature, a flow of cold water is used uniformly over the outer side of the glass enclosure to cool the cover of the still. For this effect, a main water tank is used together with a water pump of 0.5 HP with 0.75 inches inlet and 0.5 inches outlet (.e., for circulation the water). This flow of cold water increases the temperature difference between feed saline water and condensing glass cover and thus the condensation of the water vapor will be expected to be more intense. The output from the still is collected through a channel, fixed at the end of the smaller vertical side of the basin. A plastic pipe is connected to this channel to drain the distillated water to an external measuring jar. Also, the base of the inverted solar still is provided with a drain valve for cleaning the base of the still after each experiment.

On the other hand, the refrigeration cycle part of the refrigerated inverted solar still consists of a ¼ HP compressor with 134-a refrigerant, a condenser, an expansion device, and an evaporator. In addition to a flexible duct with in line fan which is used to remove the heat rapidly from the condensing surface. Combing the inverted solar still with refrigeration cycle will have two significant effects: (a) add an extra thermal energy that will be fed into the basin and it will be used to vaporize the feed saline water by using the waste heat of the condensation of refrigerant inside the condenser coil, and (b) increase the rate of the condensation of produced fresh water by removing rapidly the heat of the condensation from the condensing surface.

The compressor of the refrigeration cycle has a refrigerant inlet line (low side pressure) and refrigerant outlet line (high side pressure). The compressor will cause the refrigerant to flow in a cycle from the condenser to the evaporator. The refrigerant will flow into the condenser coil that is placed inside the basin of the inverted solar still; where the feed water will undergo distillation. The condenser will reject heat (results from the condensation of the gas refrigerant) to the feed saline water of the solar still. After rejection all the heat by the condenser, the refrigerant turns back to liquid. At the same time, this rejection heat will be used as an additional energy input to evaporate the feed saline water. The liquid will flow then to the evaporator. Evaporator is a heat exchanger that absorbs heat so the liquid refrigerant will be transformed into a gas vapor. The energy required for the evaporation of the refrigerant will be taken from the mixture of air-vapor just under the cover of the still by using the flexible air duct. Through the flexible duct, the mixture of air vapor just under the glass enclosure of the solar still will be flow to the evaporator. The heat of this air inside the evaporator will be used to evaporate the liquid refrigerant. The cold air will then leave the evaporator to be circulated again under the glass enclosure of the solar still. This arrangement of air transport will ensure that the heat dissipates from condensing water will be removed rapidly from the condensing surface and also ensure from decreasing the temperature of the condensation surface. Details of the air duct and the cooling box of the refrigerated inverted solar still is shown in Fig. 3.

3. Results and discussion

The experiments were carried out for 6 days in July with the climatic conditions of Muscat, Oman. The tests were performed using sea water as feed. All experiments were started at 7 am local time and lasted for 24 hours. The experiments were conducted in the Sultan Qaboos University (SQU), for different 3 water depths in the basin of the refrigerated inverted solar still. The amounts of distillate water were recorded at hourly intervals. Table 1 represents hourly variation of productivity of the refrigerated inverted solar still, using different water depths (i.e., 4, 6, 8 cm). It can be observed that the depth of the water in the basin of the refrigerated inverted solar still is a significant parameter. From the first glance at Table 1, one can observe that the production rate increases with the increase in water depth. Further, from the same table it is also observed that more yields are obtained during the off shine hours as compared to daytime.

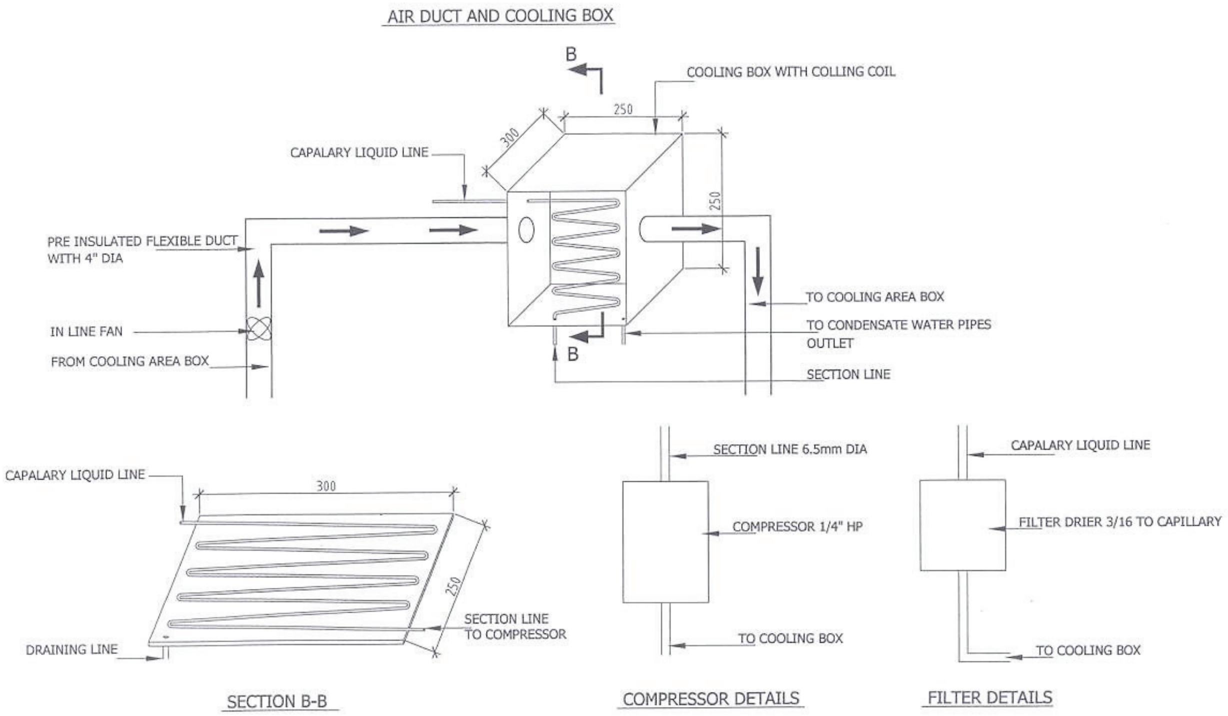


Fig. 3. Air duct and cooling box of the refrigerated inverted solar still

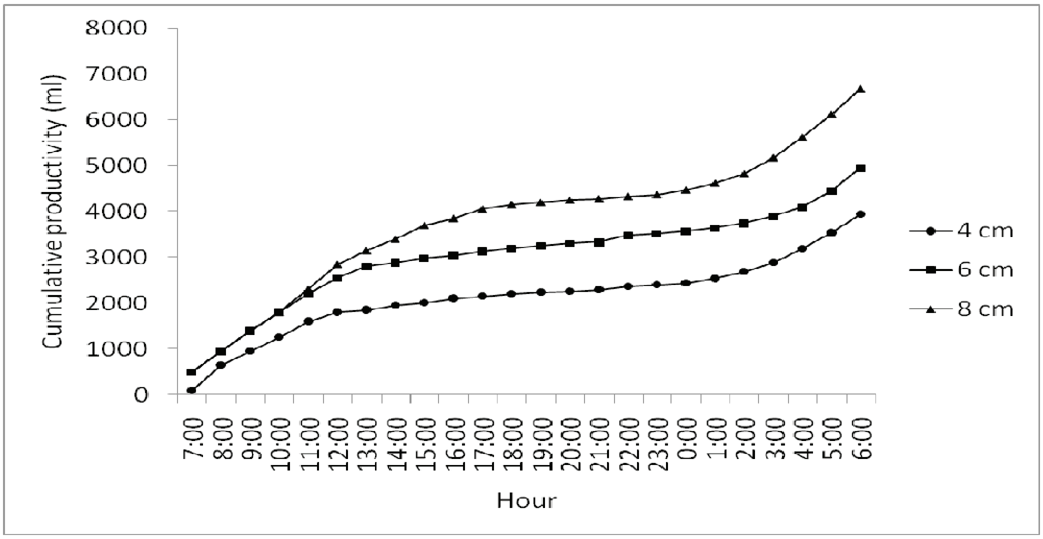
The night production in the absence of solar radiation contributed to 76.8% of the daily output (i.e., 6 cm at 30 ºC). This picture is clearer for higher water depths in solar still (6 and 8 cm). Table 2 shows the dependence of the productivity on the water depth. It can be seen that the daily yield of the refrigerated inverted solar still increases with the increase of water depth in the basin. In this work, for instance, the increase of the water depth from 4 to 6 cm increased the productivity by 57.5%. The picture of increasing the yield with the increase of the water depth becomes clearer when the total accumulation is presented as shown in Figs. 4a and 4b. As per documented literature, it is evident that as the water depth increases, the productivity will be decreased. This is due to the increase of the heat capacity of the water in the basin, results in lower water temperature in the basin leading to lower evaporation rate. However, the results of this work show the reverse behavior; that is the still with higher water depth is found to be more productive.

Table 1. Hourly measured yield (ml) at different water depths

Time (Hour)	4 cm and 35 ºC	6 cm and 35 ˚C	8 cm and 35 ˚C	4 cm and 30 ºC	6 cm and 30 ˚C	8 cm and 30 ˚C
7:00	100	80	250	200	100	50
8:00	50	100	300	100	150	150
9:00	100	60	150	100	100	50
10:00	50	90	200	100	130	100
11:00	50	60	100	150	100	200
12:00	30	60	50	70	150	100
13:00	20	50	50	100	100	200
14:00	40	30	30	50	400	150
15:00	70	150	50	70	200	150
16:00	40	40	40	60	200	300
17:00	30	50	100	100	100	150
18:00	100	70	150	150	200	200
19:00	150	100	200	200	150	150
20:00	200	150	350	350	300	300
21:00	300	200	450	400	450	450
22:00	350	350	500	450	500	500
23:00	400	500	550	500	600	700
0:00	400	500	500	600	650	900
1:00	250	450	450	550	700	1300
2:00	300	450	450	400	1200	1500
3:00	300	400	400	450	1000	800
4:00	350	400	500	500	1500	500
5:00	200	350	550	350	700	400
6:00	50	250	300	400	400	200
Total	**3930**	**4940**	**6670**	**6400**	**10080**	**9500**

Table 2. Daily yield of the refrigerated inverted solar still

Depth (cm)	Temperature of the sea water (ºC)	Daily yield (ml/day)
4	35	3930
6	35	4940
8	35	6670
4	30	6400
6	30	10080
8	30	9500



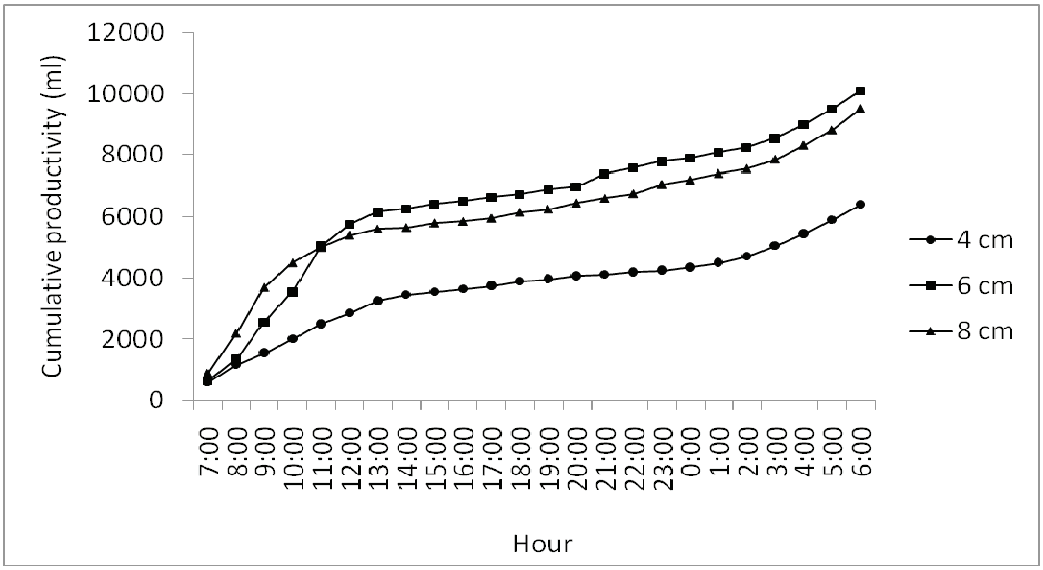


Fig. 4. (a) The effect of water depth on the cumulative productivity of the refrigerated inverted solar still at feed water temperature of 35 ºC; (b) The effect of water depth on the cumulative productivity of the refrigerated inverted solar still at feed water temperature of 30 ºC

4. Conclusion

Combining the refrigeration cycle into the inverted solar still has a significant effect on increasing the productivity of the distilled water, which is attributed to the extra thermal energy provided by the condenser of the refrigeration cycle that will be fed into the basin of the inverted solar still for faster evaporation. Accordingly, the yield from an inverted solar still was increased by combing it with a refrigeration cycle, as proposed in this work. The findings indicated that the increase of water depth increase the productivity. Also, the results indicated that more yield was obtained during the off shine hours as compared to daytime. Hence, it can be concluded that the experimental work carried out in this work indicated that the refrigeration cycle addition enhanced the inverted solar still productivity.

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