Simulation of the Solar Powered Humidification-Dehumidification Distillation Unit Performance Working Under Iraqi Conditions Using TRNSYS.

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Abstract: The problem of drinking water scarcity represents a significant threat for Middle East countries particularly in the desert regions of Iraq. Thus, there is still a need to study and investigate the techniques and methods of water desalination to be available for fresh water supply. Simulation model of the distillation unit based on the humidification – dehumidification processes (HDH) was developed using TRNSYS 16 software. A yearly performance of the HDH unit was done based on step of one hour under the conditions of Baghdad, Iraq, 33.3° N latitude, 44.14° N longitude and elevation of 34 m. Meteonorm V7.3 software was used to obtain the weather data for Baghdad city. The key variable of this work is the variation of the salty water flow rate through the parabolic trough collector. The effect of salty water flow rate on the fresh water productivity, properties of the air entering and leaving the humidifier and dehumidifier in addition to the temperature of the water leaving the collector were studied. The salty water flow rate considered in this study was 50, 55, 60 and 75 lit/hr. All the input variables have been studied experimentally in earlier work. The results showed that, increasing the water flow rate through the collector improves the HDH unit performance, the water production increases insignificantly when the water flow rate increases more than 60 lit/hr. The best volume flow rate of water through the collector around the year was 60 lit/hr, that gives a yearly productivity of fresh water 17650 lit/year which is equal to about 2011 lit/m².year. At a given salty water flow rate, the maximum productivity of fresh water is in conjugated with the lowest outer relative humidity.

Introduction
The increase in population growth in the world results in high demand for drinking water, which is expected to reach 6.900 billion m³ by 2030. The current freshwater supply is 4.200 billion m³, well below the projected demand for drinking water, and it is still no safe and drinking water available to 40% of the world's population [1]. There are many areas where power was too costly to run these processes of water desalination. At places far from the energy grid lines, fresh water is sometimes needed, requiring a local source of energy. Consequently, even countries with rich energy resources, such as the Arabian Gulf countries, have shown strong interest in desalination processes that often use renewable sources of energy [2]. Water shortages often occur in places with high solar radiation, which
typically coincides with maximum solar radiation during the hot summer months. Solar desalination could therefore be one of the most successful solar energy applications in most hot-climate countries with limited freshwater resources [2]. Most of the humidification and dehumidification desalination system investigations have been concerned with increasing productivity and efficiency after 1990 and several units were installed. These units were similar in base but differing in equipment type [3]. The problem of drinking water scarcity represents a significant threat for Middle East countries particularly in the desert regions of Iraq. Thus, there is still a need to study and investigate the techniques and methods of water desalination to be available for fresh water supply.

Zhani and Bacha (2010) [4], introduced an experimental investigation and economic analysis for the humidification-dehumidification (HDH) solar desalination system under various operating standards and meteorology. Experimental results showed that the outlet and inlet temperature of different component levels have the same patterns as solar radiation and the temperature of the outdoor air has a negligible effect on the HDH system thermal efficiency. Zhani et al. (2011) [5] investigated the HDH solar desalination unit based on mathematical modelling and experimental establishment of air and water solar collectors. The results showed that, the two-temperature model was better than one-temperature model to describe the real behavior of the water solar collector. In addition, it was found the developed mathematical models can accurately predict the trends of the water and air solar collectors thermal characteristics. The coupling of a two stage HDH system with a single stage absorption refrigeration cycle was introduced numerically by Chiranjeevi and Srinivas (2014)[6]. Two types of solar collector were used, namely; flat plate solar collectors and concentrating collectors. The productivity of water was increased after using the hot water after the cooling process as compared to without integration. The combined plant operation sequence was to preheat and humidify-dehumidify the first stage air. The results showed that, at 1 m³/s air volume flow rate the maximum productivity of the desalinated water was 670 L/h with a cooling capacity of 75 kW. Kabeel et al. (2014) [7] presented an experimental study based on the open water and closed air HDH desalination unit. Three configurations of forced circulation were investigated, namely, up, down and up-down. The effect of mass ratio of water to air (L/G), water temperature on the unit performance was studied. The results showed the best performance of the unit was when L/G equal to 2, and the air forced down. The maximum fresh water of 23.6 L/h was produced when the water temperature is 90 °C.

Zamen et al. (2014) [3] studied a two stage HDH system to produce fresh water from brackish water experimentally. The results proved that, the multi-stage process was most suitable option for improving important parameters such as productivity, specific energy consumption, investment cost and daily production per area of the solar collector. Stuber et al. (2015) [8] investigated experimentally the concentrated solar-powered desalination system of brackish groundwater, agricultural drainage and subsurface water sources. The work showed that the reduction in the heat energy consumption of was more than 49% when using the heat pump.

Elminshawy et al. (2015) [9] conducted an experimental and analytical study on productivity increases of a novel solar HDH unit. The effect of an induced outdoor air, water heaters, collector external reflector and ambient condition were studied to enhance the performance of HDH system. The study presented the great importance and advantages of using immersion water heaters, flat external reflector and induced atmospheric air that boosts the rate of evaporation and thus increases the HDH system's performance and fresh water productivity. Deniz et al. (2016) [10] conducted energy, exergy, economic and environmental analysis to study the HDH solar desalination unit. The experimental data for 6 days under actual and similar environmental conditions were used to analyze economic and environmental properties.

The economic and environmental impacts of HDH solar desalination system are determined in this study. Gang et al. (2016)[11] investigated experimentally and theoretically the multi-effect isothermal heat with tandem solar HDH unit. The investigation of a performance ratio of the unit for different mass flow rate of water and different water temperature was introduced. The results showed that the
increasing of the water and air mass flow rate affect the fresh water productivity positively. At heating temperature of 85 °C, the maximum production ratio of the system can reach up to about 2.65. The desalination system productivity per unit volume is calculated as 22 kg/m³.h. Theoretical and experimental study was introduced by Moumouh et al. (2016) [12] to investigate the fresh water productivity of a HDH desalination unit, the results was used to design the desalination system based on mass and energy balances as well as thermodynamic analysis of the cooling tower and condenser. The mathematical model predicted the heat exchanges very well and was able to determine the temperatures of the exit of each desalination unit's individual device. The model was also able to predict the rate of distilled water production with very reasonable accuracy. Sharshir et al. (2016) [13] investigated experimentally and theoretically the continuous solar still (CSS) with solar HDH unit. The HDH included an evacuated solar water collector. Closed-air and open-water cycles are regarded as the HDH process's operating principle. Different water flow rate were tested namely 1.5, 2, 2.5 and 3 L/min. The fresh water productivity of the solar still when it was feed by the exit warm water from HDH is found to be greater than that of the conventional solar still (CSS) by about 242 % and the increasing in the gain output ratio is 39 %. The maximum daily water production was 37 L/day by the continuous solar desalination unit. Behnam and Shafii (2016) [14] introduced experimental work to study the solar desalination system coupled with, evacuated tube collectors (ETC), air bubble column humidifier, and thermo siphon heat pipes. Various parameters that affected the system performance such as, flow rate of air to the humidifier, the initial water depth at the humidifier and pumping liquids (oil or water) in the space between heat pipes and ETC were investigated. The results showed that an increasing of daily fresh water of 6.275 kg/day.m² and 65%, in the unit and efficiency is due to the increasing of air flow rate. A multi-stage solar desalination process for HDH directly heated by a Fresnel lens of cylindrical concentrator type was investigated experimentally by Wu et al. (2017)[15]. The variation of the freshwater production rate and the absorber temperature with time were measured and compared with the theoretical model for the three-stage isothermal tandem heating mode. When the average solar radiation in the range of 867 W/m², the results indicated that, the maximum fresh water yielding was 3.4 kg/h and the system maximum gained output ratio was about and 2.1.
Ahmed et al. (2017) [16] studied experimentally the performance of the HDH unit using an aluminum packing of corrugated sheets in the humidifier. The effect of operating variables including, the temperature of the air and water temperature at the humidifier entrance, the humidifier water flow rate, mass of water to air ratio and the flow rate of cooling water into the dehumidifier on yield and performance were investigated. The work indicated that, the fresh water production increases with the increasing of the flow rate of water through the humidifier and dehumidifier. Also the productivity of fresh water increases with increasing of the inlet temperature. and the inlet cooling water temperature significantly enhanced the water production from 10 to 15 L/h when the inlet cooling temperature reduces from 28.5 to 17 °C. An experimental study on the HDH desalination system was presented by Rajaseenivasan and Srithar (2017)[17]. The system was coupled with a multipurpose solar collector (DPSC) to rise the temperature of water and air that required for the distillation process simultaneously. In this system, air flows over the absorber plate's top surface and the water flows through the riser pipes installed in the absorber plate's bottom side. The results indicated that the increasing of the air and water temperature and air, hot water and cold water flow rates affect positively the overall efficiency.
Zhang et al. (2018) [18] conducted an experimental investigation to study the performance of the HDH desalination system integrated with a heat pump. The effects of the temperature of inlet air, salty water temperature, and the volume flow rate of air flow on desalination system yield are investigated. The effect Seawater temperature on the system productivity is dominated. The highest fresh water productivity and the system cost were 22.26 kg/h and about 0.051 USD/kg respectively. Mahmoud et al., (2018) [19]developed a new design for a solar desalination unit. The system was based on hybrid
solar still/two effects humidification-dehumidification and powered by solar photovoltaic panels. The conservation of mass and energy equations were used for modelling an HDH unit; the model results were validated using an experimental and numerical data. Xu et al. (2019) [20] proposed a new solar-assisted heat pump with an internal heat recovery HDH desalination system. The capability of recovering heat in the enhancement of the system performance and gain the best key variables were studied experimentally. Results showed that, the estimated fresh water cost for the two-stage desalination units reduces by 17.36%. The gained-output-ratio and the fresh water productivity for the two-stage system were increased by 55.64% and 15.51, respectively compared with that for those of the single-stage.

A direct contact dehumidifiers with a four stages HDH solar desalination unit was proposed and studied experimentally by Zhao et al. (2019) [21]. The seawater temperature, quantity and the air volume flow rate all are affected the desalinated water productivity, the GR and the economic considerations are analyzed in this study. The system water production per unit volume 34.1 kg/m².h and water yield cost $3.86 USA/ ton when a 42 m² solar collectors is connected with the unit is coupled with as compared with that of the conventional systems.

In the current work the HDH unit is modelling using TRNSYS 16 software. A yearly modelling of the HDH unit is done within a step of one hour under the conditions of Iraq – Baghdad, 33.3 ° N latitude, 44.14° N longitude and elevation of 34 m. The effect of salty water flow rate and the configuration of air circuit on the HDH performance are studied. Meteonorm V7.3 software was used to obtain the weather data for Baghdad, Iraq.

1. Distillation system description and modelling

The desalination process in this work depends basically on the evaporation of salty water within a stream of air as shown in figure 1. For that purpose, a humidification – dehumidification (HDH) unit is proposed, the HDH unit consists of three main parts, namely; six parabolic trough solar collectors (PTSC) of total aperture area of 8.776 m², the humidifier and the dehumidifier. Many accessories are used, such as pumps and fan to pump the water and air. The salty water passes through copper tubes is heated by direct solar radiation that reflected by the PTSC reflector and concentrated on the copper tube that surrounded by a glass cover. The water leaving the last PTSC which is at relatively high temperature is sprayed into small droplets on the humidifier packing. The moisture content of the air leaving the humidifier increases significantly, due to the direct contact between water droplets and the blowing air from the bottom of the humidifier. Moist air coming out of the humidifier passes through the de-humidifier, where a part of moisture content of the air condenses as fresh water.

The HDH unit is modelling using TRNSYS 16 software. A yearly modelling of the HDH unit is done within in step of one hour under the conditions of Iraq – Baghdad, 33.3 ° N latitude, 44.14° N longitude and elevation of 34 m. Meteonorm V7.3 software was used to obtain the weather data for Baghdad, Iraq. Meteonorm software relies on the average hourly solar radiation for the period extended from the year 1991 to the year 2010, while the period from 2000 to 2009 is used for finding the average hourly ambient temperatures.

The key variable of this work is the variation of the salty water mass flow through the PTSC. The effect of salty water mass flow on the fresh water productivity, the properties of the air entering and leaving the humidifier and dehumidifier as well as the temperature of the water leaving the collector are studied. The salty water mass flow rate considered for study is 50, 55, 60 and 75 lit/hr. All the input variables have been studied experimentally in earlier work [22]. Figure 2 shows the HDH unit model using TRNSYS software.
Figure 1. The humidification-dehumidification distillation unit

Figure 2. TRNSYS simulation of the HDH unit
2. Results and discussions:
The weather data for two selected months of the year for Baghdad, Iraq is shown in figure 3, the Baghdad weather is characterized by a dry climate and high relative humidity in the winter. The effect of salty water volume flow rate to the PTSC on the fresh water productivity is shown in Figure 4, from the figure it can be seen that the fresh water productivity increases sharply as the salty water flow rate increases from 50 to 60 lit/hr, while the trend of the fresh water productivity curve between 60 and 72 lit/hr becomes flat, this means that the effect of increasing water volume flow rate to the PTSC on the productivity is insignificant, and may be uneconomic, since the pumps power and salty water consumption are increased with the increasing of salty water flow volume rate. Thus, the salty water flow rate of 60 lit/hr is considered as the best flow rate in this work.

Figure 3. Weather data of Baghdad, Iraq for January and July 2020.

Figure 4. The variation of fresh water productivity with salty water volume flow rate
The variation of daily production of fresh water for each month of the year is shown in Figure 5. As expected, the maximum water productivity is for summer season where the day time hours are long compared with that for winter. The maximum accumulated water productivity was at July, while the minimum productivity was at January as shown in the Figure 6. The hourly water production for two selected days namely; 1st January and 1st July is shown in Figure 7; the maximum water productivity is about 3.75 lit/hr at 1st July, while it is about 2.1 lit/hr for 1st January. The figure shows a clear shifting between the times of maximum productivity for summer and winter; the maximum productivity is at 12 in winter while it is shifted to hour 16 in the summer. From the figure it can be concluded that the maximum productivity in conjugated with the lowest outer relative humidity. As it is well known that as the relative humidity reduces the ability of air to carry water vapour increases.

![Figure 5. Variation of the daily production of fresh water for each month of the year](image-url)
Figure 5 shows the effect of inlet and outlet salty water temperatures to PTSC on the yearly fresh water productivity. It can be seen from the figure that as the outlet water temperature from PTSC increases the water productivity increases; this is due to the ability of water to evaporate increases with the increasing of water temperature. Figure 5 shows as well the effect of outlet water temperature from PTSC on the fresh water productivity, it can be observed that the maximum outlet water temperature was at July (at 5000 hr). Therefore, when the temperature of the water entering the humidifier increases, it becomes easy to evaporate the water when it contacts with the air stream. This makes the air more saturated with water vapor and thus increases the productivity of fresh water.

The processes of the air though humidifier and humidifier is shown in figure 9, five selected daytime hours at 1 July, 2020 are considered when the salty water flow rate is 60 lit/hr. It can be seen from the figure that, at early daytime namely 9.00 hr, the humidification process is weak, and less water vapour is carried by the air, this is due to the relatively low water temperature. At 11hr the increasing in the
inlet water temperature to the humidifier reflected positively on the leaving air condition. The figure shows that, the moisture content of the leaving air increases significantly due to the increasing of salty water temperature entering the humidifier and also the amount of extracted vapour in the humidifier increases.

**Figure 7.** The hourly water productivity of fresh water

**Figure 8.** The effect of salty water temperature on the water productivity
The peak moisture content of leaving air is at hour 13, where the salty water entering temperature is at maximum. After time 13 hr the humidification – dehumidification processes begin to recede, as indicated at time 15 and 17, and this affects negatively on production of fresh water.

Figure 10 shows a comparison between the current work and Juarez-Trujillo et al., 2011 [23], it can be seen from the figure that the trends of both HDH units are the same, but the productivity of Juarez-Trujillo et al is more than the productivity of the current work by about 14 to 20%, since the previous work uses the solar radiation to heat up a storage tank for the salty water.
3. Conclusion

From the obtained results it can be concluded that

1. Increasing the water flow rate through the collector improves the HDH unit performance, the water production increases insignificantly when the water flow rate increases more than 60 lit/hr.
2. The best volume flow rate of water through the collector around the year was 60 lit/hr, that gives a yearly productivity of fresh water 17650 lit/year which is equal to about 2011 lit/m².year
3. At a given salty water flow rate, the maximum productivity of fresh water is in conjugated with the lowest outer relative humidity.

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