# Experimental study of a solar desalination unit with humidification-dehumidification by using natural and forced air circulation

# دراسة عملية لوحدة تحلية المياه بالطاقة الشمسية مع الترطيب والتجفيف باستخدام الحمل الحر والجبري لدوران الهواء

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## الملخص:

يقدم هذا البحث دراسة عملية لوحدة تحلية مياه باستخدام ترطيب وتجفيف الهواء،وتمت الدراسة فى مناخ مدينة كفرالشخ مصر ،أما وحدة الترطيب(المبخر)، فهي تستخدم لترطيب الهواء عن طريق سريان الماء الساخن خلال مادة الحشو حيث سطح الاتصال ين الهواء والماء الساخن ، وقد تم استخدام ورق السيليلوز كمادة حشو حيث أن مساحته السطحية كبيرة والتي تتيح حدوث ترطيب عالى ، وتم دراسة السليلوز بمساحات سطحية مختلفة وتم تصميم وحدة تجفيف معدلة ( المكثف ) وذلك لتحسين أداء الوحدة ،وفي المكثف يحدث تبادل حراري بين السائل والهواء ويتم تكثيف البخاروتسترجع الحراره الكامنة لتكثيف بخار الماء وتستخدم فى التسخين المبدني لمياه التغذية وتعمل الوحدة من خلال دورة مفتوحة لانسياب المياه ودوره مغلقة لانسياب الهواء ويتم تسخين المياة عن طريق المجمع الشمسي (السخان الشمسي الذي يعمل بتكنولوجيا التفريغ) وذلك لضمان استمرارية الانتاجية للوحدة ، وقد تم دراسة أداء الوحدة عند الحمل الطبيعي والحمل الجبري للهواء. وتمت أيضا المفاضلة بين ثلاثة أنواع من الحمل الجبري (لأعلي -لأسفل – كليهما معا) . كما تم دراسة أثر درجات الحرارة ومعدلات السريان للماء الساخن علي اداء الوحدة وكذلك الحصول علي النسبة الأفضل بين معدل سريان الماء البارد عند مدخل المكثف الي معدل سريان الماء الساخن عند مدخل المبخر والحصول علي القيمة المثلي لها وهى الضعف ، وقد أوضحت النتائج أفضلية حمل الهواء جبريا لأسفل عن الأنواع الأخري للحمل الجبري والحمل الطبيعي .وقد تم الحصول علي الانتاجية الأفضل بقيمة (٢٣.٦كجم / ساعة) عند استخدام الحمل الجبري للهواء لأسفل والنسبة بين الماء البارد الي الساخن الضعف ومعدل سريان الماء الساخن ٤ كجم/ دقيقة بدرجة حرارة ٩٠ درجة مئوية .

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## Abstract.

An experimental investigation of a desalination system based on the humidification and dehumidification (HDH) of air is studied, at the weather conditions of Kafrelsheikh City, Egypt. The evaporator (humidifier) unit is based on a cellulose paper as packing materials substratum through which water flows, and has a large area to favor evaporation. Cellulose papers with different wet surface area are studied. In this study a modified design of condenser (dehumidifier) is used in HDH process to improve the performance evaluation of the unit. The condenser unit is a liquid–air heat exchanger, where water vapor is condensed and the enthalpy of condensation is recovered to preheat the water. The working principle of the set-up is based on the idea of open-water and closed-air cycles. An evacuated solar water heater is integrated with the desalination unit to evaluate the continuity production of distillate. The air is circulated either by natural or forced circulation. The effect of three types of forced circulating air (up, down and up-down) on the unit performance is considered. Also, the influence of inlet water temperature and inlet water mass flow rate to the humidifier on the performance HDH unit is studied. In addition the optimal ratio of cold water at condenser inlet to hot water at evaporator inlet (C/H) is obtained. The results show that the maximum productivity is obtained when C/H is 2. Also it is found that forced down air circulation gives higher performance than that obtained for forced up, forced up-down and natural air circulation. At C/H =2, inlet water mass flow rate to the humidifier 4 kg/min and forced down air circulation the unit productivity is about 23.6 kg/h with water temperature 90 °C at humidifier inlet.


### Nomenclature

| | |
|---|---|
| $T_{ace}$ | Air temperature at condenser exit (°C) |
| $T_{aci}$ | Air temperature at condenser inlet (°C) |
| $T_{wce}$ | Water temperature at condenser exit (°C) |
| $T_{whi}$ | Water temperature at humidifier inlet (°C) |
| $W_{ace}$ | Humidity ratio at condenser exit ($kg_v/kg_a$) |
| $W_{aci}$ | Humidity ratio at condenser inlet ($kg_v/kg_a$) |
| C/H | Cold to hot water ratio |
| $m_a$ | Mass flow rate of air (kg/s) |
| mw | Mass flow rate of water (kg/min) |

## 1. Introduction:

Sufficient quantity and reliability of fresh water is a fundamental need for humanity and other living beings. In many parts of the world, especially in the Middle East, people suffer from lack of fresh water and they live mostly in arid, remote areas and islands. On the other hand, in these regions, abundant of solar energy is available with the large amount of sea or underground saline water. For those reasons, by many researchers, solar water desalination systems are proposed as an economical and environmentally friendly solution to supply small settlements in these locations with enough drinking water.

Standard desalination processes such as multi stage flash (MSF), multi–effect (ME), vapor compression (VC) and reverse osmosis (RO) are suitable for large and medium capacity fresh water production. But most remote arid areas need low capacity desalination systems. The humidification–dehumidification desalination process (HDH) will be a suitable choice for fresh water production when the demand is decentralized. HDH is a low temperature process where total required thermal energy can be obtained from solar energy. Capacity of HDH units is between conventional methods and solar stills [1]. These standard desalination techniques are only reliable for large capacity ranges of 100–50,000 $m^3$/day of fresh water production [2, 3]. These technologies are expensive for small amounts of fresh water and cannot be used in locations such as islands or remote areas where maintenance facilities and energy supply are restricted. Moreover, using conventional energy sources to drive such technologies has a negative impact on the environment [4].

Nawayseh et al. [1] studied numerical a solar desalination based on the HDH process in a circulation path. They tested their simulation results with experimental data obtained in pilot units. They found that increasing the water flow rate decreases the production rate due to the lower evaporation caused by lower temperatures. Nafey et al. [5, 6] investigated theoretical and experimental, the influence of the different system configurations, weather and operating conditions on the productivity of a solar desalination system using HDH process at the weather conditions of Suez City, Egypt. The system used in their studies consists of a concentrating solar water heater, flat plate solar air heater, storage tank, humidifying tower and dehumidifying exchanger. In their experimental study a general equation to estimate the performance of the system under different operating conditions was developed. Younis et al. [7] investigated a seawater desalination process in which brackish water was pre-heated by using solar collectors and then brought into contact with inlet air in an evaporation column followed by a condensation stack for dehumidification. They presented a theoretical design procedure for this process and concluded that by increasing inlet air flow rate, the production of fresh water increases. Al-Hallaj et al. [8] constructed a small-scale HDH unit in Basrah, south of Iraq. The unit had a capacity of 12 L/d.$m^2$ of solar collector surface. The system used a water heater combined with a solar collector which was modeled to evaluate the heat and mass transfer coefficients. Soufari et al. [9] constructed a pilot unit with a capacity of 10 kg/h which was located at Karaj, Iran. This unit includes 28 $m^2$ of flat plate water solar collector, a humidifier and a dehumidifier. The tests reveal that optimization before construction will result in better performance in practice. Farida et al. [10] have carried out a simulation study to investigate the performance of solar multi-effect humidification units based on the humidification–dehumidification principle. The study has focused on analyzing the effects of various components involved in the process along with the study of the effect of water flow rate on the desalination production. They concluded that increasing the flow rate of water has been reported to increase the productivity, other publications reported the opposite [1]. Wang et al [11].studied a photovoltaic (PV) panel-driven HDH treatment process for desalination of brackish water under a free or forced convection. The highest fresh water yield was 0.873 $kg \cdot m^{-2} \cdot d^{-1}$ achieved at the evaporative temperature $T_0$=64.3 °C. Lu et al. [12] stated that evacuated tubular solar water heaters have lower thermal losses and higher efficiency than flat plate solar water heaters.

This paper presents a modified design of condenser used in HDH process to improve the performance evaluation of the unit. Cold water at condenser inlet to hot water at evaporator inlet ratio (C/H) is studied. In addition, performance of naturally and forced circulating air and using cellulose papers with different holes sizes as packing materials are studied. The effect of three types of forced circulating air (up, down and up-down) is considered.

## 2. Experimental setup and procedure:

Figures 1 and 2 illustrate a schematic diagram and a photograph of the experimental setup. The system main components are humidifier (evaporator), dehumidifier (condenser), and solar water heater (evacuated tube solar collector). The system is based on an open cycle for water and a closed cycle for the air stream. The air is circulated either by natural or forced circulation.

The HDH system consists of two loops, one for hot water and the other for cold saline water. In hot water loop, the hot water is delivered from the evacuated tube solar collector through hot water pump and sprayed at the top of the humidifier tower (evaporator). Due to heat and mass transfer between the hot water and the air stream in the humidifier the air leaves the humidifier loaded by moisture. The saturated moist air is then transported toward the condensation tower where it comes in contact with a surface where its temperature is lower than the dew point of the moist air. As a result, there is a condensate of water on this surface. This condensed water was collected from the bottom of the condensation tower, while the brine (the salty water exiting the humidifier) accumulates at the bottom of the humidifier tower. In order to increase the surface of contact between air and water, and therefore to raise the rate of air humidification, packed bed is implanted in the humidifier. In the cold water loop, the cold water is delivered from the storage tank by a cold water pump

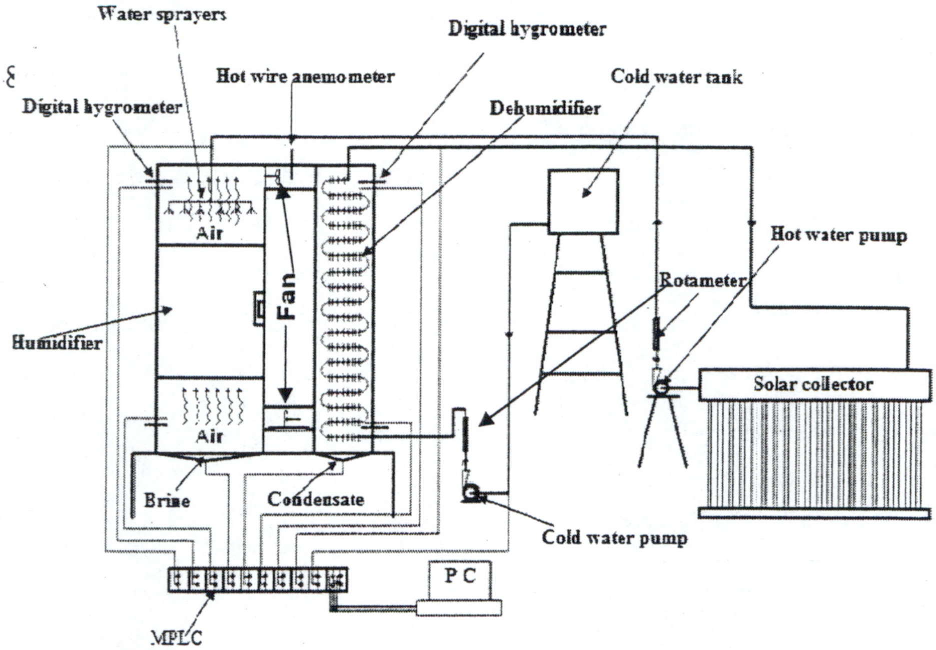


Fig. 1 .Schematic diagram of the experimental setup.

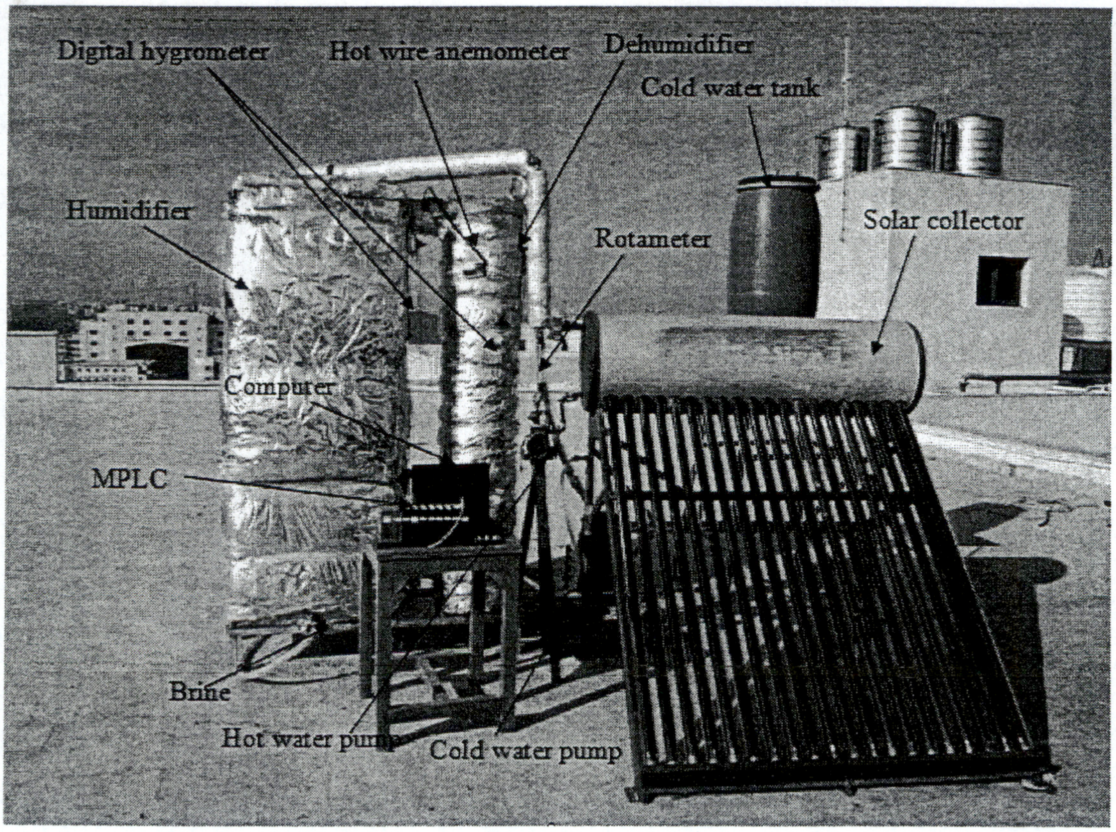


Fig. 2. Photograph of the experimental setup.

which is then preheated in the condensation tower, due to the latent heat of condensation, before entering to the solar collector.

## 2.1. Humidifier:

Humidifier tower occupies one compartment of the desalination unit at which air holds water vapor when hot water is sprayed. The air is needed to be humid as much as possible so it is humidified inside the evaporator. The humidifier is also called "evaporator", and consists of various parts (evaporator shell, swing door and backing material). The evaporator shell is made of 1.5 mm thickness galvanized steel with rectangular cross sectional area 50×80 $cm^2$ and height of 200 cm. The base of the evaporator has a gradual slope to permit the highly concentrated salt water to be blown down out of the evaporator. A built in swing door is added to the evaporator to facilitate the changeability of evaporator's packing material, which is fixed inside the humidifier. This packing material is used to increase the contact surface area of air and water to increase the mass transfer rate. The packing is supported such that it does not block the air flow path and remains continuously wet. The water is sprayed on the packing material using a hydraulic grid. Cellulous papers have approximately honey comb shape used as packing material. In this study two groups of cellulous papers are used. The first consists of ten slabs each one has dimensions of 80x50x10 $cm^3$ with openings in the form of equilateral triangle, where side length of the triangle 5 mm (cellulose 5mm).The total surface area of all triangles in this group is approximately 8 $m^2$. The second group is the same as first group except the side length of the triangle 7 mm (cellulose 7 mm) and the total surface area of all triangles is approximately 6.8 $m^2$. Figure. 3 shows view of cellulous papers.

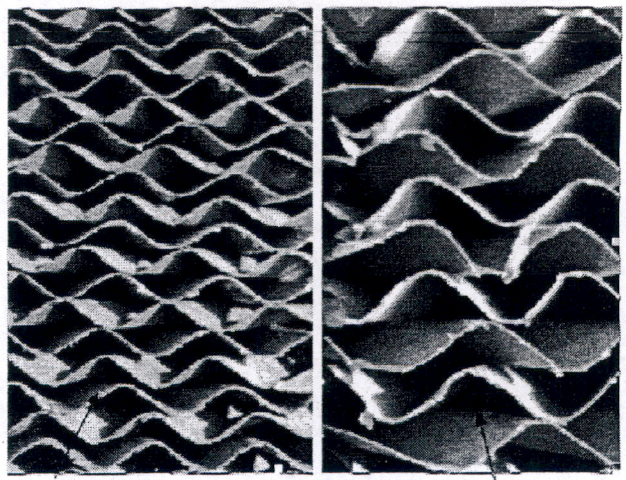


Fig. 3. Cellulous papers

## 2.2. Dehumidifier:

The other compartment of the desalination unit is the dehumidifier tower (condenser). In the dehumidifier, the water vapor is humidified by air condensate which rejects heat to the cold water entering the condenser from the salt water tank leading to rise its temperature. The dehumidifier consists of two parts. The first one is a condenser shell of cylindrical shape galvanized steel with 40 cm diameter and 200 cm height. The second part is the coil which is a copper tube of 15 m length, 1.5 mm thickness and 1.27 cm outer diameter and mounted by copper corrugated fins, as shown in Figure. 4. The lowest end of the condenser has a conical shape for collecting condensate (desalinated) water.

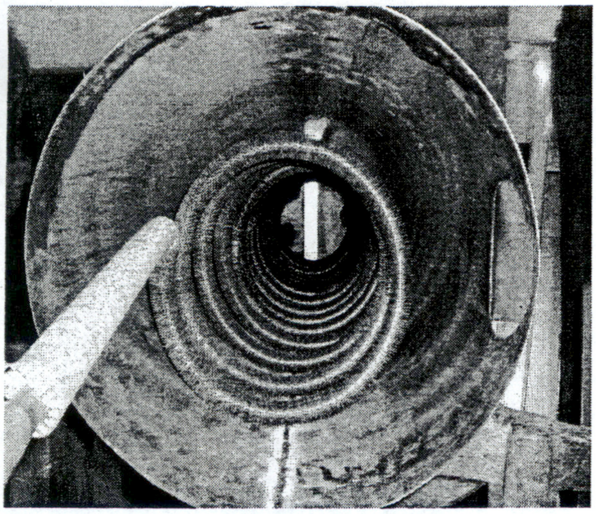

Fig. 4. Heat exchanger inside the condenser shell

## 2.3. Vacuum tube solar collector:

The evacuated solar water heater consisted of collector, water tank, expansion vessel and frame. The solar collector consists of 20 vacuum tubes; each tube has 5.8 cm outer diameter, 4.8 cm inner diameter and 1.8 m length. The solar evacuated tubes are made of borosilicate glass and used as the absorbing heat element in the solar heater system. The vacuum between the cover tube and inner tube minimizes heat loss. Inside each evacuated glass tube there is a sealed copper heat pipe running through the inner tube. The hollow copper heat pipe within the tube is evacuated of air but contains a small quantity of a low pressure water-ethylene glycol plus some additional additives to prevent corrosion or oxidation. Solar water heating systems use the sun to heat a heat-transfer fluid, such as a water-ethylene glycol antifreeze mixture. The major use of ethylene glycol is as a medium for convective heat transfer. The transfer fluid absorbs heat from the collector and rises to the top passing through a heat exchanger (hot bulb). The hot bulb, which located in the saline water storage tank, transfers heat to the saline water during the day (indirect heating). As the thermal fluid gives off its energy to saline water it cools down and becomes denser than the hot part in the collector's tubes. Hence it falls down allowing the hot part to rise to the top. Such design is called indirect (closed-loop) systems. A cylindrical stainless steel water tank insulated with 5.5 cm polyurethane foam and having 200 l capacity was used to feed the basin with saline hot water through insulated tube. The cylindrical water tank consists of two cylinders (inner from stainless steel and outer from fiber) which sandwiched the insulated foam, The frame is about 1.73 m height, 2..07 m width and 1.5 m depth.

## 2.4. Pumps and fans:

For either cold or hot water flowing from source to condenser or evaporator, two centrifugal pumps (0.5 hp) are used, one for hot water pipeline and the other for cold water pipeline. A 15 W electric fan is used to circulate the air through the unit (forced draft). Fan can be supported either the top or the bottom or the two together of the condenser duct according to the experiment need. A filter is used in the suction side to separate any impurities coming from the elevated tank. A flow meter is connected on the delivery side of the pump to measure the water flow rate. A group of valves are used to separate each part of the saline water loop from the system when necessary.

## 2.5. Water storage tank:

The water storage tank (cold water tank) having a volume of 220 liters was constructed of 2 mm thick and it was made from PVC. The tank is supported on a stand made of iron. The height of the stand is 2 m above the ground which helps to maintain a constant water flow rate.

## 2.6. Measurement devices:

During the experiments, several parameters are measured in order to evaluate the system performance. The quantities needed to be measured are, flow rate of air and water streams, temperatures of air and water at the inlet and exit of each tower, temperature of water at inlet and exit of the storage tank, relative humidity of air at inlet and exit of each tower and the productivity of the unit. To measure either cold or hot water flow rate; Two Rotameters are used, with range of (0.02-8) litters per minute. The first one is found in the line of cold water to measure the flow rate of cold water before entering the condenser, the second one is found in hot water line to measure the flow rate of hot water before entering the evaporator. A hot wire anemometer working in the range from 0 to 2000 FPM (0- 10 m/s) with an accuracy of ±0.01 fpm ($\pm 5\times 10^{-5}$ m/s) is used for measuring air velocity. Knowing the air velocity and the cross sectional area of the unit, the volume flow rate of air can easily be calculated. Four digital hygrometers with accuracy (±5%) and resolution (1%) are used to measure the relative humidity of air at various parts of the unit. Thermocouples of K- type in connection with a modular PLC are used to measure the temperatures in the unit.

## 3. Experimental results and discussion:

### 3.1 Effect of water temperature at humidifier inlet on unit performance:

The effects of water temperature at humidifier inlet ($T_{whi}$ ) on the important unit parameters such as, water temperature at condenser exit, air temperature at condenser inlet and exit, humidity ratio and unit productivity with cellulose 5 mm are shown in Figures. 5- 10. The variation of water temperature measured at the condenser exit ($T_{wce}$) with water temperature at humidifier inlet ($T_{whi}$ ) for different values of water mass flow rate (mw) is shown in Figure. 5. This figure is plotted for both naturally and forced down circulating air for cellulose 5 mm as the packing material in the humidifier. It is seen from the figure that $T_{wce}$ increases with $T_{whi}$ at a constant water flow rate. This tendency can be explained by the increase in the amount of heat gained by the air in the humidifier as $T_{whi}$ increases. Consequently, air losses more heat to the water in the condenser resulting in a higher exit temperature. For the same value of $T_{whi}$, as mw increases $T_{wce}$ decreases. This can be easily explained because higher flow rates lead to smaller temperature difference. Also, it can be observed from the figure that, the forced down air circulation leads to a higher $T_{wce}$ than that of natural for different $m_w$. This is can be explained by the increase in mass flow rate of air ($m_a$) which leads to a higher heat gain in the humidifier. Air loses this heat to the condensing water resulting in raising its temperature.

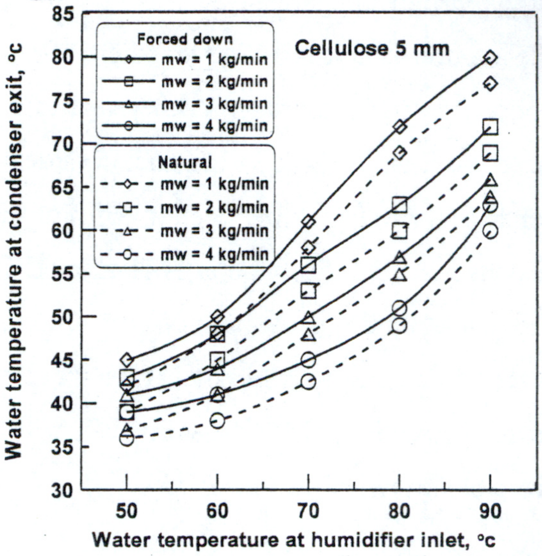


Fig. 5. Measurements of water temperature at condenser exit.

The variation of air temperature at condenser inlet ($T_{aci}$) with $T_{whi}$ is shown in Figure. 6.

The figure shows that $T_{aci}$ increases linearly with $T_{whi}$. As $T_{whi}$ increases the air is heated as it leaves the humidifier leading to higher air temperature at humidifier exit ($T_{ahe}$) which is approximately equal to $T_{aci}$. Where, the results indicated that the air conditions at humidifier exit are approximately the same as those at condenser inlet. The figure also shows that $T_{aci}$ increases with the increase in mwfor a given $T_{whi}$. As mw increases, the heat supplied by water in humidifier increases. As a result, the air becomes hotter as it leaves the humidifier and enters the condenser. From the figure it is noticed that forced air circulation leads to lower values of $T_{aci}$ compared with that for natural circulation. This is attributed to the increase in mass rate of air, $m_a$ for the same heat supplied by the humidifier which results in lower air temperature at humidifier exit (i.e., condenser inlet). It is also noticed that the difference between $T_{aci}$ for natural and forced circulation increases at higher values of $T_{whi}$.

Figure.7 represents the results obtained for the variation of air temperature at condenser exit ($T_{ace}$) with $T_{whi}$. Also, It is seen that $T_{ace}$ increases with $T_{whi}$ for a constant flow rate. It is known that $T_{ace}$ is always smaller than $T_{aci}$ for all cases as dictated by the energy balance. However, as hotter air enters the condenser, it becomes cold but leaves the condenser at a temperature higher than the value corresponding to lower $T_{whi}$ since $m_w$ in the condenser is fixed.

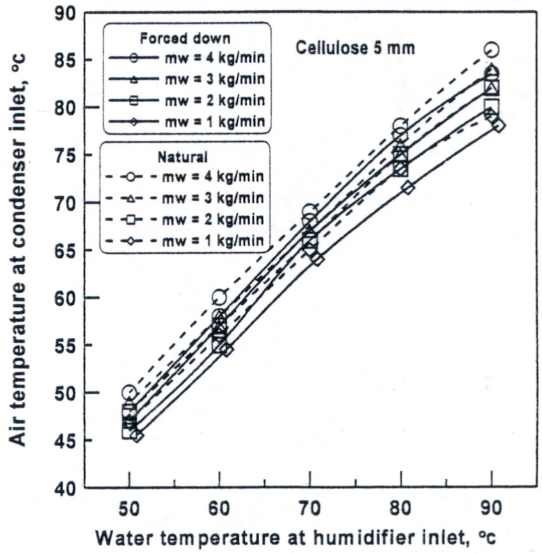


Fig. 6. Measurements of air temperature at condenser inlet.

For a constant $T_{whi}$, it is seen that $T_{ace}$ increases as $m_w$ increase for both natural and forced air circulation. But in the case of forced convection air leaves the condenser at a temperature $T_{ace}$ higher compared with that in the case of natural, although $T_{aci}$ for natural is higher than $T_{aci}$ for forced as a result of the increase of air mass flow rate in case of forced convection.

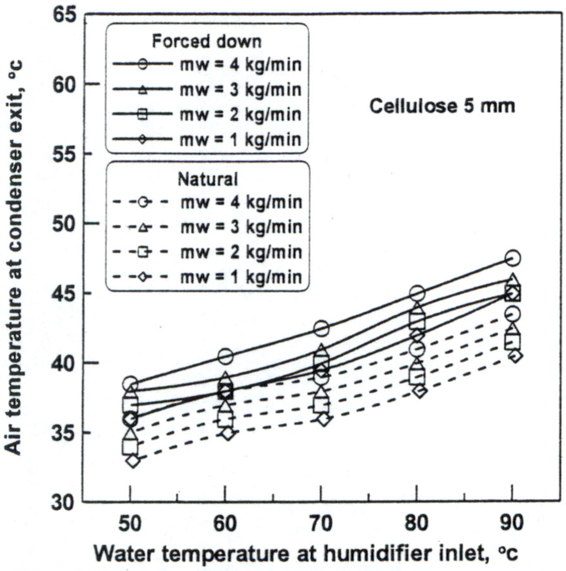


Fig. 7. Measurements of air temperature at condenser exit.

Figures. 8 and 9 show the variation of humidity ratio, $W_{aci}$ and $W_{ace}$ at both condenser inlet and exit respectively with water temperature at humidifier inlet $T_{whi}$ for different values of mw. The figures indicate that as $T_{whi}$ increases, the temperature of the air leaving the humidifier increases which also increases its ability to hold water vapor and hence its humidity ratio increases. It is noticed also that the rate of increase in $W_{aci}$ is higher at larger values for $T_{whi}$. It can be noticed also that $W_{ace}$ slightly increases as $T_{whi}$ increases as shown in figures since the temperature of air at condenser exit increases. The figures also indicate that as $T_{whi}$ increases, the rate of increase of humidity ratio at condenser inlet becomes steeper for a constant mass flow rate of water. The humidity ratio increases slowly as mw increases, but the rate of increase becomes more rapid at higher values of mw This is may be due to the great larger amounts of vapor carried away by the air stream. Higher humidity ratios lead to larger unit productivity.

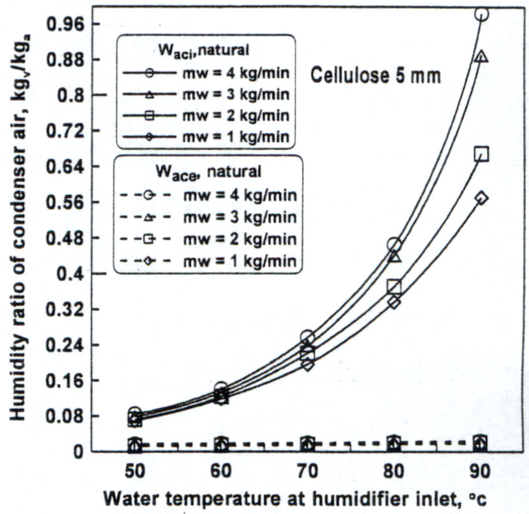


Fig. 8. Variation of measured air humidity ratio at condenser inlet and exit

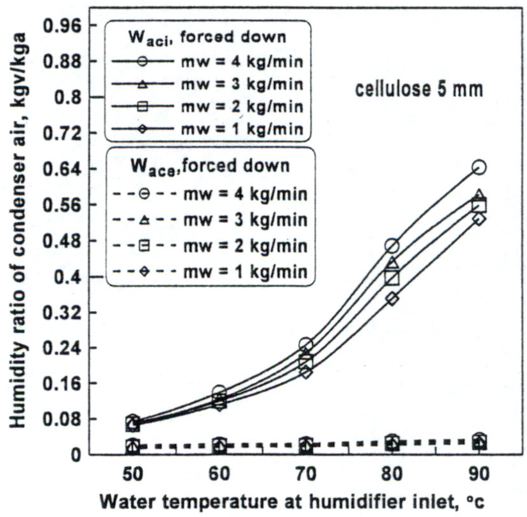


Fig. 9. Variation of measured air humidity ratio at condenser inlet and exit.

The dependence of unit productivity $m_d$ on water temperature at humidifier inlet $T_{whi}$ for different values of mass rate flow of water is depicted in Figure.10. From the figure it is clear that for a constant water flow rate, the productivity of the unit ($m_d$) increases as $T_{whi}$ is increased for both natural and forced circulation of air. This can be explained when $T_{whi}$ increases, air accommodates more moisture in the humidifier. This moisture is condensed in the condensation tower giving higher unit productivity. Since the mass transfer coefficient in the humidifier is much higher in forced circulation than that in natural one. Therefore, the unit gives more distillate in forced down circulation operation compared with that for free convection. Data of extensive experiments are listed in Table (1) under different operating conditions.

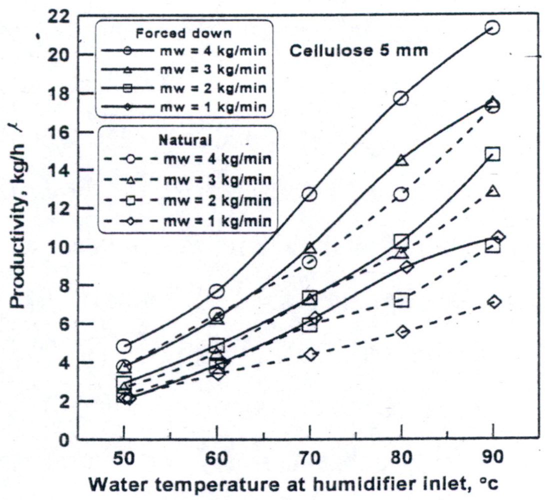


Fig. 10. Measured unit productivity.

## 3.2. Effect of condenser water mass flow rate on the unit productivity:

Unit productivity plays a vital role in the process of distillation. Therefore, it is important to study the effect of cooling water mass flow rate of condenser to hot water mass flow rate of humidifier ratio (C/H) on the unit productivity. Figure.11 shows the effect of this ratio (C/H) on the hourly system productivity at different values of $T_{whi}$ in case of natural circulation at hot water flow rate 2 kg/min. From this figure it can be observed that, the hourly productivity increases with increasing mass flow rate of cooling water and reaches to maximum value when the cold water mass flow rate becomes double that of hot water. Where, it is clear that increasing the cooling water mass flow rate causes a significant drop of the surface temperature of the condenser. This results in an increase in the rate of the condensation of the water vapor on the condenser surface and, thus, the system provides a higher yield. It is also clear that when cold water mass flow rate becomes higher than double of hot water, there is no significant gain in the productivity is obtained, where the inlet and exit for both ($T_{aci}$, $T_{ace}$, $W_{aci}$, $W_{ace}$) are nearly constant. Figure.12 shows the effect of the ratio (C/H) on the hourly system productivity for forced down air circulation at hot water flow rate 4 kg/min. From the figure, at C/H =2, the unit productivity is about 23.6 kg/h at hot water temperature 90 °C.

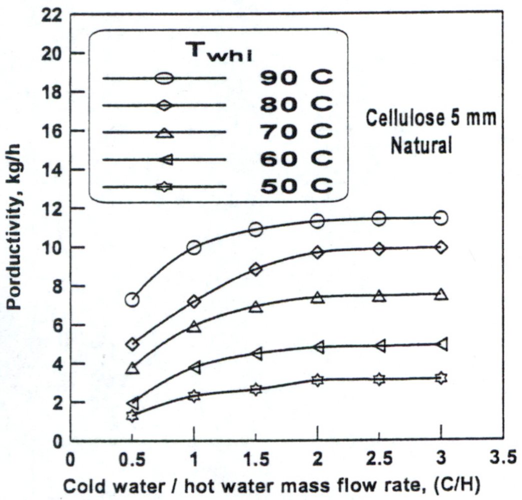


Fig. 11. Effect of C/H ratio on hourly water productivity for natural circulation at hot water flow rate 2 kg/min.

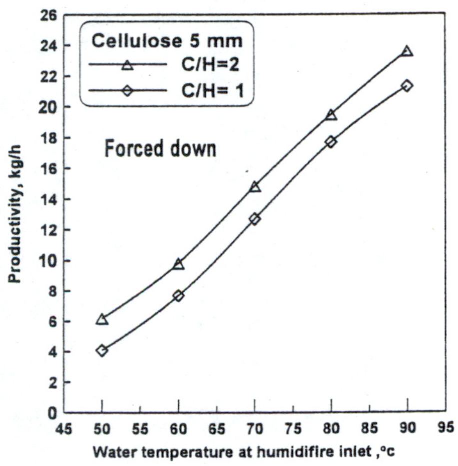


Fig. 12. Effect of C/H ratio on hourly water productivity forced down air circulation at hot water flow rate 4 kg/min.

## 3.3 Effect of packing material on unit performance.

Cellulose 5 and 7 mm packing materials have been used in this investigation. The humidifier surface area per unit volume of the packing has been kept constant. However, the wetted area differs from one type to another depending on the opining holes of each cellulose 5 and 7 mm. where, the total wetted surface area is approximately 8 and 6.8 $m^2$ for cellulose 5 and 7 mm respectively.Effect of packing material on air temperatures at condenser inlet and exit in case of forced air circulation are presented in Figures. 13, 14.

Fig. 13 shows the variation of $T_{aci}$ with $T_{whi}$ for the tested celluloses. From this figure it can be indicated that cellulose 5 mm gives higher values of $T_{aci}$ compared to cellulose 7 mm. Forced circulation leads to higher temperatures values at the condenser exit and lower values at condenser inlet. This is attributed to the increase in $m_a$ for the same heat supplied by the humidifier which results in lower air temperature at humidifier exit (i.e., condenser inlet). It is also noticed from all measurements (though not presented) that the difference between $T_{aci}$ for natural and forced circulation increases at higher values of $T_{whi}$. Figure.14 indicates that $T_{ace}$ is considerably independent on cellulose type as it slightly varies for the two different types.

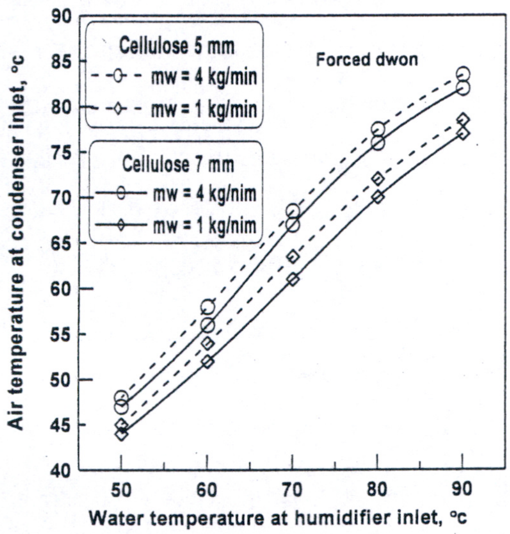


Fig. 13. Effect of packing material on air temperatures at condenser inlet in case of forced circulation.

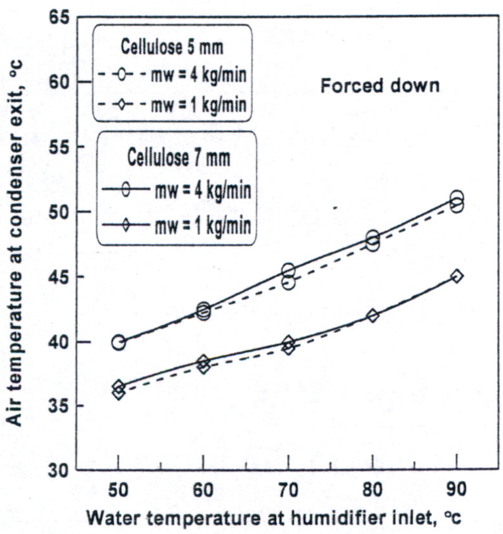


Fig. 14. Effect of packing material on air temperatures at condenser exit in case of forced circulation.

The variation of humidity ratio with $T_{whi}$, when celluloses 5 and 7 mm packing materials are used, is shown in Figure. 15 for forced air circulation of the condenser. The results indicated that cellulose 5 mm gives higher values for humidity ratio than cellulose 7 mm for both natural and forced air circulation, . But, the difference between humidity ratio at inlet and exit of the humidifier is much larger in case of cellulose 5 mm. This in turn leads to a higher unit productivity using cellulose 5 mm as shown in Figure.16. Also, from the figure hot water temperature at humidifier inlet 90 °C and hot water flow rate 4 kg/min, the unit productivity for cellulose 5 mm is about 21.3 kg/h and the unit productivity for cellulose 7 mm is about 17 kg/h at. For forced down air circulation.

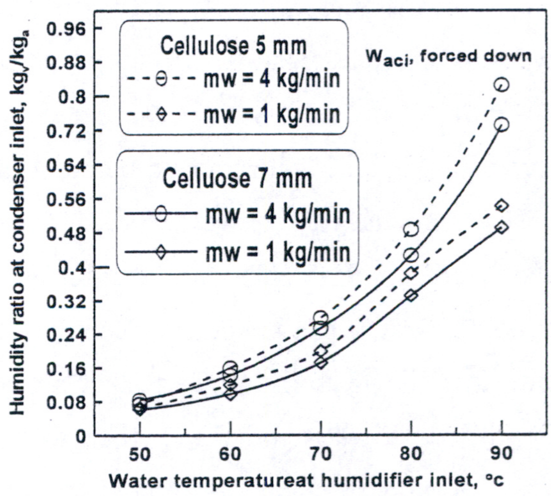


Fig.15. Effect of packing material on humidity ratio at condenser inlet in case of forced circulation

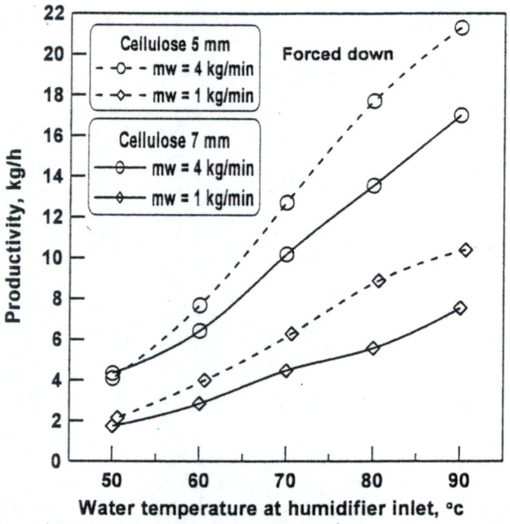


Fig. 16. Effect of packing material on unit productivity with $T_{whi}$ in case of forced circulation at water flow rate of 1 and 4 kg/min.

## 3.4. Effect of types of forced air circulation on the unit performance:

In the present study, effect of three types of forced circulating air (up, down and up-down) on the unit performance is studded. Figure.17 illustrates a comparison of unit productivity between forced down and forced up air circulation (fan is fixed at bottom or at top of the unit), for cellulose 5 mm. It is shown from the figure that forced down gives higher productivity than forced up. This is because $T_{aci}$ form forced down is always higher than $T_{aci}$ form forced up. This is attributed to the increase amount of water vapor inter the condenser. However $T_{ace}$ for forced down leaves the condenser always at smaller value than that for forced up. As a result the productivity for forced down is always higher than that for forced up at fixed mass flow rate. Also, from the figure at hot water temperature at humidifier inlet 90 °C and water flow rate 4 kg/min, the unit productivity for cellulose 5 mm is about 21.3 and 18 kg/h for forced down and forced up air circulation respectively.

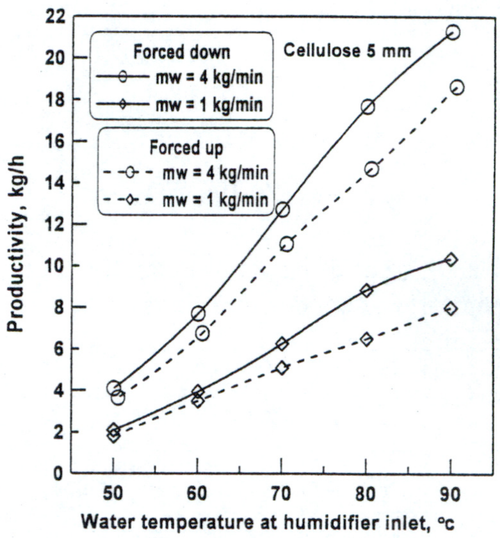


Fig. 17. Effect of fan installation on the unit productivity

## 3.5. Comparison between forced and natural air circulation on the unit productivity:

Figure. 18 illustrates a comparison between natural and forced down, up, up - down air circulation. It can seen from the figure, that the forced down air circulation gives the maximum productivity. Also it can be noticed that forced up-down air circulation gives productivity very similar to that of natural. This is because, in the case of forced up –down, the saturated air enter and exit the condenser with very small temperature difference and hence a small amount of water vapor is condensed.

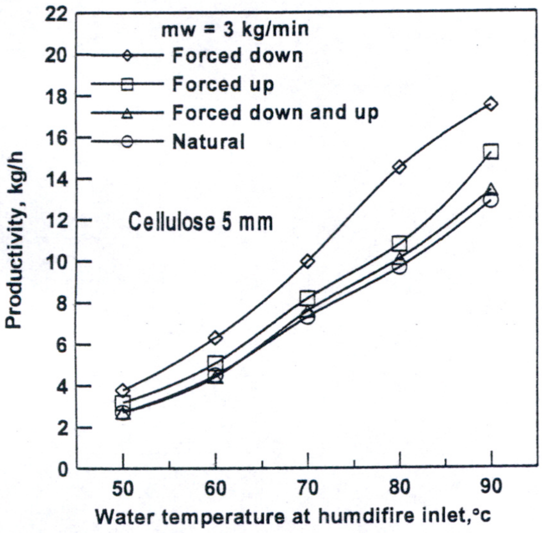


Fig. 18. Effect of air circulation on the unit productivity.

## 5. Conclusions:

This paper presents an experimental study of a solar desalination system based on humidification and dehumidification HDH. From the presented experimental results the following conclusions can be drawn:

- The condenser with cylindrical shell and corrugated fins led to increase the rate of heat transfer and the air humidity ratio at the condenser outlet doesn't exceed 0.03 for natural and forced down.

**Table (1) Productivity of cellulose 5 mm**

| $T_{whi}$, °C | mw, kg/min | Productivity, kg/h | | |
|---|---|---|---|---|
| | | Natural | Forced | % Increasing of forced about natural |
| 90 | 4 | 17.25 | 21.3 | 23.47% |
| | 3 | 12.86 | 17.5 | 36% |
| | 2 | 9.98 | 14.75 | 47.79% |
| | 1 | 6.85 | 10.36 | 51.24% |
| 80 | 4 | 12.69 | 17.7 | 39.47% |
| | 3 | 9.68 | 14.5 | 49.79% |
| | 2 | 7.2 | 10.25 | 42.36% |
| | 1 | 5.33 | 8.85 | 66% |
| 70 | 4 | 9.2 | 12.72 | 38.26% |
| | 3 | 7.31 | 9.98 | 36.52% |
| | 2 | 5.95 | 7.35 | 23.52% |
| | 1 | 4.2 | 6.25 | 48.88% |
| 60 | 4 | 6.5 | 7.7 | 18.46% |
| | 3 | 4.53 | 6.32 | 39.5% |
| | 2 | 3.8 | 4.9 | 28.94% |
| | 1 | 3.2 | 3.95 | 23.43% |
| 50 | 4 | 3.8 | 4.31 | 13.42% |
| | 3 | 2.9 | 3.6 | 24.1% |
| | 2 | 2.52 | 2.95 | 17.06% |
| | 1 | 1.95 | 2.1 | 7.69% |

- Maximum productivity is obtained when the ratio of cold water at condenser inlet to hot water at evaporator inlet (C/H) is 2.
- Forced down air circulation gives higher performance than forced up, forced up-don and natural air circulation.
- Forced up-down air circulation gives approximately the same productivity as natural air circulation.
- Cellulose 5 mm gives higher productivity than using cellulose 7 mm under both natural and forced flow condition, this is because it has higher wet surface area than cellulose 7 mm.
- wet surface area is the main parameter for HDH desalination system.

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