An entirely solar-powered hybrid thermal-membrane desalination system integrated with Solar heaters and preheating technique

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An entirely solar-powered hybrid thermal-membrane desalination system integrated with Solar heaters and preheating technique

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Abstract: *An experimental study of a hybrid desalination system using Humidification–Dehumidification (HDH) process integrated with RO unit, evacuated tube solar water heater (SWH) and solar air heater (SAH). The results showed that the productivity of the unit strongly depends on the temperature of water at the humidifier inlet and RO unit inlet. The results show that maximum productivity of (14.25 L/hr.) is obtained when cold water flowrate is double that of hot water, inlet water mass flow rate to the humidifier (2 kg/min), Using SAH with (5 m/s) humidifier inlet air velocity, and 95 °C at humidifier inlet. The productivity obtained from the HDH system while operating a full day is 56.6 L/day and daily productivity obtained from the RO unit of 416 L/ workday was obtained at average 40 °C RO unit Feed Water. The hybrid system provides 472 L/day as a Sumption of Condensate water and Ro unit productivity.*

Keywords: Desalination; Humidification-dehumidification; Preheating; Reverse Osmosis; Solar energy.

1. INTRODUCTION

The drinking water availability is decreasing steadily, while the requirement for fresh water is expanding rapidly. Worldwide, People's access to safe drinking water is decreasing every day [1]. The majority of human illnesses are caused by pollution or a lack of water resource purification. Even today, the world is facing massive water shortages due to unexpected means and pollution caused by artificial behaviors [2]. Drinking water shortages are supposed to be the world's major challenge in this century, owing to Uncontrollable consumption patterns and population expansion [3]. Pollution of freshwater resources (rivers, groundwater, lakes) with industrial waste has exacerbated the problem [4]. The total amount of water reintroduced in the world is about 1.4 billion cubic kilometers. The freshwater is found in the atmosphere, polar ice, and groundwater which form about 2.5% of the whole amount, and the oceans present the greatest proportion of the water, which is about 97.5% of the total amount. This shows that only about 0.014% is available directly to live organisms and humans [4]. Desalination of brackish water and/or seawater is an essential option because the ocean is the only unlimited resource of water. In addition to the water shortage problem, process capacity represents another problem field. A large amount of energy is required for the desalination process. It is expected to consume 10 million tons of fuel and produce one million cubic meters of water per day [4]. Renewable energy sources have gained great interest to overcome the high cost of traditional energy sources, as well as the environmental damage caused by them [5, 6].

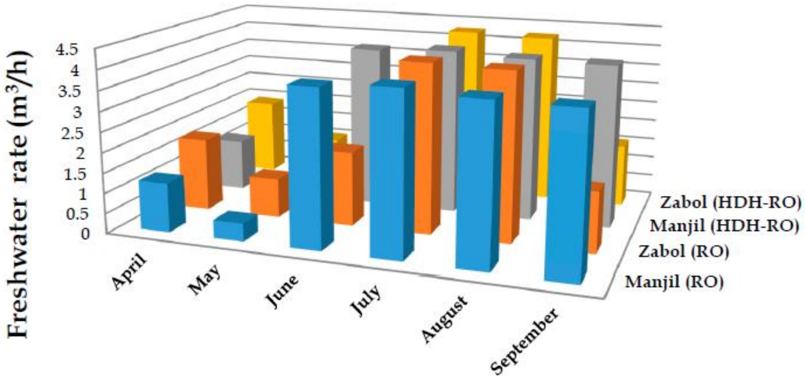
Many different desalination technologies have been created. Desalination techniques are categorized into two main sections: thermal techniques (phase change) and membrane techniques (single phase) [7]. In the thermal techniques process, a thermal energy source, for example, solar energy, nuclear energy or fossil fuels, may be applied to vaporize water, which then is condensed to supply fresh water [8]. The membrane processes desalination processes include solar distiller [9], Vapor Compression distillation (VC) [10], Freezing distillation [11], Multi-Stage Flash distillation (MSF) [12], and multi-Effect distillation (ME) [13]; in the single-phase processes, two commercially important desalination technologies, reverse osmosis RO and electrodialysis (ED) distillation, use membranes. The idea of HDH depends on mixing air with vapor. The higher the temperature of the air, the greater its ability to hold more water vapor. When the air temperature rises from 30 °Cto 80 °C, for example, 1 kilogram of dry air can hold 0.5 kilograms of water vapor as reported in [14]. Oppositely, the purified water is found by keeping moist air in contact with the cooling surface, which condense portion of the vapor integrated with the air. A SAH, a SWH, a humidifier (evaporator), a dehumidifier (condenser), a RO unit, a solar panel, and a storage tank make up the HDH desalination unit.

The hybridization of HDH with RO units is still under study, especially those systems operated via renewable energy sources. Rostamzadeh et al. [15] studied an HDH-RO system depending on generated power from a wind turbine besides recovering the waste heat from the generators as a thermal heat source. The system was investigated for two different locations. It was found that the developed system was complex and not feasible compared to separate RO unit. The results of the production and consumed power are presented in Fig. 1.

In the current study, a solar-operated HDH-RO system is proposed and experimented. The system works on the general principle of the theoretical published work by Abdelgaied et al. [16]. It depended on closed water–open air circuit, which basically consists of three paths as follows. The first path is SAH Which raises the air temperature greatly, which is then further heated to a higher level by the second path SWH, by high-temperature water vapor used in the humidifier. The SWH heats sea water, which is then pumped into the humidifier, which presents the second path. In the humidifier, heated sea water and air come into contact with backing materials.

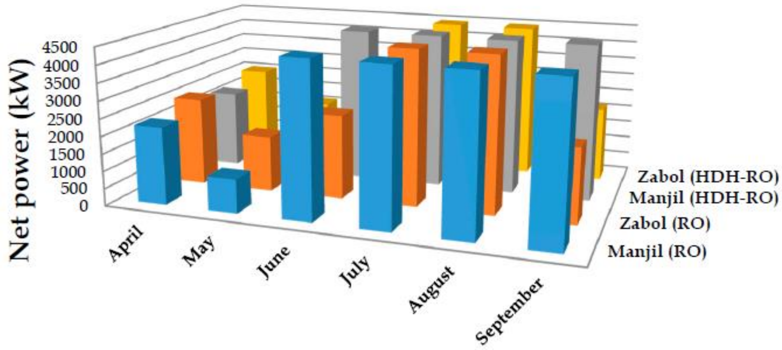
As the dehumidifier and humidifier are linked together, humidified air goes through the dehumidifier. Cold water, which presents the third path, travels through a cooling coil that is surrounded by humidified air. The water vapor then condenses on the dehumidifier's surfaces, resulting in freshwater. Water was collected at the bottom of the well.

The HDH unit's condenser and evaporator have been created and tested to increase the HDH's performance. The condenser is a cylindrical shell air-water heat exchanger with corrugated fins and a copper coil. The evaporator, on the other hand, is a rectangular cross-sectional shell with a small entrance for changing packing material. By employing a vacuum tube solar collector, the sequence of experiments and computations for the influence of the feed water temperature (ranging from 65 to 95 °C) on the evaporator is repeated with C/H = 2 (Ratio of cold-water Dehumidifier inlet to hot water Humidifier inlet) with different speed of the blower. SPC of RO unit has decreased due to using hot brine rejected from the humidifier.



	April	May	June	July	August	September
Manjil (RO)	1.228	0.4473	3.862	3.986	3.877	3.846
Zabol (RO)	1.811	0.9796	1.845	4.184	4.133	1.487
Manjil (HDH-RO)	1.293	0.4771	4.027	4.117	4.037	4.018
Zabol (HDH-RO)	1.919	1.033	1.915	4.284	4.24	1.562

(a)



	April	May	June	July	August	September
Manjil (RO)	2237	983.3	4457	4456	4457	4457
Zabol (RO)	2529	1603	2427	4456	4456	2146
Manjil (HDH-RO)	2236	982.7	4456	4456	4456	4456
Zabol (HDH-RO)	2528	1602	2426	4455	4455	2145

(b)

Fig. 1 Results of HDH-RO hybrid system powered via wind energy for two regions vs. a solo RO: (a) freshwater production and (b) Net power [15].

2. EXPERIMENTAL SETUP

Lately, the great challenge facing the world is to build a desalination unit with high productivity and low energy consumption. Further to that, this research targeted to clarify a creative hybrid desalination mechanism combining two familiar methods of high production of freshwater: HDH and RO. The solar (PV) systems were used to power the hybrid HDH-RO unit, as illustrated in Fig. 2. From the literature, the production rate of freshwater HDH desalination unit extremely depends on the temperature of air and water entering the humidifier as well as the air-water flow ratio. The membrane process reverse osmosis (RO) is generally used in desalination techniques as it is described by easy operation in the long run and low energy consumption. However, we need ways to make RO technology consume less energy, which makes it significantly suitable for most regions in the world.

The system depends on PV Panels to supply the system with the required power. To achieve high performance of

PV Panel, it is needed to be cooled to a specific range of temperatures; this is achieved by using part of brackish which is used for the main process of desalination. This cause brackish water gets heated to a few degrees which makes sure that PV Panels achieve higher efficiency and increase the overall system efficiency by increasing inlet water temperature to the HDH system. This water is then pumped to solar water heater, which heats the brackish water up to approximately boiling temperature (90:98 ℃). The hot water is then pumped using a pump through a piping system; this water enters the humidifier from the top and is sprayed through a set of nozzles which convert it onto steam; at the same time, air is forced by a blower onto SAH which heat the air which helps in improving air capability to carry more steam, this air entering the humidifier from the bottom. Inside the humidifier, the air moves from the bottom to the top due to density difference, and steam move from the top to the bottom due to gravity force, as the humidifier contains backing material inside it which plays an important role in the humidification process, as it increases the contact surface area between the steam and the hot air which increase humidification rate. As a result, the air at the top of the humidifier is almost saturated air, and the water at the bottom is considered as rejected water (Brine) (represent Ro unit inlet water at temperature range (40-45) ℃). The second stage of the system is done at the dehumidifier; as the humidifier and dehumidifier have a connection from the top, the saturated air enters the dehumidifier from the top, and at the same time, cold water is fed to the dehumidifier from the bottom, but it has its own path through the coil inside the dehumidifier, this coil has the effective role on purification process, and it presents the contact area between the cold water and hot saturated air and where the heat transfer occurs and water is condensate and this present the pure water from the HDH system. Due to heat transfer through the dehumidifier, cold water gain heat and this hot water is recirculated to the SWH. HDH unit productivity is considered low because of low evaporation and condensation as in HDH system. The modification to increase productivity is using RO system with the outlet hot water from the humidifier. Hot water is pumped to the RO unit; RO is considered as a filter as water pass through a membrane which works on separating the salt and dissolved particles from the water, thus increasing productivity by producing additional amount of pure water, on the other hand, the rest of water entering the RO unit is rejected. Using RO unit with HDH also has a great advantage as it reduces the amount of power required for RO unit.

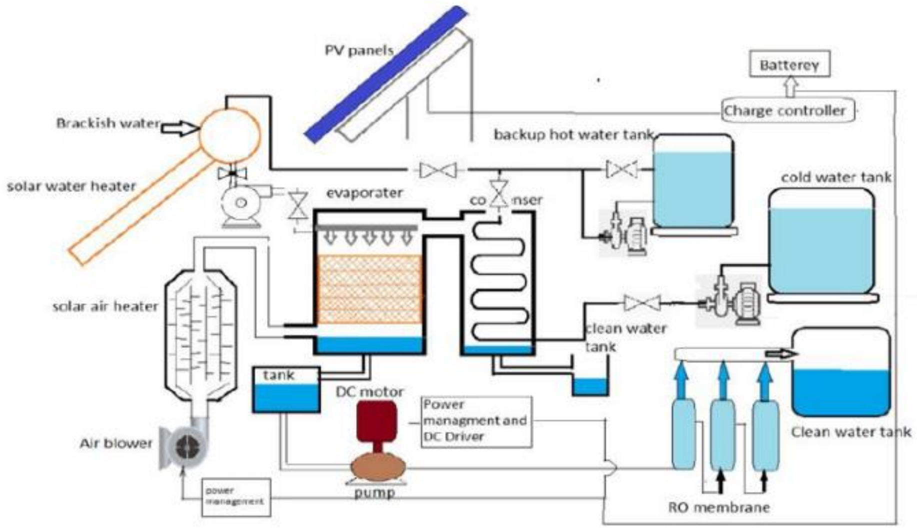


Fig. 2. Schematic diagram of the hybrid desalination system.

3. RESULTS AND DISCUSSIONS

All results are obtained when C/H = 2 (Ratio of cold-water Dehumidifier inlet to hot water Humidifier inlet), the mass flow rate of water at the entrance of the humidifier is (2 kg/min); using a Solar Air heater with various air velocities (air is forced by blower onto solar air heater) and cellulose 5 mm as the packing material in the evaporator.

3.1 Effect of using Solar Air Heater (SAH) on Unit Productivity

Fig. 3 shows the effect of using SAH on the unit productivity under different operating conditions. For constant water flow rate, the productivity of the unit increases by using SAH at a high range of Humidifier Inlet temperature (85-95) ℃; due to using Air solar heater which raises air temperature; as a result, the capability of humidifier inlet air to carry vapor is increased which plays an important role at condensation processes and increase unit productivity. As shown in Fig. 3, below through the range of Humidifier Inlet temperature (85-95) ℃ using a blower to provide air at evaporator inlet at 5 m/s. The productivity without SAH at 95 ℃ is about 12 L/hr. But with SAH the productivity has increased to 14 L/hr. by 16.7 percent.

3.2 RO Unit Productivity

The effect of RO unit inlet water temperature on the performance, productivity and power consumption are experimentally tested. As mentioned before, we used evaporator outlet water as an input to RO unit because of its high-temperature range, which plays an important role in unit performance as a result of rise of water feed temperature, the viscosity of water will decrease such shear stress due to water movement in RO membrane will decrease which decrease specific power consumption and increase unit productivity, this is shown in Fig. 4 RO productivity at various temperature as RO feed water temperature has increased from 40 to 45 °C the productivity has increased by 8 percentage, and Fig. 5 shows that as RO feed water temperature has increased from 40 to 45 °C, the power consumption has decreased by 33 percentage.

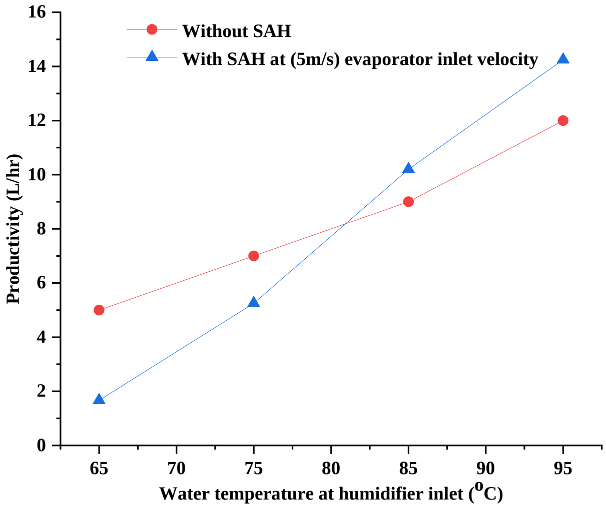


Fig. 3. Effect of using Solar Air Heater (SAH) on Unit Productivity.

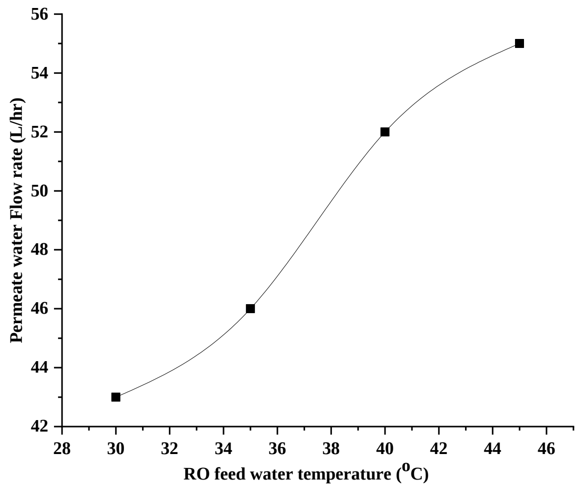


Fig. 4. RO productivity at various temperature.

3.3 Effect of RO feed water temperature on Unit Productivity

Fig. 6 shows the effect of RO feed water temperature on the unit productivity at different periods of time. For a constant water flow rate, the productivity of the component rises by increasing feed water temperature. The figure shows the effect of increasing feed water temperature on permeate water flow rate, as the temperature of feed water has increased by 5 °C; the productivity has increased by 8 percent.

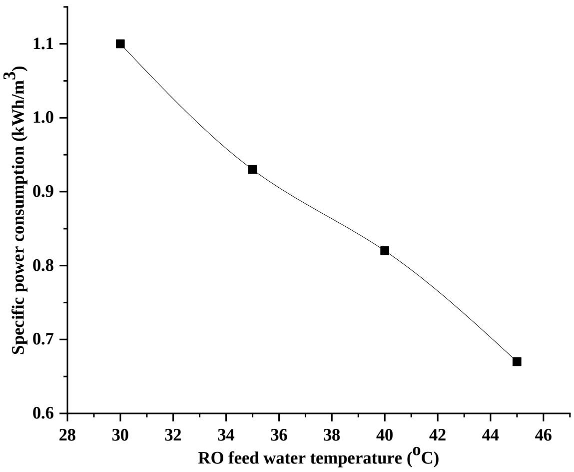


Fig. 5. RO Specific power consumption.

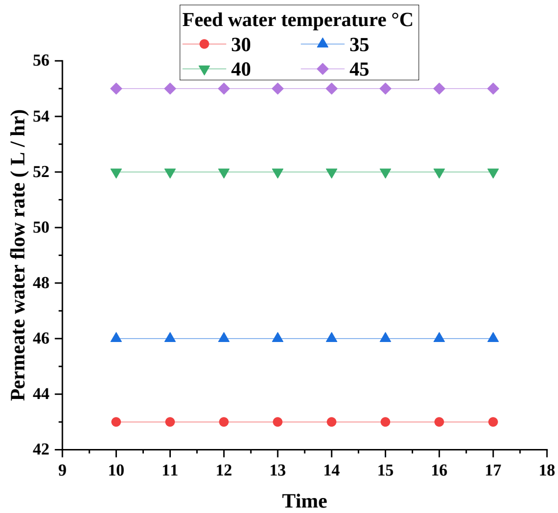


Fig. 6. RO productivity at different periods of time with various temperature ranges.

3.4 Hybrid system productivity

Fig. 7 shows the effect of changing $Twhi$ on the overall Hybrid system Using Humidification–Dehumidification Process integrated with RO unit and solar air heater, and maximum productivity is about 70 L/hr at 95 °C.

3.5 Hybrid system productivity Vs HDH unit Productivity

Fig. 8 shows the effect of using a hybrid system on increasing the productivity of the whole unit, the HDH unit productivity increases with $Twhi$ as well as RO unit productivity. So, the productivity of a hybrid system is more than HDH unit and RO unit individually. The maximum productivity is about 70 L/hr, which has increased by 550 percent difference from HDH unit productivity and 39 percent difference in RO unit at 95 C water temperature at humidifier inlet.

4. CONCLUSIONS

Solar humidification-dehumidification desalination technology combined with air, solar water heaters and a reserve osmosis unit powered by PV panels has been reviewed in this paper. It is found that the HDH desalination method will be a great option for freshwater because the amount of available drinking water is decreasing daily while drinking water demand is rising quickly. HDH is a low-temperature method when all the necessary thermal energy is produced by solar energy. The HDH units' capacity is comparable to that produced by traditional techniques and solar stills. And HDH productivity is about 10 L/hr. with C/H = 2. Moreover, HDH is characterized by simple operation and maintenance. Solar energy is obtained from PV panels which are effective and cheap, and it requires cooling to get its high performance. PV panels help in decreasing the cost per liter produced. RO unit also helps in increasing the productivity of all systems as it is fed with the hot brine outlet from the humidifier; this is that when the feed temperature increases by 1-degree, membrane productivity increases by 2-3% as water permeability increases. Also, increasing the temperature of feed water decreases the viscosity of water, thus decreasing the required driving pressure across the membrane; this, in turn, decreases the SPC of RO plant and makes RO desalination cost-effective. The hybrid system of PV-HDH-RO has the advantage of higher productivity reaching 70 L/hr, which has increased by 550 percentage difference than HDH unit productivity, and lower RO SPC reaches 0.8 KWh/m^3 , effectiveness about 77 %, using SAH with 5 m/s evaporator inlet air velocity with 7% increase compared to the system without using Solar air heater. Using solar air heater increases the ability of air to hold a huge amount of water vapor at the humidifier which increases the productivity as this increases the evaporation rate at humidifier and condensation rate at dehumidifier, but this can be achieved at high ambient temperature with high velocities of air through it, and this leads to an increase in power consumption.

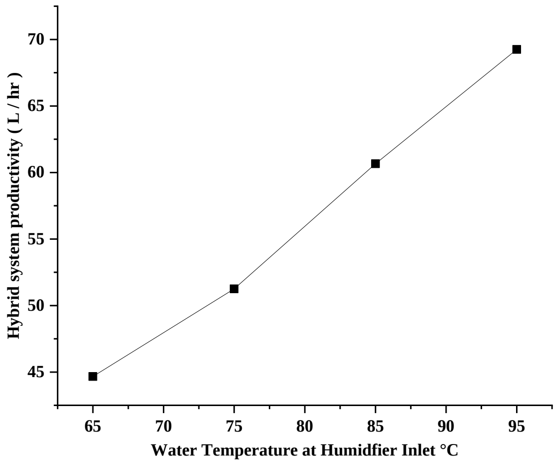


Fig. 7. Hybrid system Productivity.

The results of this work:

- The hybrid HDH-RO desalination mechanism is a great option for the production of freshwater with low power consumption.
- Using solar air heater increases the ability of air to hold a huge amount of water vapor at humidifier, which increases the productivity as this increases the evaporation rate at humidifier and condensation rate at dehumidifier, but this can be achieved at high ambient temperature with high velocities of air through it, and this leads to an increase in power.
- The accumulated productivity obtained from the Ro unit while operating a full day is 416 L/workday was obtained at an average 40℃ RO unit Feed Water (average Temperature of Evaporator Output).
- The accumulated productivity obtained from the HDH system while operating a full day is 56.6 L/ workday.
- The production of freshwater from the hybrid HDH-RO desalination unit is 472 L/day.

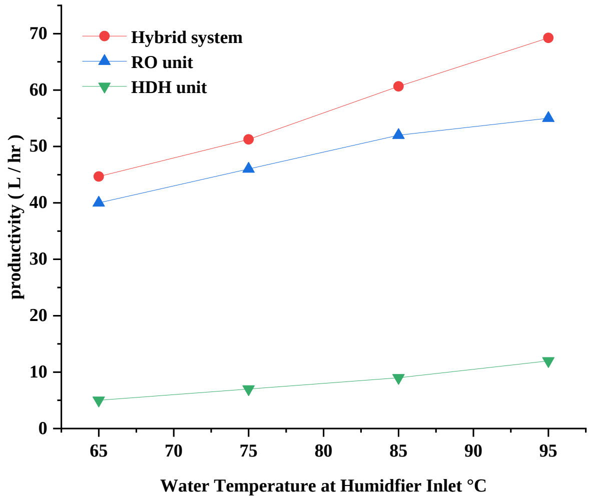


Fig. 8. Hybrid system productivity Vs HDH unit Productivity.

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