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# Experimental investigation on a solar assisted heat pump desalination system with humidification-dehumidification

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ABSTRACT

In this study, a novel solar assisted heat pump desalination unit for drinkable water is proposed and investigated experimentally. The experimental unit, which mainly consists of compressor, condenser, evaporator, packing humidifier, centrifugal fan, precooler and seawater tank, et al., was designed and fabricated. The effects of the cooling seawater, the process air, the mixture ratio (the ratio of the remaining seawater flow rate from the humidifier to total hot seawater flow rate) and the thermodynamic cycle on the system performance were investigated. The experimental results show that there exists the optimal flow rate of the process air corresponding to the studied unit under given conditions. The maximum productivity of the unit is 12.38 kg/(kWh) when the flow rate of cooling seawater and process air are 0.3 $m^3$/h and 450 $m^3$/h respectively, which is higher than those of other solar assisted heat pump desalination units in previous works. A big mixture ratio is preferred for improving the system performance. A further performance comparison between open cycle and closed cycle indicates that the yield of the open cycle increases with the increase of the cooling seawater flow rate, which is opposite to that of the closed cycle.

## 1. Introduction

Fresh water is an indispensable part in our lives, and its storage has been highly concerned by people [1,2]. With the continuous population growth, seawater desalination technology has been used as an effective method to reduce the pressure of fresh water supply due to the increasing demand for drinkable water and the global shrinkage of fresh water resources. Both large-scale reverse osmosis (RO) and conventional thermal process desalination have been performed in many regions for drinkable water. However, it is still confronted with great challenge to provide drinkable water for small areas such as islands or ships. Therefore, the methods of RO and conventional thermal process desalination may be unsuitable for small-scale seawater desalination applications because of limited space or energy supply [3]. In this case, humidification-dehumidification (HDH) for desalination has been confirmed to be a potential method for solving the problems of the small-scale water supply.

Up to now, HDH process has been successfully performed to solar desalination depending on the low-temperature heat source, clean and renewable energy, which can be classified into two generic groups according to the heating medium: water-heated and process-air-heated [4]. Some works [5–8] on the form of the water-heated desalination with HDH have been studied, and the results showed that the performance of the system is more sensitive to the change of the water flow rate. Contrary to the process of water-heated, the process air will be heated by solar collectors or provided by subsidiary factories [9–13], which provides power for the evaporation of fresh water in the humidifier. Meanwhile, the performance of other forms of solar HDH desalination systems has been studied both experimentally and theoretically [14–17]. However, the performance of the above systems is very susceptible to the solar irradiation; consequently, the stable demand for fresh water will not be guaranteed. In other words, other heat sources are still needed when the solar irradiation is weak or not available. In view of the working principle of the HDH process, both heat pump (HP) evaporator and condenser can play a positive role in the process of HDH. In this context, solar assisted heat pump cannot only make up for the shortcoming that the seawater temperature cannot be increased quickly by the solar energy, but can also further improve the seawater temperature.

In recent years, some studies on solar assisted heat pump desalination (SAHPD) have been reported. Actually, these works chose to focus on the different combination types of solar energy and heat pump to enhance the system performance. A novel solar evaporator-collector desalination system was presented by M.N.A. Hawlader et al. [18], and

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the effects of different operating and meteorological conditions of Singapore on the system performance were studied. The GOR of the unit is about 0.77–1.15. Z.M. Amin and Hawlader [19] investigated a direct expansion solar assisted heat pump desalination system. The effects of solar irradiation and compressor speed on the system performance were studied. The results showed that the average COP is 8.0 and the highest fresh water production is 1.38 kg/h. P.H. Gao et al. [20] investigated mathematically the performance of a new heat pump desalination system with HDH. This unit utilized the heat and mass transfer between hot process air and seawater to drive the humidification of the process air, the maximum fresh water production is about 5.15 L/h. The maximum productivity of the unit is about 11.44 kg/(kWh) when the power consumption (only compressor) is 450 W. There are also some studies concentrating on the combination of solar energy desalination with HDH and air conditioning system to implement the diversification of function. S.A. Nada et al. [21] investigated experimentally on the performance of a solar integrated system for air conditioning and HDH water desalination in hot and humid regions, and the parametrical study for the unit were analyzed under different operating conditions. The system productivity is about 600 kJ/kg when the inlet air temperature and humidity are 30 °C and 24 g/kg, respectively, which is equal to about 6 kg/(kWh) (only compressor). A. Fouda et al. [22] presented an integrated A/C and HDH water desalination system assisted by solar energy. Transient analysis and parametrical study for system performance under different operating conditions were carried out theoretically. The system was also compared with a basic system under the same conditions. The maximum fresh water production is about 27 kg/h when the total power consumption is about 7.5 kW, which is also converted to 3.6 kg/(kWh). Halima et al. [23] presented a combination of solar still and a compression heat pump, and the mathematical model of the system was established by using the method of mass and heat balance. The maximum daily production of the solar still reached 13.5 kg/m$^2$. And the productivity of a combination of heat pump and conventional solar still is 75 % greater than that of the single conventional solar still. However, the aforementioned SAHPD unit had drawbacks of poor productivity compared with RO and conventional thermal process. Narayan et al. [24], Pinto [25] and Hallaj [26] reviewed the potential of solar HDH and the desalination economic feasibility. For RO technology, at a worldwide level, the water cost is about 0.98 \$/m$^3$ (capacity 6000 m$^3$/d). Even though it is far below the water cost (3–15 \$/m$^3$) [4] of the HDH process desalination system, the biggest advantage for HDH process is that the water produced by HDH process is distilled water.

The main objective of this paper is to study the performance of the unit, which is investigated under different operating conditions. It has been noted from the published works that many researchers have investigated the different application forms of solar assisted heat pump desalination system. However, the hybrid solar assisted heat pump with HDH process have not been reported systematically before, especially the heat and mass recovery in both seawater cycle and process air cycle. In this paper, a novel solar assisted heat pump desalination system with HDH process was designed, and the experimental setup was built. Compared with the previous published desalination units, this rig can not only realize the “waste heat recovery” in both seawater cycle and process air cycle, but also maintain the basic fresh water production when the auxiliary heat sources are not available. Moreover, the produced fresh water is drinkable.

## 2. Theory

The schematic diagram of the SAHPD rig is shown in Fig. 1. The system consists of three main loops: the heat pump loop provides both heat source (condenser) and cold source (evaporator). The seawater loop can be divided into two sub-cycles, the hot seawater sub-cycle and the cooling seawater sub-cycle. The hot seawater sub-cycle is utilized for heating seawater by condenser and solar collector, and the cooling seawater sub-cycle is used to cool the process air to the dew point temperature for producing fresh water and providing fresh seawater to the hot seawater loop. The process air loop, including open cycle and closed cycle, acts as the carrier for humidification and dehumidification. In this study, the open cycle means that there is no moisture and heat recovery when the process air flows out of the evaporator. In contrary, the closed cycle means that both moisture and heat will be reused when the process air flows out of the evaporator. The closed cycle is taken as an example to introduce the working principle of the unit.

Hot seawater is uniformly sprayed on the humidifier by a sprayer to form the liquid membrane on its surface. The process air flows through the humidifier by a centrifugal fan which is connected by a converter to control the process air flow rate. The process air will become hot and humid in a nearly saturated state because of heat and mass transfer in the humidifier. Then it passes through the precooler and evaporator where it is cooled to the temperature below its dew point. The water vapor is condensed to fresh water as a consequence of decreasing the temperature and humidity of the process air. Finally, the process air will be refed to the humidifier.

The condensation latent heat of the water vapor passing through the precooler is utilized to preheat the cold seawater. The preheated seawater out of the precooler is departed into two parts, one part is used as supplemental water for the seawater tank, and the other is discharged directly from the unit. At last, the rest of seawater in the humidifier, which has not yet been evaporated completely, still remains higher temperature and is collected at the strong hot seawater basin. In the hot seawater basin, a drainage pipe is used to ensure that the concentration of hot seawater will not progressively increase.

In addition, the states of process air can be described by the psychrometric diagram which is shown in Fig. 2.

It can be found that the thermodynamic behavior of the process air for both open cycle and closed cycle can be understood better based on Fig. 2. The solid line flow path of the process air in the SAHP desalination system is the closed cycle, including $T_{b3}$-$T_{b1}$-$T_{b1,dew}$-$T_{b2}$-$T_{b3}$. $T_{b3}$-$T_{b1}$ is the procedure of heating and humidifying the process air in the humidifier, which can also be regarded as a combination of $T_{b3}$-$T_3$ (sensible heating) and $T_3$-$T_{b1}$ (adiabatically humidifying). When the process air passes through the precooler, the dry-bulb temperature of state point $T_{b1}$ will decrease firstly to the state point $T_{b1,dew}$ (the dew point corresponding to state point $T_{b1}$). $T_{b1,dew}$-$T_{b2}$ and $T_{b2}$-$T_{b3}$ are the condensation processes of the process air through the precooler and evaporator, respectively. In the psychrometric chart, the condensation temperature range of $T_{b2}$-$T_{b3}$ is lower than that of $T_{b1,dew}$-$T_{b2}$. It means that compared with other HDH processes using cold seawater as working fluid, the heat pump evaporator is preferred to produce more fresh water because of the lower cooling temperature, especially when the process air temperature is lower. Meanwhile, the flow path of process air can also be selected as $T_{b3}$-$\overline{T}_{b1}$-$T_{b2}$-$T_{b3}$ when the solar irradiation is not available, which is a heat pump desalination with HDH. Here, the state point $T_{b2}$ is the dew point corresponding to state point $\overline{T}_{b1}$.

The short dash dot line flow path, $T'_a$-$T'_{b1}$-$T'_{b1,dew}$-$T'_{b2}$-$T'_{b3}$, is the open cycle of the process air in the SAHP desalination system. Different from the closed cycle, the inlet air of the humidifier is obtained from the environment rather than the outlet of the evaporator. It is indicated that the system performance of the open cycle will be affected strongly by the environment temperature. For the open cycle, both the temperature ($T'_a$) and humidity of the ambient air are lower than those of the process air from the evaporator. Without moisture and heat recovery, the fresh water production is decreased compared with the closed cycle. Because the whole process air temperature of the open cycle is lower than that of the closed cycle, it will further lead to a reduction of the temperature difference between process air and precooler/evaporator.

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