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# SOLAR POWERED AIR CONDITIONING SYSTEM USING ROTARY HONEYCOMB DESICCANT WHEEL

## *نظام تكييف شمسي يعمل باستخدام عجلة تجفيف دوارة على شكل خلية النحل*

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**ملخص**

في هذا البحث تم دراسة نظام تكييف شمسي يعمل باستخدام عجلة تجفيف حيث يستعمل التجفيف للتغلب على الحرارة الكامنة فى التبريد. يتكون الجهاز من سخان شمسي يحتوى على مادة مسامية كسطح ماص للحرارة وذلك بغرض الحصول على درجات حرارة مرتفعة تساعد فى عملية إعادة التوليد بالإضافة الى عجلة دوران تحتوى على فرشة على شكل خلية النحل مشبعة بمحلول كلوريد الكالسيوم وذلك بغرض عمليتي الامتصاص وإعادة التوليد. عجلة الدوران مقسمة إلى جزأين للامتصاص وإعادة التوليد بنسبة 1: 3 على الترتيب تمت الدراسة على كميات سريان مختلفة خلال اليوم لتوضيح تأثير الإشعاع الشمسي على البارومترات المختلفة

أوضحت النتائج إن هذا النظام ذو فعالية أكثر في حالة إعادة التوليد بالمقارنة بعملية الامتصاص كما يمتاز هذا النظام بالسهولة ويمكن استخدام هذا النظام أيضا للحصول على المياه من الهواء الجوى بتبريد الهواء المشبع من عملية إعادة التوليد الى درجات حرارة اقل من درجة حرارة التندي وقد تم استنتاج معادلة معملية لحساب هذه الكمية كما تم استنتاج معادلات أخرى لحساب أداء عجلة الدوران فى حالة الامتصاص وإعادة التوليد

## Abstract

A solar powered air conditioning system using a liquid desiccant is proposed to overcome the latent heat part of the cooling load in the air conditioning system. A solar air heater containing a porous material is used as a heat absorber. In addition, a rotating wheel containing a honeycomb clothes saturated with Calcium Chloride solution, is utilized for the regeneration and absorption processes. Different system parameters are investigated. The effect of airflow rate and solar radiation intensity on the system regeneration and absorption abilities are studied. The obtained results show that the system is highly effective in the regeneration process. Also, the system is feasible and energy-efficient in comparison with the traditional electric dehumidification. Furthermore, the system can be used to extract a reasonable amount of water from air. An empirical equation to calculate the removed moisture as a function of air flow rate at solar noon is obtained.

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## Introduction

Desiccants are chemicals with great affinity to moisture. Therefore, desiccants can be used as supplement to conventional vapour compression systems in order to remove the latent heat load. Desiccants are efficient in handling latent heat load (i.e., reducing the humidity), but the evaporator in the vapour compression system is efficient in handling the sensible cooling loads (i.e., lowering the air temperature). Davanagere [1] summarized the advantages of using desiccant in the following points.

1- It consumes very little electrical energy, and for regeneration process it allows the use of solar energy and waste energy.
2- It is efficient when latent heat load is larger than the sensible load.
3- It is a clean technology, which can be used to condition the internal environment of buildings and operates without the use of harmful refrigerants.
4- The achieved control of humidity is better than when employing vapor compression systems
5- The cost of energy to regenerate the desiccant is lower when compared with the cost of energy to dehumidify the air by cooling it below its dew point.
6- Improvement in indoor air quality is more likely due to the normally high ventilation.
7- It has the capability of removing airborne pollutants.

In hot and humid climates, the humidity puts an extra load on the electric vapor-compression air conditioning system. Liquid and solid desiccants can reduce the moisture content of humid air and thus reduce the latent heat load imposed on the vapor compression air conditioning system.

A solar air-conditioning system employing relatively inexpensive low-temperature collectors, coupled with an innovative desiccant dehumidification and evaporative process, provides a new prospect for cost-effective solar cooling. A forced flow solar collector/regenerator using liquid desiccant was studied by Alizaeh and Sman [2]. They employed an aqueous solution of Calcium chloride as desiccant and studied the influence of air and desiccant solution flow rates on the regeneration performance. They conclude that the performance of the regenerator increased as the airflow rate increases. Henning *et al* [3] conducted a parametric study of a combined desiccant/chiller solar assisted cooling system. They showed no only their feasibility but also their primary energy saving of up to 50% with a low increased overall costs Mavroudaki *et al* [4] and Halliday *et al* [5] conducted independently two feasibility studies of solar diverse European Citics representing different climatic zones on the content. A decline in energy savings was recorded in highly humid zone. The liquid desiccants are attractive because of their operational flexibility and capability of absorbing pollutants and bacteria [6]

Mullick and Gupta [7] have carried out studies on solar collector cum regenerator. Several materials were employed as the desiccant, including both solid and liquid substances. Conventional solid desiccants include Silica gel, Activated Alumna, Lithium Chloride salt, Molecular Sieves, Lithium Silicate and Synthetic Polymers. Liquid desiccants include Lithium Chloride, Lithium Bromide and Calcium Chloride. Liquid desiccants have several advantages compared with solid desiccants. Liquid desiccant can be pumped and thus several small units can be connected to meet the demands of large buildings. Also, it can be stored for regeneration by some inexpensive energy sources. More details about desiccant properties and the regeneration process are given by Kinsara et al [8].

Evaluation and optimization of a solar desiccant wheel performance were studied by Ahmed *et al* [9]. Results show that there is a maximum value of each design parameter at each operating condition. Further, an efficient wheel performance requires an effective range between 1 and 5 kg/min of airflow rate.

Two different solar desiccant-dehumidification regeneration systems have been studied by Shyu *et al* [10]. Both systems have the same glazed area. The solid desiccant used is Silica gel. Both systems are feasible and efficient in energy saving.

Several aspects of the solar assisted desiccant cooling system have been discussed by Henning *et al* [11]. Experiences with a pilot plant indicate that the technology is market available and works well; expected solar fractions for cooling could be nearly realized. Also ,results show that the combined desiccant/chiller solar assisted cooling systems are feasible from an energetic as well as an economic point of view, especially in warm-humid climates. The performance of solar assisted and desiccant-cooling systems for a domestic two storage residence located in Baghdad was evaluated by Joudi and Dhaidam [12].

Hamed [13] studied the desorption characteristics of desiccant bed for solar dehumidification/humidification air conditioning systems. The bed is divided into seven separate layers. Calcium Chloride is used as the working desiccant. Transient adsorption/desorption characteristics show that the mass transfer rate has a significant effect on the concentration gradient in the bed.

Investigation of forced flow of the solar regenerator/collector were described and compared with the free convection solar regenerator collector by Kabeel [14]. Daou et al [15] studied Desiccant cooling air conditioning systems

A solar assisted adsorptive desiccant cooling process with a honeycomb absorber has been experimentally tested by Kodama, Akio et al [16]. It investigate an actual performance of the cooling process with a typical configuration (one desiccant wheel, one sensible heat exchanger and two water spray evaporative coolers) driven with solar heated water. At higher humidity condition, the amount of dehumidified water became higher than that dehumidified at low humidity condition due to increasing relative humidity of outside air or effective adsorption capacity of the desiccant rotor. However, resulting temperature decrease in this condition was just 6.9$^{o}$ C. This behavior is mainly due to humidity increase and simultaneous temperature rise in the dehumidified air

In the present work, the effect of using porous type solar air heater and honeycomb rotary wheel on the absorption as well as the regeneration process during the day were studied. The effect of air flow rate on the regeneration and absorption processes are studied during the day time. Also, the feasibility of using the proposed system to extract water from air was studied.

## EXPERIMENTAL SETUP

The aim of the experimental work is to study the performance of a solar air conditioning system with a rotary desiccant wheel. For this reason, an experimental system has been designed and built. The main parts of the test setup are shown in the schematic diagram in Figure (1-a). A photograph of the system is shown in Fig. (1-b). The system consists of four main parts:

a- Solar air heater.
b- Rotary desiccant wheel.
c- Heat exchanger.
d- Measuring instruments.

### a- Solar air heater

The test section of the solar air heater used in this system is shown in Fig. 2. It consists of a main duct being filled with a porous material (the aluminum foil). The main duct has dimensions of 1.2 m × 1m × 0.07 m. The back and sides are insulated using a glass wool with 0.05-m thickness, the glass cover thickness is 0.004 m. The porous material thickness is 0.005 m . Both sides and back are made of an iron sheet with thickness of 2 mm. The collector is inclined with an angle of $30^{o}$ relative to the horizontal. A small fan (0.25 hp) is used to below the air in the solar air heater and regeneration part with different flow rates. The air flow rate is controlled using a controlling valve .

### b- Rotary desiccant wheel

The rotary desiccant wheel is made of galvanized iron of 0.4 m diameter and 0.6 m length. It is divided into two parts. The first part is the regeneration part that equals 33.33% of the total surface area. The second part is the absorption part that equals 66.66 % of the total surface area. The two parts are separated carefully. The rotary wheel contains 8 cylinders. Each cylinder is covered from the outer and inner surfaces with clothes layer. The thickness of the clothes layer is 2 mm and is saturated with Calcium Chloride solution. The rotary motor (0.3 hp) is used to drive the desiccant wheel at a velocity of 120 revaluation per hour to alternate the position of the absorption and regeneration areas.

### c- Heat exchanger

The heat exchanger is used to enhance the absorption process. The shell is made from galvanized iron of 0.3 m diameter, 1 m length and 0.02 m thickness. The inlet water passes through duct, that is made from copper tube with 0.05 m diameter and 5 m length. During this process, the water moving inside the duct coil is heated and leaves at a higher temperature. A small fan (0.2 hp) is used to allow the air passing through the heat exchanger and absorption part.

### d- Measuring instruments

Different parameters are measured in this work; these include:

- Inlet and outlet temperature of the solar air heater.
- Inlet and outlet air dry bulb and wet bulb temperatures for both absorption and regeneration processes
- inlet and exit air temperature of the heat exchanger
- Solar radiation intensity measured at tilt angle 30 degree.
- Ambient air dry bulb and wet bulb temperatures
- Air flow rate.

Copper constantan thermocouples are used to measure the temperatures at different points. The thermocouples are connected with a temperature recorder that gives the temperatures with a resolution 0.1 C. The solar radiation intensity is measured during the day using a Pyranometer. A humidity multi-meter measures the relative humidity with a resolution 0.1%. The

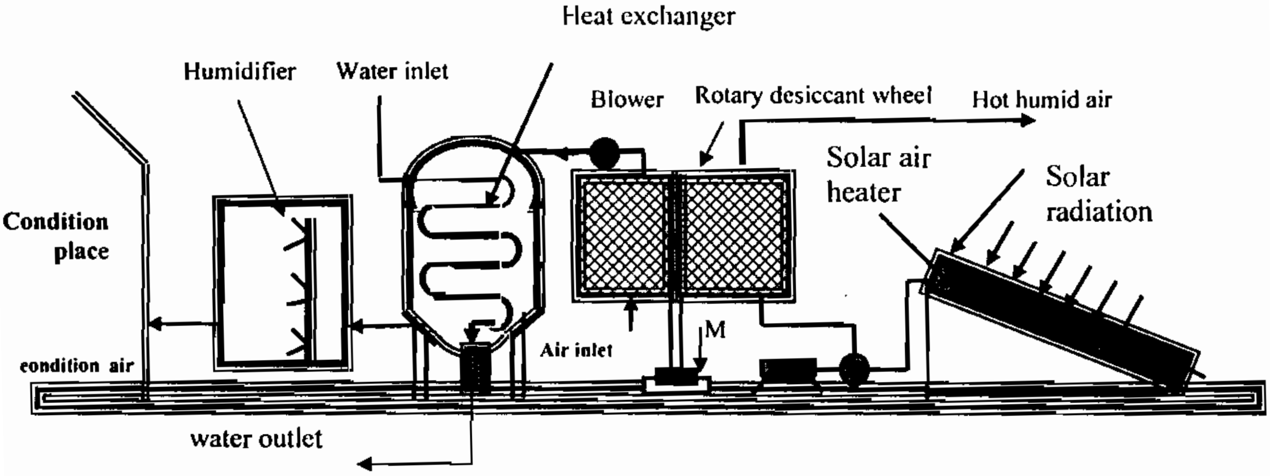


*Fig. 1-a : Schematic of the proposed system.*

*Fig. 1-b: View of the experimental setup.*

air flow rate was measured down stream of the solar air heater and exit air from the absorption part only at the beginning of experimental work. A hot wire anemometer is used to measure the velocity of air with an accuracy of ± 0.05 m/s. The experimental data are recorded at intervals of one hour during the daytime. The experiments were carried out during some selected clear sky days from 10/5/2004 to 15/8/2004 .

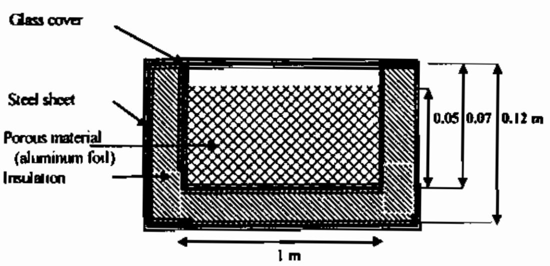


Fig. 2: Sectionional view of the solar air heater

## System operation

There are two air paths in the tested system. In the first path the air exits from the air heater at a high temperature then flows through the regeneration part in order to regenerate the moisture from the solution. This increases the solution concentration on the desiccant after a specific time. In the other air path, the moist air flows though the absorption part to absorb the moisture from it. This will decrease the concentration of the solution on the bed after a certain time.

## Experimental analysis

The air performs two processes simultaneously in the system, namely the dehumidification process and the regeneration process :

### 1- Dehumidification process

The temperature humidity processes of the system during absorption are shown in Fig. 3. At point I, the ambient air is at high temperature and humidity. By passing the air through the desiccant bed in the rotary wheel, the humidity is decreased but the temperature increases in the process air (point 2). Then, the hot and dry air passes to the heat exchanger and cooled to point 3 as shown in Fig. 3 The air can be used from this system directly into space . At point 3, it can be controlled to the desired condition by adding air washer to the system before supplied to the condition place (process3-6).

### Regeneration process

The outside air at point 1 enters to the solar air heater and then is heated to point 4. Then the heated air passes to the desiccant bed in the rotating wheel in which the humidity will be increased and the temperature decreased (point 5). At this state, the air can be used to extract water by cooling to a temperature lower than the corresponding dew point temperature (process 5-7).

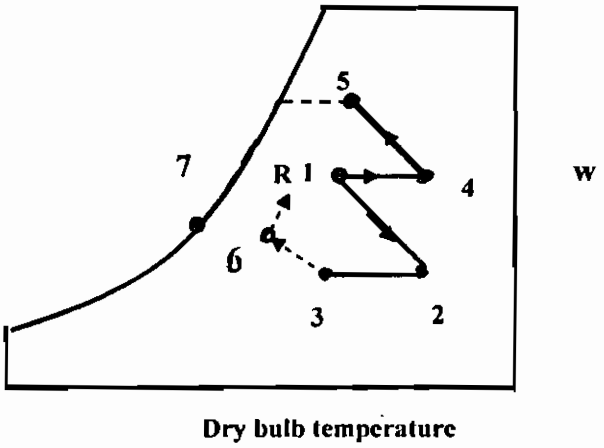


Fig. 3: Psychometric chart of the system processes.

The specific cooling capacity of the supply air can be determined as

$$\Delta H = h_1 - h_2 \qquad (1)$$

The total moisture removal capacity of the supply air is given by:

$$M_{w1} = m_1 (w_1 - w_2) \qquad (2)$$

The rates of the moisture added to air by the regeneration is given by

$$M_w = m_1 (w_5 - w_4) \qquad (3)$$

This moisture can be used to extract the fresh water from the air after cooling it. The cooling capacity of desiccant assisted air conditioning $Q_c$ is obtained as

$$Q_c = m_2 \Delta H \qquad (4)$$

The thermal coefficient of the system performance (SCOP) is defined as the ratio between the cooling capacity and incident solar radiation intensity and can be obtained as

$$SCOP = \frac{m_2 \Delta H}{A\,G} \qquad (5)$$

Where:

G is the solar radiation intensity ($W/m^2$)

The wheel effectiveness can be expressed as [18]

$$\psi = \frac{w_1 - w_2}{w_1 - w_{2,ideal}} \qquad (6)$$

where $w_{2,ideal}$ is the ideal specific humidity of the desiccant wheel. Assuming the air is completely dehumidified at this point, the value of $w_{2,ideal}$ can be considered zero.

The thermal efficiency of the flat-plate collector is obtained by using mass and heat balances on the collector. It is given by

$$\eta = \frac{m_1 C_p (T_{out} - T_{ini})}{G\,A} \qquad (7)$$

$$\text{Air flow ratio} = \frac{m_1}{m_2} \qquad (8)$$

Where:

$m_1$ is flow rate in absorption part

$m_2$ is the flow rate in regeneration part

During the experimental tests, the flow ratio is kept constant and equals 3, i.e when $m_1$ is increased this means following increase in $m_2$

## Experimental results

The aim of the experimental work is to study the performance of a desiccant air conditioning system that uses a porous type solar air heater and a honeycomb rotary desiccant wheel. The results were obtained at different climatic conditions and different air flow rates.

Figure 4 represents the dry-bulb temperature of a collector inlet air temperature (ambient air), collector exit air temperature and solar radiation intensity during the day for the two values of air flow rates. Figure (4-a) shows the air temperature variation at flow rate 60, 180 kg/hr. It can be seen that both of exit temperature and solar radiation intensity are increasing with time till reaching a maximum value and then decreasing. The temperature difference between exit and inlet air depends on the solar radiation intensity falling upon the collector surface. It reached its maximum after the solar noon. Also, the difference depends on the flow rate that passes through the collector. This difference equals 15 C at flow rate 60 kg/hr and equals 20 ° C at a flow rate of 30, 90 kg/hr as seen in Figure (4-b).

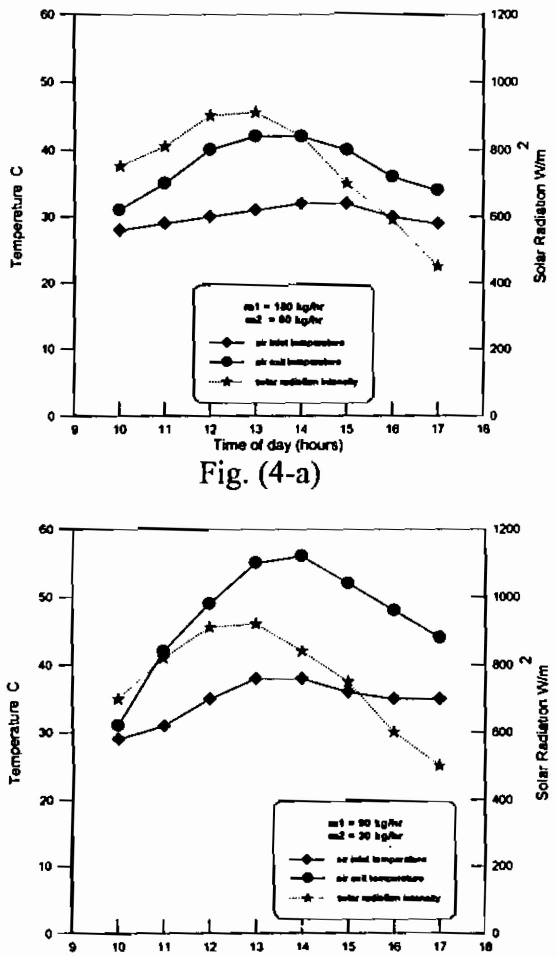


Fig. (4-a)

Fig. (4-b)

*Fig. 4: Variation of air collector inlet, exit temperatures and solar radiation intensity during the day*

Difference between the measured specific humidity (g/kg) of air stream passing through the honeycomb rotating wheel for the absorption and regeneration process are shown in Fig 5. For the regeneration process, the transient variation of the air humidity at the rotary wheel exit increases in humidity with time from a minimum value to the maximum value after solar noon and then decreased. The regeneration depends on the air temperature which depends on the intensity of solar radiation. Eventually based upon daytime, the trend of humidity difference is approximately similar to that temperature rise in the collector. Also, the regeneration depends on the valuc of air flow rate. The humidity difference reached 8 g/kg at a flow rate of 80, 240 kg/hr, equals 6 g/kg at a flow rate of 120, 360 kg/hr, 4.5g/kg at flow rate of 30, 90 kg/hr and 10 g/kg at a flow rate of 60, 180 kg/hr.

The amount of absorbed moisture depends on different parameters such as air flow rate, ambient condition and bed condition. The trend of the absorption is similar to that of the rcgeneration process. The absorbed moisture reached 5g/kg at a flow rate of 80, 240 kg/hr, 4g/kg at a flow rate of 120, 360 kg/hr, 7.5 g/kg at a flow rate of 30, 90 kg/hr and 6 g/kg at a flow rate of 60, 180 kg/hr. From the figure, it can be seen that the humidity difference is higher in regeneration process compared with the absorption process. Its value is approximately equals a twice original value. But in fact, the amount of moisture absorbed is higher than the amount of moisture regenerated when taking the effect of surface area for the two processes.

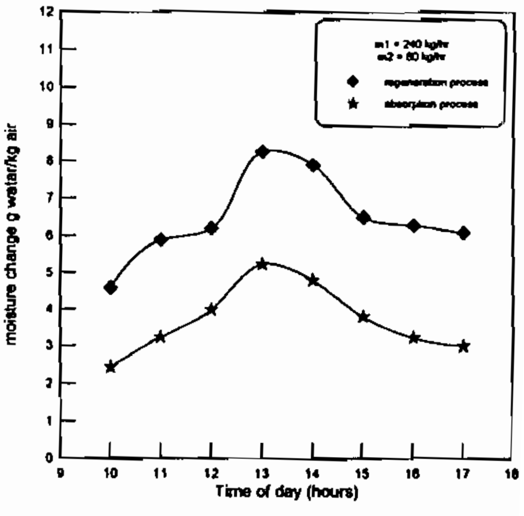


Fig. (5-a) *Instantaneous humidity difference between inlet and exit conditions of regeneration and absorption process*

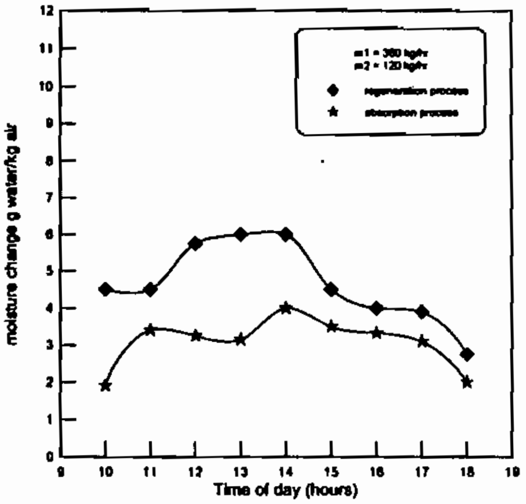


Fig. (5-b)

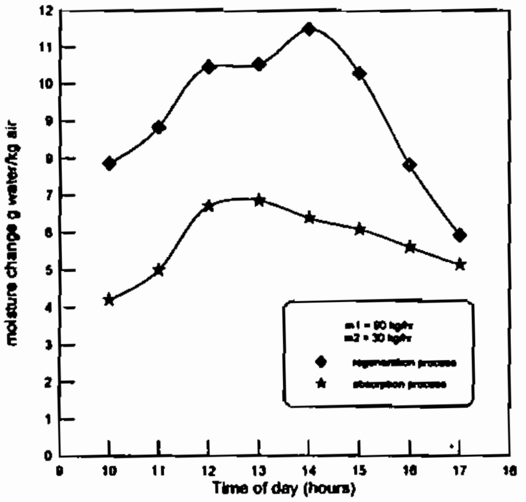


Fig. (5-c)

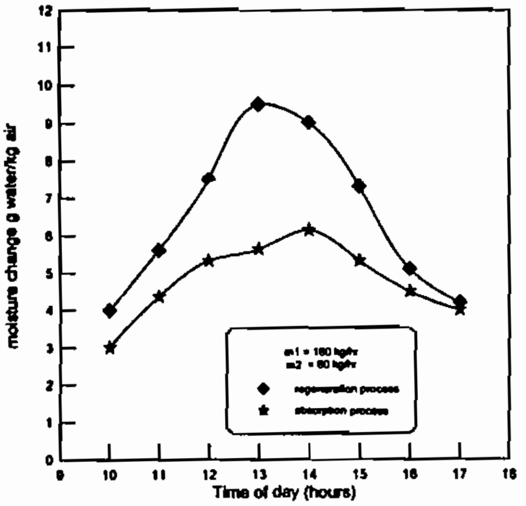


Fig. (5-d)

*Fig. 5: Instantaneous humidity difference between inlet and exit conditions of regeneration and absorption process*

The variations of the solar air heater efficiency for the two days during the daytime at two different values of air flow rate are shown in Figure 6. It increases till a maximum value after solar noon and then decreased. The figure shows also that the efficiency increases with the flow rate. It reached 0.55 at a flow rate of 40 kg/hr and 0.6 at a flow rate of 80 kg/hr.

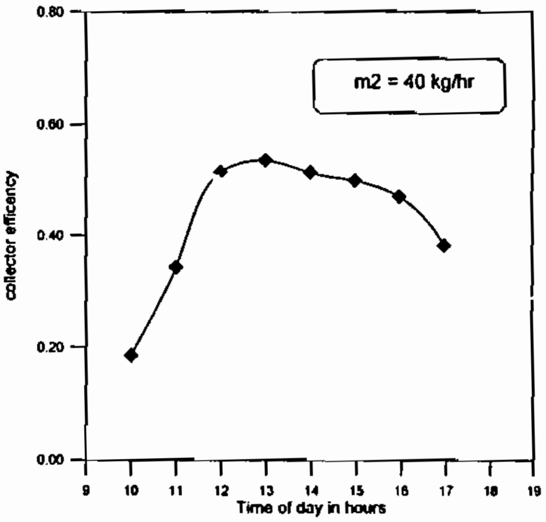


Fig. (6-a)

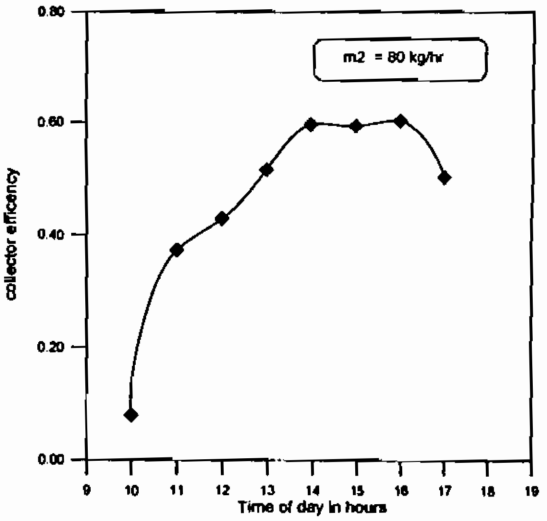
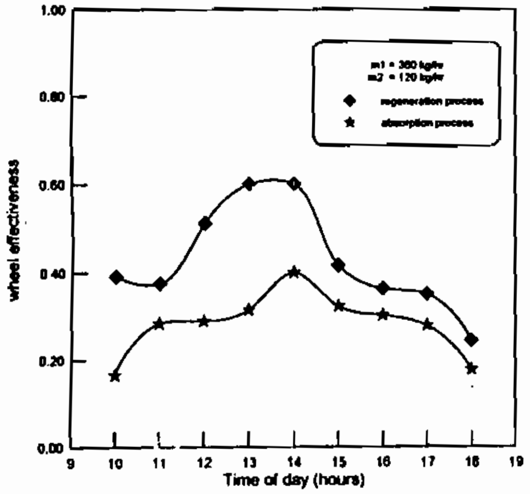


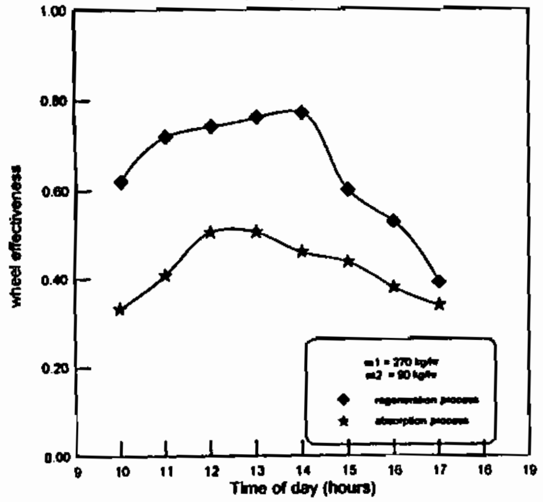
Fig. (6-b)

*Fig. 6: Variation of porous type solar air heaters efficiency during the day.*

The variation of the wheel effectiveness at different values of air flow rates versus daytime hours is shown in Fig.7. The Figures shows the variation for both regeneration and absorption processes. It can be seen that the wheel effectiveness is higher in regeneration process compared with that of the absorption process for all days. The value increases to a maximum value after solar noon and then decreases. In the regeneration process, the wheel effectiveness reached 0.6 at a flow rate of 120, 360 kg/hr, 0.8 at a flow rate of 90, 270 kg/hr, .78 at a flow rate of 60, 180 kg/hr and 0.93 at a flow rate of 30, 90 kg/hr. In the absorption process, the wheel effectiveness reached 0..38 at a flow rate of 120, 360 kg/hr, 0.5 at a flow rate of 90, 270 kg/hr, 0.57 at a flow rate of 60, 180 kg/hr and 0.62 at a flow rate of 30, 90 kg/hr.



(7-a)



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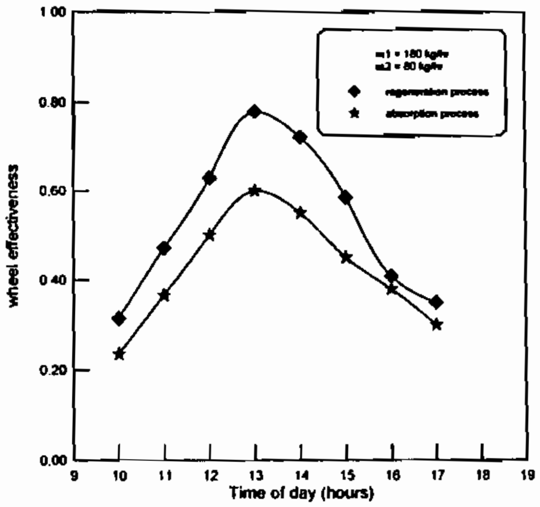
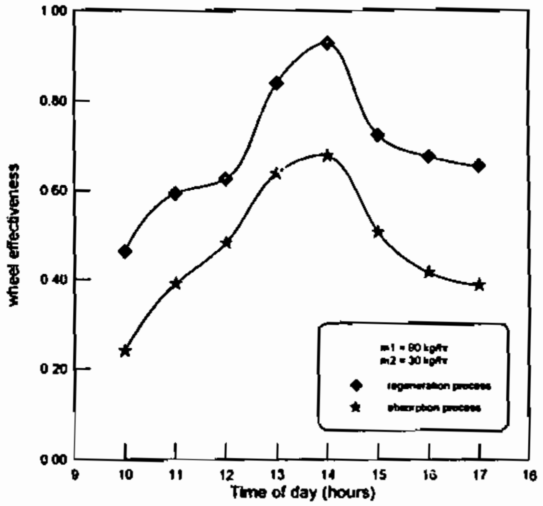


(7-c)



(7-d)

*Fig.7: Variation of wheel effectiveness for regeneration and absorption process during the day.*

The hourly amount of moisture added to air in the regeneration process at air flow rate 120 kg/hr for one day as an example during the daytime (Equation 3) is shown in Fig. 8. The amount of moisture realized is changed with time during the day. It reached 1000 g/hr after solar noon. The area under the curve represents the total accumulated amount of moisture realized during the day. This amount is approximately equals 5600 grams. The fresh water can be extracted from this moist air by cooling. This means that the proposed system can also be used to collect an amount of fresh water.

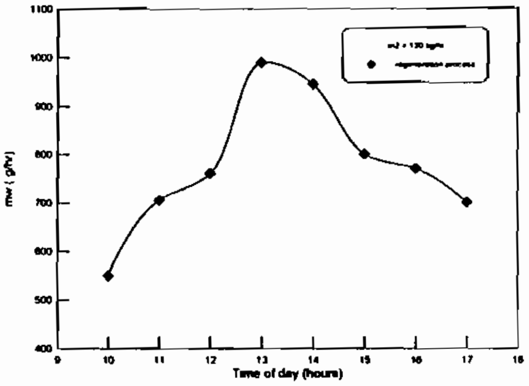
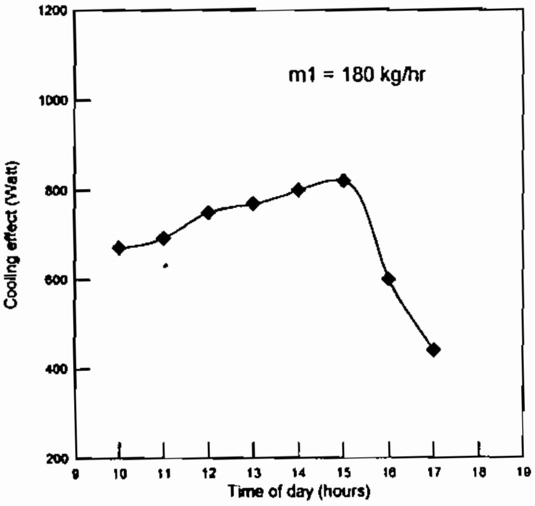
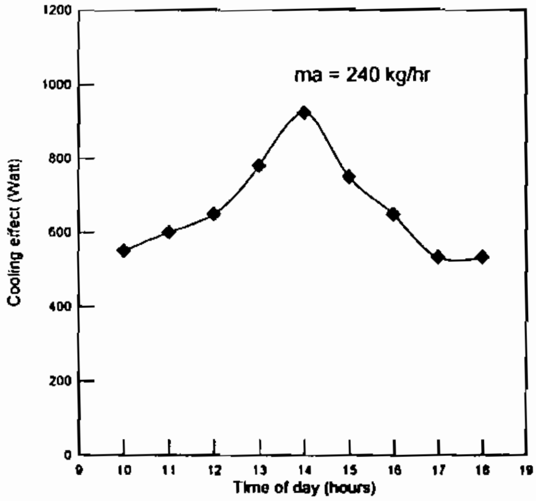


*Fig.8: The hourly amount of moisture removed for regeneration process during the day.*

Figure 9 shows the hourly variation of the cooling capacity during the day time at two different values of air flow rates. The cooling effect depends on the day time and the air flow rate. The maximum value reached 800 Watt at a flow rat of 180 kg/hr and reached 950 Watt at a flow rate of 240 kg/hr.



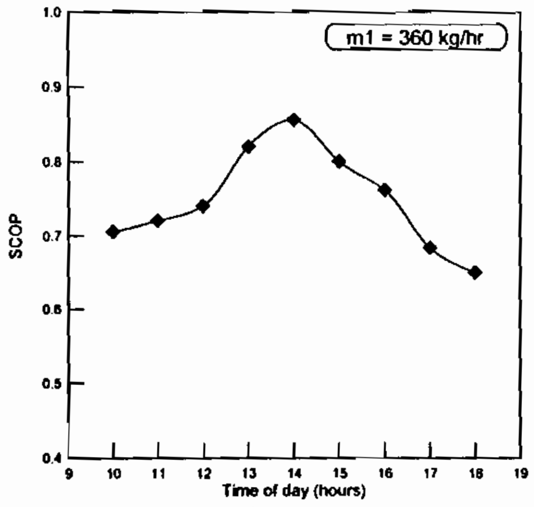
(9-a)



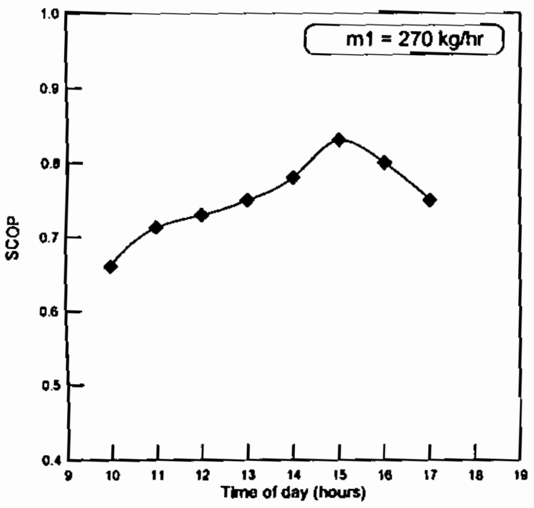
(9-b)

*Fig. 9: The hourly variation of cooling effect during the day.*

The thermal coefficient of the system performance (SCOP) is shown in Fig. 10. It depends on the time of day and the air flow rate in wheel regeneration. It reaches its maximum after solar noon and then decreases. The value reached 0.87 at a flow rate of 360 kg/hr and 0.82 at a flow rate of 270 kg/hr.



(10-a)



(10-b)

*Fig.10: The hourly variation of thermal coefficient of performance during the day time.*

Figures 11 and 12 illustrate the effect of air flow rate on the wheel effectiveness at solar noon for both regeneration and absorption processes. From these figures, it can be observed that the wheel effectiveness is higher for regeneration process compared with that of absorption process. Also, the figures show that the wheel effectiveness decreases with increasing the air flow rate. The following equations are obtained from the experimental results.

for regeneration process:

$$\psi = 1.05 - 0.0012\ m_2 \tag{8}$$

for absorption process:

$$\psi = 0.79 - 0.0033\, m_1 \tag{9}$$

$$\text{for } 30 \le m_1 \le 120 \text{ and}$$
$$100 \le m_2 \le 400$$

It will help the designer to predict the wheel effectiveness ψ at different flow rates, $m_1$ for absorption and $m_2$ for regeneration process.

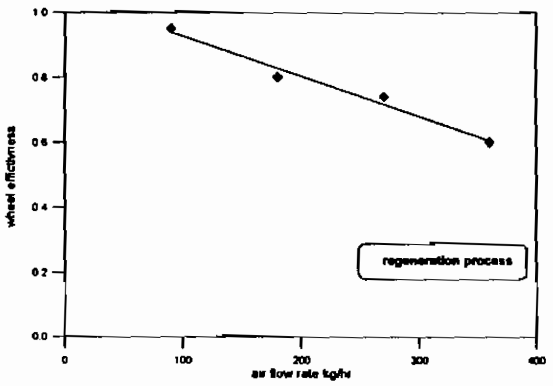


*Fig.11: Effect of air flow rate on the wheel effectiveness at solar noon* for regeneration process

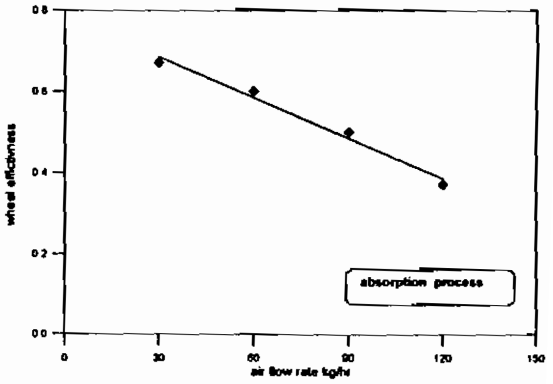


*Fig.12: Effect of air flow rate on the wheel effectiveness at solar noon for absorption process*

The variation of moisture removed in regeneration process at solar noon which can used to extract water from air with air flow rate is shown in Figure 13. It can be seen that the collected water increases with flow rate increases. The maximum value reaches 950 gm/hr at solar noon. Fitting of the experimental data presented in Fig. 13 is carried out and an empirical formula can be obtained,

$$mw = 250 + 5.5\, m_1 \quad \text{for } 30 \le m_1 \le 120 \quad \text{gm/hr} \qquad (10)$$

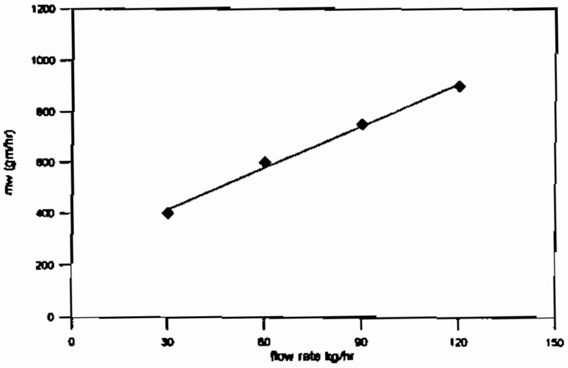


*Fig 13. The variation of the moisture which can be collected at solar noon with air flow rate*

## Conclusions

The performance of a solar powered desiccant air conditioning system using a rotary honeycomb wheel are studied at different conditions. The system parameters were investigated. These include the flow pass through the regeneration and absorption parts as well as the solar radiation intensity. In addition, employing the system to extract water from air was investigated. The following conclusions are extracted:

- The moisture change during regeneration and absorption process depends on both the solar radiation as well as the flow rate.
- The moisture change reached 9 g/kg air in the regeneration process and 4 g/kg air for the absorption process at a flow rate of 270 kg/h.
- The achieved efficiency of the porous type solar air heater is 0.6.
- The system is highly effective in the regeneration process for all flow rates.
- The wheel effectiveness depends on the solar radiation and the air flow rate. It approaches 0.9 for the regeneration process and 0.5 for the absorption process at a flow rate of 270 kg/h.
- The system can be dual effect for extracting water from air. It can extract 5 L/day at a flow rate of 270 kg/h.
- The cooling effect approaches 800W at a flow rate of 360 kg/h and 950 W at a flow rate of 360 kg/h.
- The empirical wheel effectiveness equations at solar noon can be as follows:

for regeneration process

$$\psi = 1.05 - 0.0012\ \mathrm{m}_2$$

for absorption process

$$\psi = 0.79 - 0.0033\, \mathrm{m}_1$$

$$\text{for } 30 \le m_1 \le 120 \text{ and}$$

$$100 \le m_2 \le 400$$

- The moisture removed which represented the collected water can be calculated from the following equation at solar noon.

$$mw = 250 + 5.5\, m_1 \text{ gm/hr}$$

$$\text{for } 30 \le m_1 \le 120$$

The above results are restricted to the system used.

## Nomenclature

| | |
|---|---|
| *A* | *Collector area, $m^2$* |
| Cp | Specific heat capacity (kJ/kg C) |
| *G* | *Solar radiation intensity, $W/m^2$* |
| $\Delta H$ | Specific cooling capacity, kJ/kg |
| $h_1$ | Enthalpy of air at ambient condition, kJ/kg |
| $h_2$ | Enthalpy of air after absorption process, kJ/kg |
| $M_{w1}$ | moisture removal capacity of supply air, g/hour |

| | |
|---|---|
| $M_{w2}$ | moisture added to air by regeneration process, g/hour |
| $m_1$ | Air flow rate in wheel regeneration part, kg/hr |
| $m_2$ | Air flow rate in wheel absorption part, kg/hr |
| $Q_C$ | the cooling capacity of desiccant assisted air condition, Watt |
| $w_1$ | Specific humidity of air at ambient condition,( g/kg) |
| $w_2$ | Specific humidity of air after absorption process,( g/kg) |
| $w_4$ | Specific humidity of air after regeneration process,( g/kg) |
| $S_{COP}$ | System coefficient of performance |
| $\psi$ | wheel effectiveness |
| $T_{out}$ | Collector exit temperature, C |
| $T_{inl}$ | Collector inlet temperature |
| $\varepsilon_w$ | the performance of the desiccant wheel's effectiveness |
| $\eta$ | the thermal efficiency of flat-plate collector |

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