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Water Desalination Using a New Humidification-Dehumidification (HDH) Technology

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Abstract: The high global population rate has driven the demand for fresh water to increase rapidly. However, the scarcity of fresh water is creating an escalating pressure on the global community to find other alternative water resources such as wastewater reuse and desalination. Desalination is an effective technique for providing fresh water supply. However, most of current desalination technologies consume large amount of energy. Hence, the cost of fresh water produced is strongly depends on the cost of energy used in the desalination processes. For this purpose, a new water desalination system has been developed through theintegration of a thermal pump system, wetting technology and dehumidification. Power consumption in water desalination has been reduced by controlling water and air flow rates in the new system. The results showed that 1.71 kg /h of fresh water could be produced using only 0.726 kWh which is an important achievement in reducing the energy consumed in the water desalination in small capacity units.

1 Introduction

Global demand for water is increasing rapidly due to the significant soaring of the rate of population growth. However, the available freshwater is already a scarce resource and does not satisfy the global increasing need of pure water. Many think that fresh water shortages will cause the next great global crisis. Furthermore, recent research show that around 25% of the world population does not have an adequate supply of fresh water, both in terms quality and quantity[1]. Therefore, finding alternative resources for fresh water suitable of human uses and irrigation is one of the most important research challenges which scientists are facing today.

The total amount of global water reserves is about 1.4 billion cubic kilometers. Oceans constitute about 97.5% of the total amount, and the remaining is only 2.5% fresh water. This fresh water presents in the atmosphere, polar ice, and ground water which means that only about 0.014% is directly available to human beings and other organisms [2,3]. Therefore, development of new clean water sources is imperative. Desalination of sea and/or brackish water is an important alternative, since the only inexhaustible source of water is the ocean. However, energy required by the desalination processes is an important challenge in this research area. Desalination processes require significant amount of energy. It is estimated that the production of 1 million m3/day requires 10 million tons of oil per year [4]. Due to the high cost of conventional energy sources, which are also environmentally harmful.

The current fresh water available cannot cover requirements of the industrial and agricultural development and the exponential growth of the population. Therefore, Desalination has become necessary for several reasons. The most pressing reasons are:

1- The increasing demand for fresh water due to population growth, especially in dry climates and other similar geographical regions, with limited access to high-quality, low-salinity water.
2- The increasing investment in capital due to the development of industry, agriculture and urbanization, which requires the availability of high-quality water.

Desalination is a good technique to provide technically freshwater supplies, which are used in various fields. Desalination has been used regularly over the past 50 years in different regions of the world. There are four factors that have the greatest effect on the cost of desalination per unit of fresh water produced. These factors are; the level of salinity of feed water, energy consumption, the required quality of produced water and finally the cost of construction and unit size. Energy consumption requirements are considered as a major contributor to the relative high cost of desalinated water. Figure 1 shows cost breakdown of desalinated water.

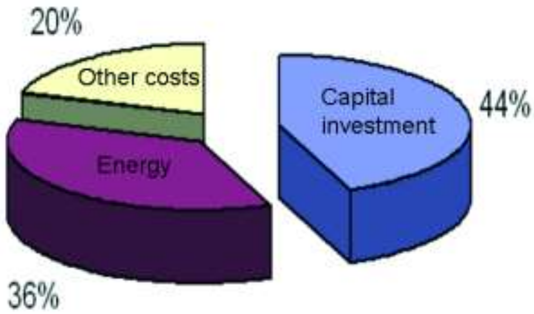

Figure 1: Cost breakdown of desalinated water, adopted from Abdel Gawad [3]

2 Desalination technologies

Currently there are many methods of desalination, which can be categorized into two different processes, mainly thermal processes and membrane processes [5]. In thermal processes, we havemulti-effect distillation, multi-stage flash distillation, solar evaporation, freezing and vapor compression distillation. Reverse osmosis and electro-dialysis fall under membrane desalination processes as show in figure 2.

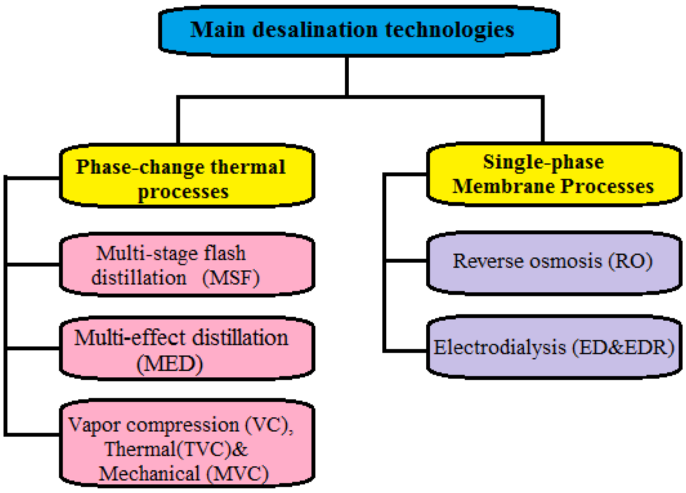

Figure 2: Desalination technologies.

All technologies mentioned above, are good for the desalination of salt water. However, these are often not suitable for remote areas or in use domestic due to the large infrastructure associated with them. Hence, the small-capacity desalination units are an effective solution for the provision of fresh water in remote areas and home use. The development of alternative, compact small-capacity desalination units is imperative for the populations of such areas[2].

The desalination by heat pump can be a viable way of producing fresh water from brackish water for domestic uses. Conventional basin solar stills with a relatively large footprint and humidification-dehumidification solar desalination plants are examples of such simple technologies. Extensive research using of the heat pump technologies have been carried out by many researchers aiming to create an affordable and feasible way to produce fresh water[3].

Mohammad et al.[4]. Evaluated multi-stage technique to improve the efficiency of a solar powered (HDH) process through simulation model. The results show that multi-stage (HDH) process has good potential in process improvement.Reza et al.[6]. Developed a theoretical model to optimize a novel (HDH) desalination system. The results show that the production rate was particularly influenced by the inlet water temperature, the incident radiation and flow rate of the water.Hitesh et al.[7]. Examined the effect of coupling an evacuated heat pipe collector on the solar still. It was found that coupling increases the productivity by 32%.

Reza Enayatollahi.[8]. Studied the desalinating of the saline water using the (HDH) method. An open air open water cycle was selected, whilst forced air circulation was applied. The energy required for heating the air was provided by solar radiation whilst the energy required for heating the water was provided by electricity. The maximum production of potable water was achieved to be 1.55 L/day.m^2.

Hawlader et al.[9].Designed and constructed a novel system of solar assisted heat pump desalination. A series of experiments has been conducted under different operating conditions. The COP obtained from the experiments ranges from 0.77 to 1.15.Mark G. et al.[10]. Investigated thetheoretical model of an affordable small-capacity solar desalination unit using the (HDH) process coupled with an evacuated tube solar collector with an area of about 2m^2. The results proved that the performance of the system could be improved to produce a considerably high amount of fresh water, namely up to 17.5 liter/ day m^2.

Tobias B. Tjandra.(2007)[11], studied the performance of a desalination system with a solar assisted heat pump at the National University of Singapore. The experimental results showed that the system could reach a Coefficient of Performance (COP) of 10.The water production rate is generally close to 1L/hr for the system . In terms of water production, the energy consumed was 0.8kWh for each kg of fresh water produced.

It is clear from the literature review above that the desalination process used humidification-dehumidification with solar energy technology has limited capabilities. The work of these units was limited only in daylight sunny hours. Moreover, a significant amount of energy is consumed for the desalination and the size of the units used in desalination was very large compared with the amount of fresh water produced in these units. Therefore, the desalination process by using heat pump represents a potential alternative to be used in desalination systems. Thus, an economical and effective new desalination technology has been developed. The desalination unit based on humidification-dehumidification technique and assisted by the heat pump as a source of water evaporation and condensation have been designed and sat up.

3 Humidification-Dehumidification(HDH) Desalination

Desalination using Humidification-Dehumidification technology (HDH) is an efficient and simple technique. This technology simulates the water cycle of nature and it ability to work with solar heating or any other heat source. The philosophy behind the HDH desalination method is the rain cycle in the nature[12]. Typical HDH units are designed based on the same principles of the water cycle in nature.

Almost all of humidification-dehumidification desalination structures, have three segments; a heater, an evaporator and a condenser. Depending on the heating technique applied for the desalination unit, the heating process can be used for water or air, or both of them. Depends on the accessibility of different source of energies, the heating source might be; solar, geothermal, electric heaters or even direct burning of fossil fuels. Different types of evaporators and condensers can be used based on the effectiveness and area necessary for the system.

based on the heating process, HDH desalination systems can be categorized in three groups; water heated, air heated and water and air heated systems. HDH systems can be also classified based on the cycle of streams of water and air, whether it is an open or closed cycle [13]. Therefore, they are classified into four groups; open air-open water, open air-closed water, closed air-open water and closed air-closed water. Furthermore, desalination system can be classified by the method using for air circulation into two categories; forced and natural circulation. Combination of these three methods of classification yields the diagram illustrated in Figure 3.

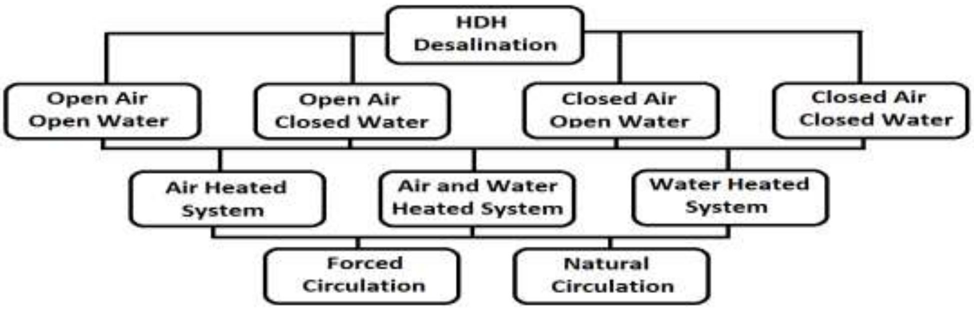

Figure 3: Classifications of HDH desalination [14]

4 Description of the system

The present system has been mainly conceived on two ideas of air humidification and dehumidification process using the heat pump as a heating and cooling sources in the system. Fig.4 illustrates a schematic of the desalination unit .The desalination unit consists from a vertical tower containing the dehumidification chamber in the upper part and the humidification chamber in the lower part. The humidification chamber contains the water distribution tray , packing material and the condenser heat pump. The dehumidification chamber contains an evaporator heat pump and a distillate collector tank. The system also consists from a water pump, a feed water tank and an air blower.

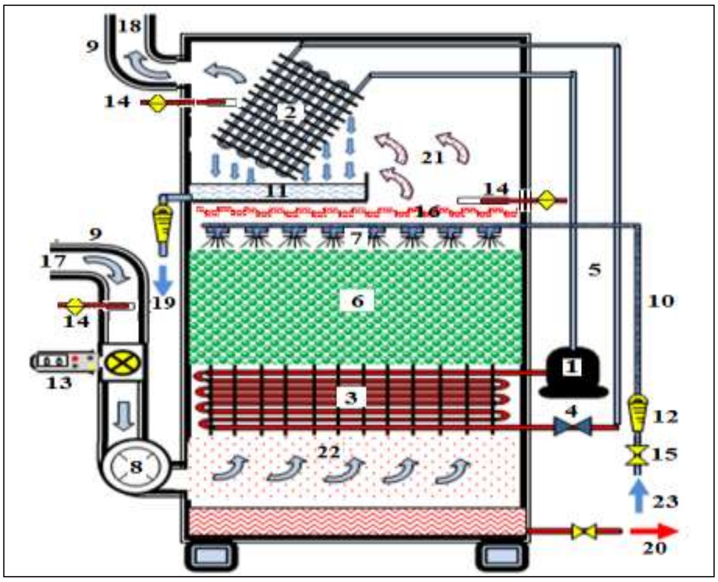

Figure 4. illustrates a schematic of the desalination unit. (1-Compressor, 2-Evaporator, 3-Condenser 4-Capillary tube, 5-Heat pump pipes, 6-Packing material, 7-Water distributor, 8-Air blower, 9- Air duct, 10-Water pipes,11-Distillate collector, 12-Rotameter,13-Anemometer, 14-Thermometer and Hygrometer,15-Water valve, 16-Droplet eliminator, 17-Inlet air, 18- Out let air,19-Fresh water ,20- Brine, 2-Humid air ,22- Water droplets, 23- Feed water).

5 The working principle of the new system

The present system has been mainly conceived on two ideas of air humidification and dehumidification process using the heat pump as a cooling and heating sources in the system. Fig.4 illustrates a schematic of the desalination. The desalination unit consists from a vertical tower containing the dehumidification chamber in the upper part and the humidification chamber in the lower part. The humidification chamber contains the water distribution tray , packing material and the condenser heat pump. The dehumidification chamber contains an evaporator heat pump and a distillate collector tank. The system also consists from a water pump, a feed water tank and an air blower. The HPHDH system consists of two loops, one for water and the other for air with an interface of the humidification chamber. In the water loop, the saline water is delivered from the feed tank using a submersible water pump. The saline water is sprayed at the top of the humidification chamber. The water falls down to the bottom of the humidification chamber where it is pumped again by another submersible water pump. In the air loop, air is drawn using a centrifugal blower (installed at inlet of the dehumidification chamber). The air flows through the humidification chamber where the evaporated water is carried to the dehumidification chamber. At the dehumidification chamber, the air is cooled and dehumidified then recycled again.

The water desalination is achieved by the HDH- HP technique, which requires a heating unit for producing vapor and a cooling unit for condensation of vapor. Therefore, the new system integrates the heat pump and the humidification dehumidification system. The heating unit is in the condenser side of the heat pump and the cooling unit is in the evaporator side of the heat pump.

In order to performance evaluation of a new system for water desalination different combinations of input parameters were studied. Although there are several factors that affect the efficiency of the unit, the parameters chosen to vary in this experimental work are the most crucial and most easily controlled and adjusted which the varying parameters include mass flow rates of the air and water[13].

6 Performance evaluation of a new system

Several tests will be performed to determine the effects of different variables and the performance of the system is evaluated by the set parameters of the system which are carefully chosen to perform a detailed system analysis. Where there are several ways to characterize performance in desalination systems the performance parameters that are chosen and studied to evaluate the system are; The productivity, the gain output ratio, power consumed in the desalination process.

6.1 The Gain Output Ratio (GOR)

The GOR which is defined as the amount of the energy consumed in the production of the fresh water to the energy input by external energy source is always used as a measure of the overall performance of the humidification and dehumidification systems[14]

$$GOR = \frac{m_{\text{fresh}} \cdot h_{fg}}{Q_{in}} \quad .... \quad (1)$$

6.2 Power Consumed in the Desalination Process

Defined as the total amount of energy required to produce one kilogram of fresh water from brackish water, which represents the economic feasibility of the process of desalination water. It is measured by the units (kJ/kg) and can be calculated using the following equations:

$$P_{Cons} = \frac{P_{Tinput}}{m_{fresh}} \quad .... \quad (2)$$

6.3 Refrigeration unit coefficient of performance.

The COP is a dimensionless value defined as the energy transferred for cooling by the refrigeration unit (in watts) divided by the energy consumed by compressor of heat pump (in watts). COP represents the efficiency of refrigeration unit coefficient a heat pump [15]. are calculated from the following equation:

$$COP = \frac{Q_{Evaporator}}{W_{Comp}} \quad .... \quad (3)$$

7 Results and discussion

In OAOW system, air and water are not recycled between the humidifier and the dehumidification chamber (evaporator) in a closed loop. Instead, they are drained directly after exit from the humidifier and evaporator, as shown in Figure 4.

7.1 Effect of water and air flow rates on productivity

Figure 5 shows the effect of feed water and air flow rates on fresh water productivity. It can be noticed that the productivity directly proportional with the increase of flow rates of feed water and air until reaching the maximum productivity value of 1.14 kg/hr. After that, the productivity starts to decrease with increasing of feed water and air flow rates. The reason of the increase in the productivity in the first step comes from the increasing of feed water flow rate. This leads to enhanced distribution of water within the humidifier which produces large surface area for evaporation and it leads to an increase of mass transfer coefficient which results in increasing of evaporation rate. As a results of increasing evaporation rate, moisture content of the air increases. Therefore, the fresh water productivity increases in this step. However, in the second step, the increase of feed water flow rate leads to a large decrease in the condenser temperature which also causes a decrease in heating rate of both conducted air and water within the humidifier. This cause the evaporation rate to decrease which results in decreasing of productivity.

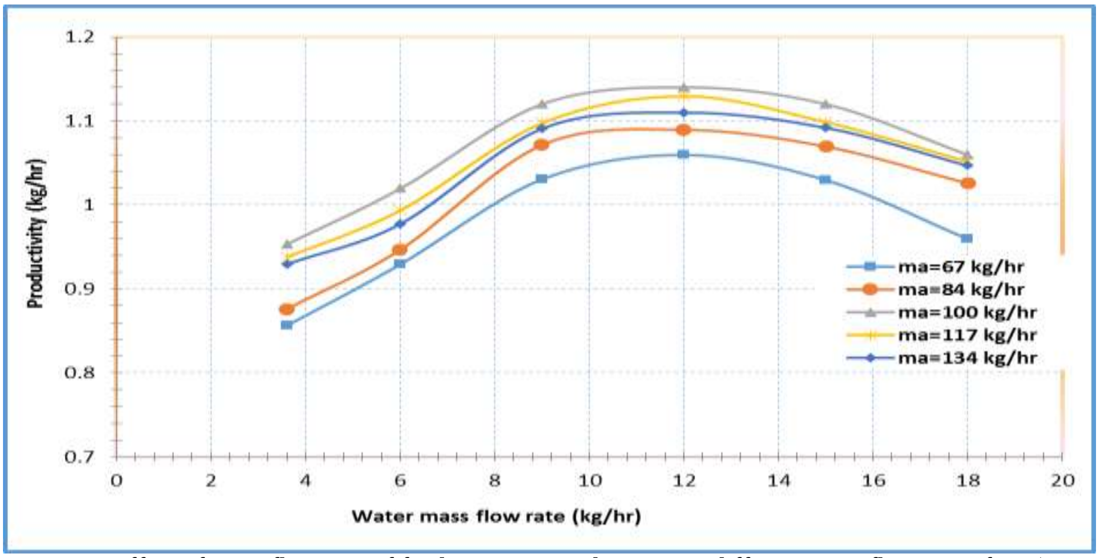

Figure 5: Effect of mass flow rate of feed water on productivity at different mass flow rate of air (OAOW).

7.2 Effect of water and air flow rates on the GOR

The gained output ratio (GOR) changes proportionally with the productivity and inversely with the consumed power. The increase of GOR represents the increase of the unit efficiency in the desalination process. Therefore, the value of GOR is influenced by operating conditions of the unit and the energy consumed during operation of the unit. Figure 6 show the effect of the mass flow rate of the feed water on GOR at different air flow rates. It is seen that the increase of GOR continues with increasing of feed water flow rate until reaching the water flow rate of 15 kg/hr where the GOR reaches maximum values at different air flow rates. GOR then starts to decrease with the increase of feed water flow rate. In the first stage, the increase of water flow rate leads to an increase of productivity as explained previously. The condenser cooling rate also increases which leads to a decrease in pressure of the refrigerant inside the condenser and thus, the energy consumed by the compressor decreases. Consequently, GOR increases at this stage. On the other hand, further increase of water flow rate leads to the productivity decrease and an increase of consumed power by the water pump. As a result, GOR starts to decrease with the increase of water flow rate at this stage.

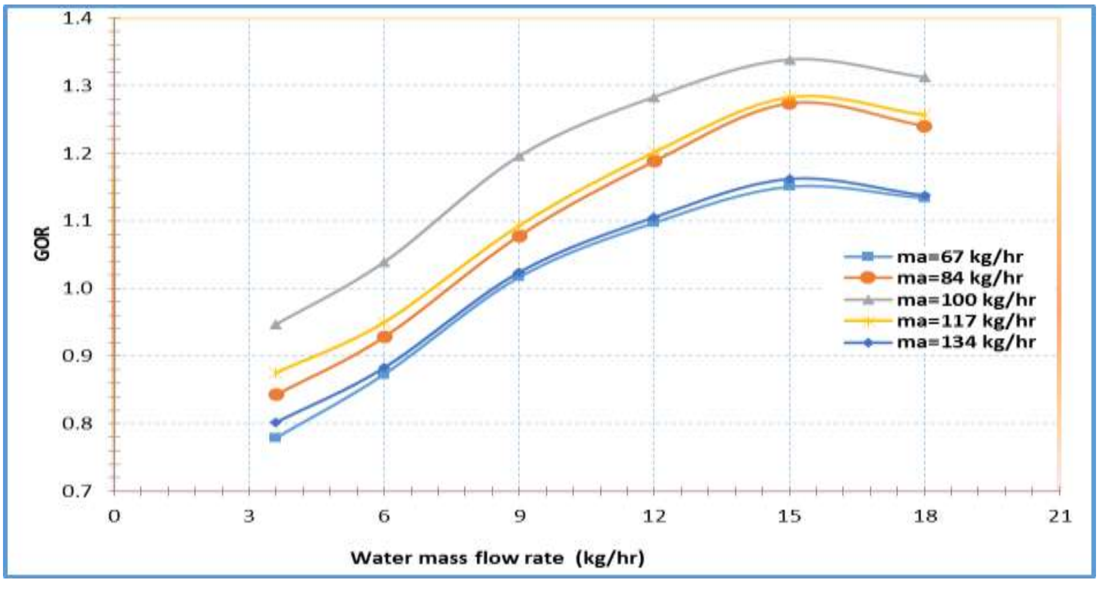

Figure 6: Effect of mass flow rate of feed water on the gained output ratio(GOR) at different mass flow rate of air (OAOW).

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The effect of air and water mass flow rates on GOR are almost the same. Figure 7 describes the effect of air mass flow rate on GOR at constant temperature, 25ºC, and relative humidity, 55%, at different water mass flow rates. It can be noticed that GOR increases with the increase of air mass flow rate until air mass flow rate of 100 kg/hr is reached where GOR records maximum values at all water mass flow rate. Then, GOR starts to decrease. Possible explanation for this GOR behavior is that the increasing air flow rate leads to an increase of productivity.
Furthermore, a decrease of the consumed power by the compressor occurs as a result of the decrease in the temperature condenser. However, the power consumed by the air blower increases with the increase of air mass flow rate. Thus, GOR increases in this stage. The increase of air mass flow rate more than 100 kg/hr however leads to a decrease in productivity and a large increase in the consumed power by the air blower. Consequently, in this stage, GOR decreases, and the power consumed by the compressor decreases.

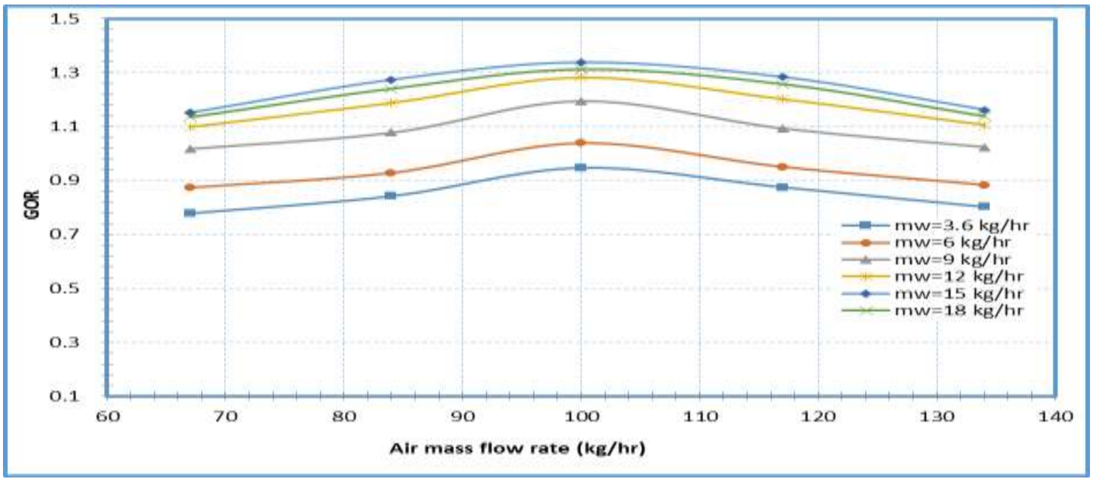

Figure 7 Effect of mass flow rate of air on the gained output ratio (GOR) at different mass flow rate of feed water (OAOW).

7.3 Effect of water and air flow rates on the power consumed (P_C).
Figure 8 describes the relationship between the flow rate of feed water and consumed power to produce 1kg of fresh water at constant air and water temperature, 25ºC, and relative humidity, 55% , at different air mass flow rates. It can be noticed that the consumed power decreases with the increase of feed water flow rate. This is because that increasing the feed water flow rate leads to the decrease of the consumed power by the compressor as previously explained.

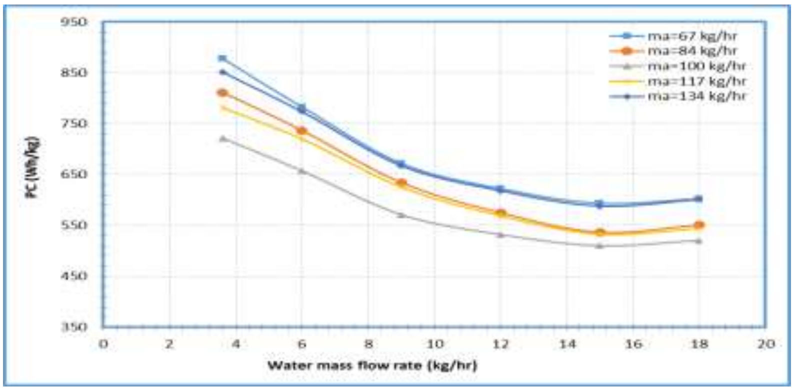

Figure 8: Effect of mass flow rate of feed water on the consumed power (Wh/kg) at different mass flow rate of air (OAOW).

Air and water mass flow rates differ in their effects on the consumed power per 1kg fresh water produced. Fig.9 shows the effect air mass flow rate on the consumed power at constant temperature of 25ºC for both air and

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water, relative humidity 55% and the feed water flow rate, 15 kg/hr. From his figure, it is observed that the consumed power decreases with increasing of air flow rate until the minimum value of 1839 kJ/kg where air mass flow rate reaches 100 kg/hr. After that, the consumed power increases with the increase of air flow rate. The reason for this behavior is that an increase of air flow rate leads to an increase of productivity and a decrease of power consumed by the compressor. Thus, the consumed power decreases. If the increase of air mass flow continues, productivity decreases and the air blower power consumed increases. Thus, the consumed power increases.

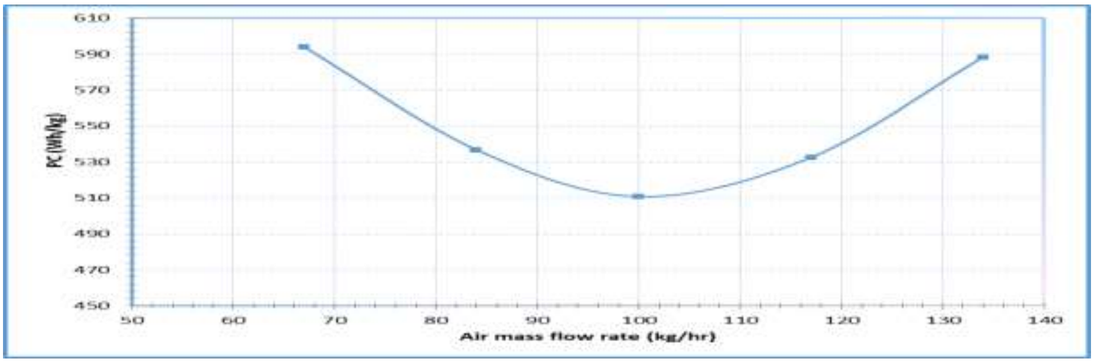

Figure 9: Effect of mass flow rate of air on the consumed power (Wh/kg) at constant mass flow rate of feed water (OAOW).

7.4 Effect of water and air flow rates on the COP

The coefficient of performance (COP) is one of the important factors that describes the efficiency of the heat pump system. Its increase means increasing of the energy recovery efficiency of the heat pump system. The COP represents the ratio between the absorbed energy by the evaporator and the consumed energy by the heat pump compressor.

Figure 10 describes the effect of air flow rate on the COP of the heat pump at constant air temperature and relative humidity of 25°C and 55% respectively at different water feed flow rates. It can be noticed that the COP increases directly with the increasing of air flow rate until the air flow rate reaches 117 kg/hr where COP almost stays constant with further increasing of air flow rate at all different feed water flow rates. The reason of this behavior is the inverse relationship between the enthalpy of outlet air of the humidifier and air residence time in the evaporator and the air flow rate.

In the first stage, the low air flow rate increases the outlet air enthalpy and also increases the residence time of air in the evaporator. This causes the rate of energy absorbed by refrigerant in the evaporator to increase, thus COP increases. In the second stage, the increasing of the air flow rate leads to the decrease of outlet air enthalpy. The residence time of air in the evaporator and the consumed energy by the compressor also decreases. These factors lead the COP to be almost flat with the increase of air flow rate.

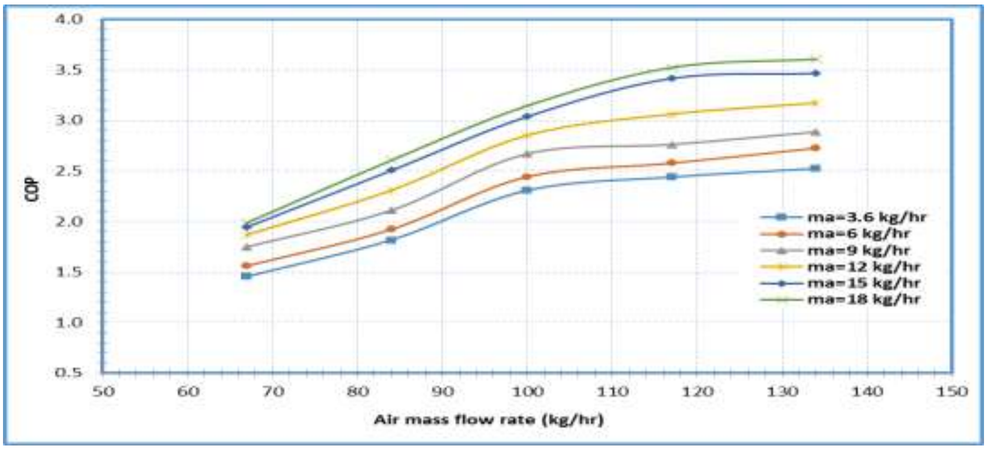

Figure10: Effect of mass flow rate of air on the (COP) at different mass flow rate of the feed water (OAOW)

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8 Conclusions

In the present work, a new desalination configuration has been introduced to reduce the power consumed in water desalination systems. The new desalination system has many advantages such as its small size, portable design and low temperature operation. Furthermore, the new configuration integrates advantages of the thermal pump system, wetting technology and dehumidification. In the integrated system, the maximum productivity was 1.14 kg/hr fresh water with a minimum power consumption of only 1839 kJ/kg. The maximum value of GOR that obtained was 1.34 at water and air flow rates of 15 and 100kg/hr respectively. The maximum value of the COP obtained is 3.6 at flow rate of water and air of 18 and 134 kg/hr respectively. This result is an important achievement in reducing the energy consumption in small-capacitydesalination units.

Symbols

HDH-HP	Humidification and Dehumidification process using the Heat Pump.
OACW	The open air system closed water.
COP	Coefficient Of Performance
PR	Performance Ratio
m_{fresh}	Mass flow rate of fresh water,(kg/hr)
h_{fg}	Enthalpy of vaporization, (kJ/kg)
Q_{in}	Energy input to unit,(kJ)
m_w	Mass flow rate of feed water
m_a	Mass flow rate of air.(kg/hr)
P_{cons}	Power consumed in the desalination process,(kJ/kg)

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