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RESEARCH ARTICLE

Design and Evaluation of a New Desalination System Using Heat Pump

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Abstract

Global demand for freshwater 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 fresh water. Desalination is an efficient technique to provide freshwater supplies. However, desalination is an energy-intensive technology. Therefore, the cost of fresh water produced by this technology is strongly based on energy cost which is rising with dwindling oil supplies.
The integration of humidification-dehumidification system and heat pump presents an impressive method of desalination. From an energy point of view, the heat pump provides a high overall efficiency as it makes a high recovery of both mass and heat. The objectives of this research include design and performance evaluation of a heat pump system for a small-capacity desalination unit. After the experiment setup was built up, a series of experiments were conducted under the meteorological conditions of Iraq to evaluate the system performance under different applications and operating conditions.
Desalination is carried out in Humidification-Dehumidification and Heat Pump technique. The heating part was incorporated with the condenser side of the heat pump and the cooling part was connected in parallel to the evaporator unit of the heat pump.

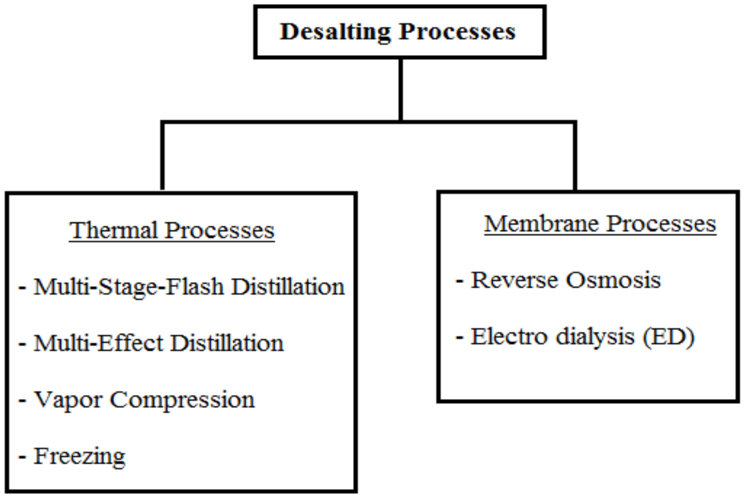
In the integrated system the maximum productivity was found 2.46 kg/hr and the maximum performance ratio, 2.83. The minimum power consumed in desalination process was found 869kJ/kg. The maximum coefficient of performance of the heat pump system was found to be 4.68. This result is an important achievement in reducing the energy consumed in the desalination process in small-capacity desalination units.

Introduction:-

Water is essential to the survival of all living beings; yet, it is estimated that only around 0.77% of all the earth's water is renewable freshwater [1]. Water shortages affect many developing countries, mainly in Asia, which has more than half of the world's population. Also, due to the increase in domestic, agriculture and industrial demands, water consumption is estimated to double every 20 years, about twice the rate of population growth [2]. 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. Desalination is a good technique to provide freshwater supplies. 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, power consumption, the required quality of produced water and finally the cost of construction and unit size. Generally, desalination process consumes a very large amount of energy. Reducing the energy consumed in the desalination process is a key factor for cutting the cost of fresh water produced by the desalination process.

Desalination technologies:-

Currently there are many methods of desalination, which can be categorized into two different processes, mainly thermal processes and membrane processes[3]. In thermal processes, we have multi-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 fig.1



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[4].

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[5].

Mohammad et al.[6]. 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.[7]. 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.[8]. 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.[9]. 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.[10].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.[11]. Investigated the theoretical 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.

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.

The requirements and challenges implementation of small-capacity desalination units:-

For successful desalination process in small-capacity desalination units, a number of requirements and challenges must be considered :

Requirements :-

1- The capacity of these units must be in the range of a few hundred liters per day and the units should not need any special qualified operators. Anyone can run those units easily.
2- The size of the desalination unit must be small and easy to navigate and control.
3- The energy consumed in the desalination process should be low.
4- They have to work in the autonomous mode.
5- Should have high recovery of energy and minimum waste water.
6- Operates with a minimum of operation and maintenance costs.
7- Use of chemicals should be avoided and waste production should be small.

Challenges :-

1- If the solar energy is directly used in the desalination process, the efficiency is low due to climate changes and the intensity of solar radiation during daylight hours.
2- The large amount of waste water produced in desalination units such as RO units where each liter of fresh water produced three liters of raw water is wasted[12].

3- Units that use solar energy usually arise and install outdoors, exposing them to dust deposition and possibility of damage due to direct exposure to heat.
4- Small-capacity units consume more energy compared to large-capacity units.

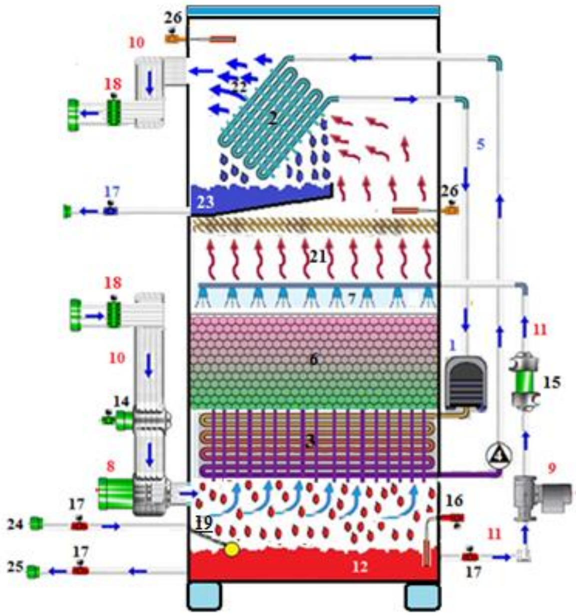
Description of the system :-

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. 2 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.

The working principle of the new system:-

In this new system, the raw water is pumped to the top of humidification chamber using a submersible water pump in the feed water tank, which is located in the bottom of the humidification chamber, as shown fig.3 Water is sprayed by water dispenser which is located at the top of humidification chamber. The water spreads through a packed bed installed in the humidification chamber. Mass transfer and water evaporation occur which increases the moisture content of air to become saturated. The remaining water continue to fall to the bottom of the humidification chamber. Then, it contacts with the condenser coil of the heat pump where heat is transferred from the condenser to the water. The water is then recycled to the humidifier for the purpose of evaporation of another part of the water again. Saturated air will continue to rise until it contact with the evaporator coil of the heat pump which is located at the top of dehumidification chamber. The water vapor condenses on the surfaces of the evaporator coil, where releasing latent heat from condensate water to the refrigeration fluid inside the evaporator 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].



1-Compressor 2-Evaporator 3-Condenser 4-Capillary tube 5-Heat pump pipes 6-Packing material 7-Water distributor 8-Air blower 9-Water pump 10-Air duct 11-Water pipes 12-Feed water tank 13-Distillate collector 14-Rotameter 15-Anemometer 16-Thermometer 17-Water valve 18-Air valve 20-Droplet eliminator 21-Humid air 22-Dry air 23-Fresh water 24- Makeup water 25-Brine 26- Hygrometer

Fig.2. A schematic diagram of the desalination unit.

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 outlet temperature of Air of humidifier , productivity, the performance ratio, power consumed in the desalination process and the coefficient of performance.

Performance Ratio (PR):-

The PR is defined as the amount of fresh water produce per 2326 kJ of energy input. The value 2326 kJ reflects the theoretical amount of energy needed to evaporate one kg of water. A higher PR indicates higher fresh water production per unit of energy input [14]

$$PR = \frac{m_{\text{fresh}} .\ 2326}{Q_{in}} \qquad .... \qquad 1$$

Coefficient of performance (COP):-

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 [10].are calculated from the following equation:

$$COP = \frac{Q_{Evapartor}}{Q_{in}} \qquad .... \qquad 2$$

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:

$$P_{Cons} = \frac{P_{Tinput}}{m_{fresh}} \qquad .... \qquad 3$$

Results and discussion:-

In the open air and closed water (OACW) system, the water is recycled in closed loop, while air is drained after leaving the evaporator, as shown in Fig. 2. In order to study and evaluate the performance of the OACW system, the system has been tested at constant makeup water temperature of 25 ºC, different air mass flow rates with constant temperature, 25 ºC, and relative humidity, 55%. The effects mass flow rates of the water and air on different parameters have been studied. These parameters are; the temperature of outlet air of humidifier, productivity, PR, energy consumed in the desalination process and COP.

Fig.3 describes the effect of mass flow rate of feed water and air on temperature of outlet air of the humidifier. It can be noticed that the outlet air temperature decreases with the increase of feed water mass flow rate. The reason is that the increase in the feed water flow rate leads to an increase in the heat transfer coefficient and then an increase of the cooling rate of condenser coils.

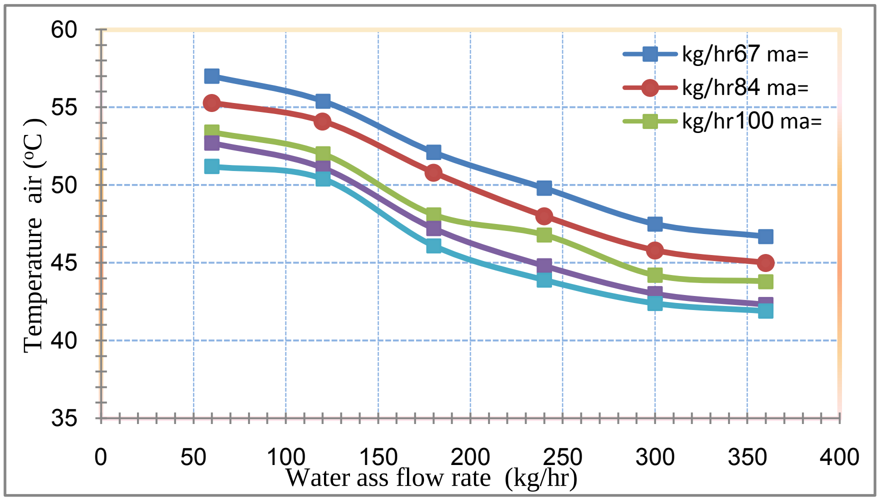


Fig.3. Effect of mass flow rate of recycled water on temperature air outside humidifier at different flow rate of air.

Therefore, air outlet temperature decreases with decreasing of the condenser temperature. It also can be noticed that the outlet air temperature decreases with increasing of air flow rate because that the increase in flow rate of air leads to an increase in the mass transfer coefficient which leads to the increase of water evaporation rate conducted on the condenser surface. Thus, the condenser temperature decreases causing outlet air temperature of the humidifier to decrease.

Fig. 4 shows the effect of feed water and air mass flow rates on fresh water productivity. It can be noticed that the productivity directly proportional with the increase of mass flow rates of feed water and air until reaching the maximum productivity value of 2.46 kg/hr. After that, the productivity starts to decrease with increasing of feed water and air mass flow rates. The reason of the increase in the productivity in the first step comes from the circulation of water in a closed-loop has a significant effect on rising its temperature. As a result, mass and heat transfer coefficient for both water and air increase.

Using water recycle by relatively large flow rates also leads to improve water distribution within humidifier and increase the air/water surface area of contact. Therefore, the evaporation rate increases and in turn increases productivity .

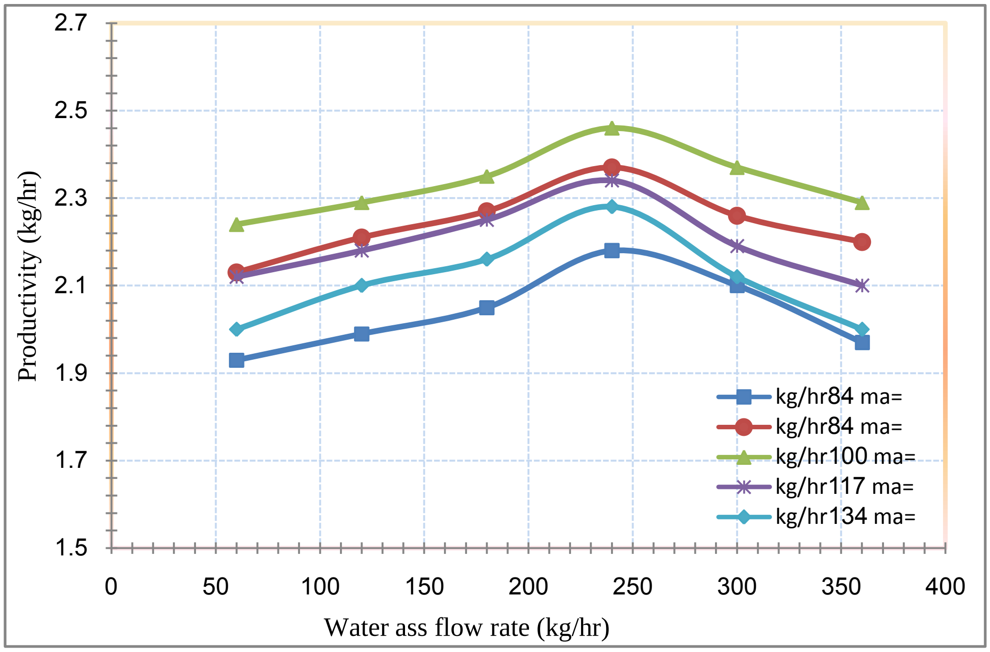


Fig.4. Effect of mass flow rate of recycled water on productivity at different mass flow rate of air.

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.

The increase in the productivity have a positive effect on the PR ,where the performance ratio (PR) changes proportionally with the productivity and inversely with the consumed power . The increase of PR represents the increase of the unit efficiency in the desalination process. Fig. 5 show the effect of the mass flow rate of the feed water on PR at different air mass flow rates. It is seen that the increase of PR continues with increasing of feed water mass flow rate until reaching the water flow rate of 12 kg/hr where the PR reaches maximum values at different airflow rates. PR then starts to decrease with the increase of feed water flow rate.

In the first stage, the increase of water mass 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, PR increases at this stage. On the other hand, further increase of water mass flow rate leads to the productivity decrease and an increase of consumed power by the water pump. As a result, PR starts to decrease with the increase of water mass flow rate at this stage.

The effect of air and water mass flow rates on PR are almost the same. Possible explanation for this PR behavior is that the increasing air mass 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, PR increases in this stage.

The increase of air mass flow rate more than 10 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, PR decreases, and the power consumed by the compressor decreases.

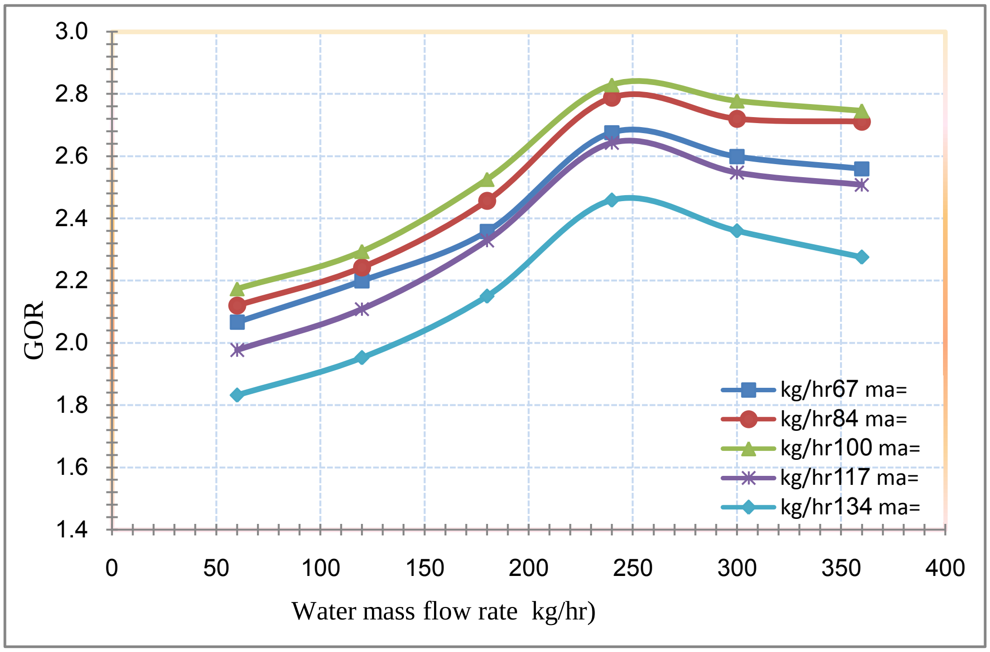


Fig.5. Effect of mass flow rate of recycled water on the PR at different mass flow rate of air.

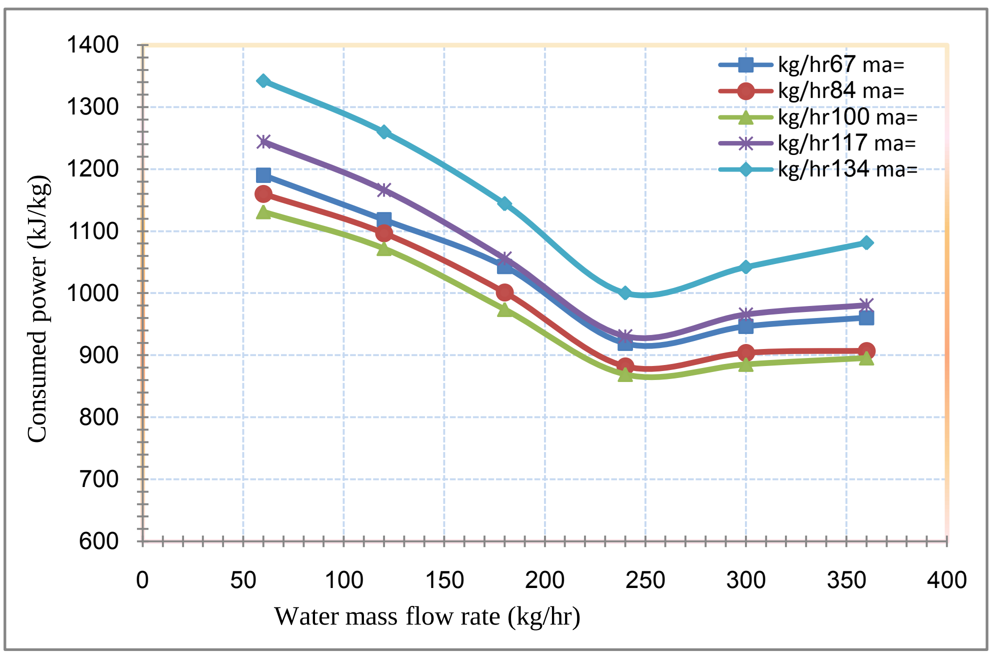


Fig.6. Effect of mass flow rate of recycled water on the power consumed (kJ/kg)at different mass flow rate of air.

The COP is an important parameter in the evaluation of the efficiency of the heat pump as a heating source in the desalination system. The increase in COP leads to an increase in the efficiency of the desalination process. This means that the rejected is larger than the power input to the system. Fig. 7 shows the effect of air flow rate on the COP for the heat pump system 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 100 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.

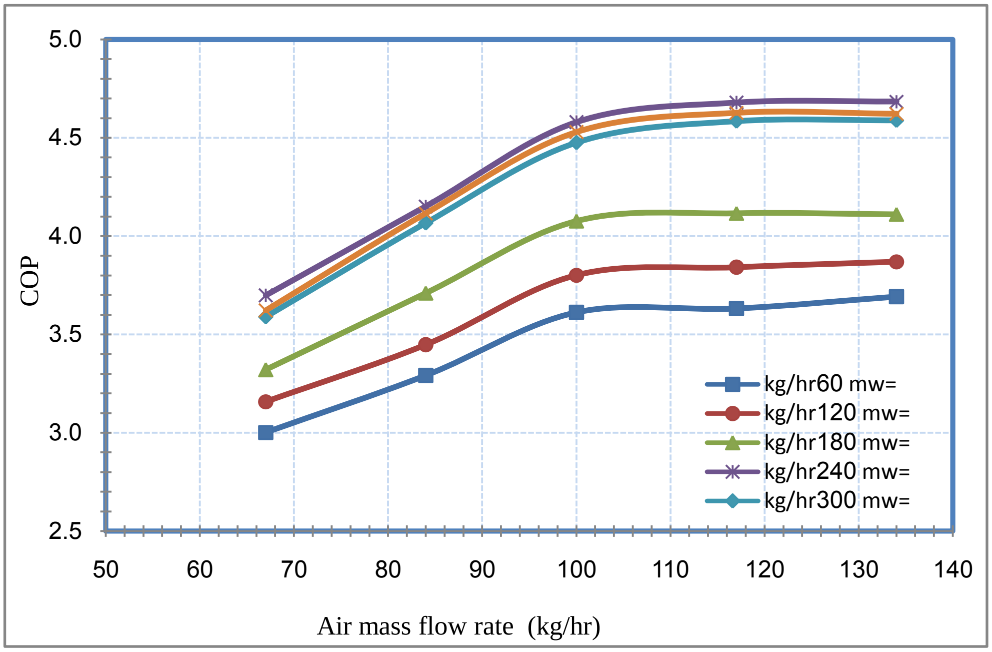


Fig.7. Effect of mass flow rate of air on the COP at different mass flow rate of the recycled water.

Conclusions:-

The small-capacity desalination unit using a heat pump has been introduced as an efficient desalination process for domestic uses. The new desalination system has many advantages such as a small and portable design and low temperature operation. Furthermore, it has been found that this system exhibits a great potential for future developments and will likely to be more economically feasible. In the integrated system, the maximum productivity was 2.46kg/hr and the maximum PR was 2.83. The minimum consumed power in the desalination process was only 869kJ/kg while the maximum COP of the heat pump system has been found about 4.68. The new desalination system has been achieved a good reduction in the energy consumption as a small-capacity desalination unit.

Nomenclatures and 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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