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# The Influence of Air Flow Rate and its Temperature on the Moisture Absorption and Regeneration Processes.

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# THE INFLUENCE OF AIR FLOW RATE AND ITS TEMPERATURE ON THE MOISTURE ABSORPTION AND REGENERATION PROCESSES

**تأثير معدل سريان الهواء ودرجة الحرارة على عمليات امتصاص الرطوبة وإعادة التجديد**

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**خلاصة :**

إنتاج الماء العذب بامتصاص الرطوبة من الهواء الجوى قد يكون البديل الوحيد المتاح في بعض الأماكن والظروف. من الطرق المستخدمة لتحقيق هذا الغرض طريقة امتصاص بخار الماء من الهواء ثم إعادة توليد البخار وتكثيفه ويمكن أن تتم عملية الامتصاص عن طريق امرار الهواء على قماش مشبع بمحلول ملحي مناسب. في هذا البحث تمت دراسة تأثير حالة الهواء الداخل من حيث معدل سريانه ودرجة حرارته بهدف الوصول إلى أقصى معدل امتصاص وأفضل إعادة توليد البخار لتركيز المحلول. وقد تمت المفاضلة أيضاً بناءاً على أقل قدرة مستهلكة في تسخين أو تبريد الهواء، وكذلك تلك المستخدمة في دفعه. لهذا تم تصميم وإنشاء جهاز تجريبي، حيث استخدم محلول كلوريد الكالسيوم $CaCl_2$ في تشبيع القماش الذي تم تشكيله على شكل شمع عسل النحل. وقد تم استخدام ثلاث وحدات وضعت الأولى في اتجاه السريان والثانية في الوسط ثم وضعت الوحدة الأخرى وذلك بغرض دراسة مدى التغير في معدل الامتصاص والتجديد للثلاث وحدات وتحديد أيهما أفضل تغير درجة الحرارة أم زيادة كمية السريان في الحالتين. وقد أجريت التجارب على مجموعتين خلال إجرائي الامتصاص وإعادة التجديد مع تحليل نظري للنتائج أجريت المجموعة الأولى بتثبيت معدل سريان الهواء مع تغيير درجة حرارته، بينما حدث العكس في المجموعة الثانية. كما تم حساب الطاقة المستهلكة بناءاً على النتائج المقاسة. وقد أثبتت هذه النتائج أن تغير درجة حرارة الهواء لها تأثيراً أكبر خلال إجراء الامتصاص وكذلك أثناء إجراء إعادة تحديد تركيز المحلول. تم عرض النتائج في هذا البحث بطريقة لابعديه و بيانية.

## ABSTRACT

Production of fresh water by absorption of moisture from atmospheric air may be the only choice in some places and circumstances. This can be performed by introducing the air into a packed bed of clothes saturated with a suitable desiccant to absorb water vapour from air with subsequent regeneration and condensation of water vapour. In this work, the effect of air flow rate and its temperature on the rate of moisture absorption and the regeneration process is experimentally investigated. The power consumed in heating or cooling the air, and the blowing power are considered. For this purpose, an experimental setup is designed and constructed. A three honey comb packed bed units are arranged in the flow direction, such that the face of the upstream units is perpendicular to the flow. The middle and down stream units are fixed in the same way. The three beds are saturated with Calcium Chloride ($CaCl_2$)as a desiccant. The Experimental work is divided into two groups during the absorption and regeneration processes. The first group is carried out for constant air flow rate and different air temperatures, while the second group is carried out at constant air temperature and different flow rates. The power consumption is caleulated according to the measured data. Results have shown that increasing the air flow rate during absorption proeess is more effective, while increasing its temperature in the regeneration process is preferable. Results of this work are presented in dimensioless and graphical form.

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## INTRODUCTION

Due to rapid increase of population and per captia consumption, the demand of the water has been increased. The fresh water can be produced by different technical methods, desalination systems and by extraction of the moisture from atmospheric air. In some places such as Sahara in Arabic countrics which are far from the sea, potable water can be obtained by transportation from other location or extraction of water from air

Many researches were carried out to extract water from air by cooling it to a temperature lower than the air dew point [1-6]. The application of honeycomb bed as a desiccant carrier for absorption of moisture from air was also investigated [7].

Absorption and regeneration processes of water depend flow rate over the bed and its temperature. Increasing the air flow rate will increase the rate of absorption. On the other hand the required power increases with increasing the flow rate. Also, lowering the temperature of the flowing air increases the absorption and regeneration rate rises with increase in temperature. But the power consumption of the whole process will be increased.

To enhance the absorption or regeneration process as the power can be consumed in any of the following ways: increase the flow rate, decrease the air stream temperature during absorption and increase its temperature during regeneration, therefore it is interested to determine the way at which power consumption will be more efficient. The aim of the present study is to evaluate and compare the effectiveness of power consumption for enhancing either absorption or regeneration processes.

## THEORETICAL ANALYSIS

The efficiency of water extraction system depends on the power consumed, which depends on the air flow rate and its temperature. Increasing the air flow rate will increase the consumed power. Heating or cooling also increases the power consumption. Therefore to evaluate the effect of air temperature change and air flow rate on the system performance, the power consumed must be caleulated for these two conditions.

The power consumed $P_m$ due to pressure drop in the bed ean be caiculated from the following equation:

$$P_m = V.\Delta P \tag{1}$$

where $V$ is the volume flow rate of the air through the bed.

$\Delta$P is the pressure drop in the bed depends on the air velocity and the shape of the bed, it can be calculated from the following equation [8]:

$$\frac{\Delta P}{l} = \frac{-\mu.v}{K} - F.\rho.v^2 \tag{2}$$

where,

$\mu$ is the viscosity of the air,

$v$ is the air velocity,

$\rho$ is the air density,

$l$ is the bed thickness.
K is the permeability,
$F$ is the inertia coefficient of the porous medium that can be calculated from the following relation,

$$F = \frac{B(1-\varepsilon)}{\varepsilon^{2}} \quad (3)$$

where
$B$ is a dimensionless constant which depends on the Reynolds number, plate thickness, porosity distribution. According to Lavan et al [9], values of $B$ ranges from 1.5-1.7, $\varepsilon$ is the orthogonal porosity of the bed.

To evaluate the power at different values of air flow rate, the value of the first term of equation 2 equals 0.000031, it can be neglected, because it is very small, this results is identical with reference [9]. Therefore, the pressure drop in the cell can be evaluated from the following relation:.

$$\Delta P = -F.\rho.v^2 \quad (4)$$

$$\Delta P = k.v^2 \quad (5)$$

where $k$ is the equivalent resistance coefficient. It depends on the flow area and the inertia coefficient. It is calculated from the experimental work by measuring flow velocity and the pressure drop through the bed. In the present work its value is 0.0812.
From equation (1) and (5)

$$P_m = c.v^3 \quad (6)$$

where c is constant
Equations 5 and 6 show that the pressure drop and the consumed power depend only on the air velocity.

The heat consumed for heating or cooling the flowing air stream Q can be evaluated from the following equation

$$Q = m\,.c_p.\Delta T \quad (7)$$

where $m$ is the air flow rate, $c_p$ is the specific heat of air and $\Delta T$ is the temperature difference (rise or drop).

In case of generation the heat required can be assumed as that rejected from a heat pump which consumes power $P_h$:

$$P_h = \frac{Q}{(COP)_H} \quad (8)$$

where, $(COP)_H$ is the coefficient of performance of the heat pump. Assuming Carnot cycle operation,

$$(COP)_{II}=\frac{T_h}{T_h-T_a} \quad (9)$$

where $T_h$ is the regeneration temperature and $T_a$ is the ambient air temperature.

In ease of absorption with air cooling, the power required $P_c$ is assumed as that consumed by a cooling system, operating with Carnot cycle and can be calculated as follows:

$$P_c=\frac{Q}{(COP)_c} \quad (10)$$

where $\eta_c$ is the Carnot efficiency, which can be calculated from the following equation:

where $COP_c$ is the coefficient of performance of the cooling cycle.. Assuming reversed Carnot cycle,

$$COP_c=\frac{T_c}{T_h-T_c} \quad (11)$$

where $T_a$, $T_c$ are ambient and cooling temperatures, respectively. In this condition, power is consumed to decrease the ambient temperature to $T_c$.

## EXPERIMENTAL SET UP

Figure (1) shows a schematic diagram of the experimental set up which is described in previous work [7]. It that contains a centrifugal fan with variable speed from 0 to 1450 r.p.m in order to control the rate of air stream. Variable capacity heater is also used to control the temperature of the inlet air to the test section that consists of three identical honeycomb, the first is in upward direction, the second is downward direction and the third is in the middle. Each honeycomb have a dimensions (18 cm x 18 cm x 5 cm) placed in series. The face (18 x 18 cm) of the honeyeomb bed units is devided into 16 cells (4 x 4) facing flow. Each honeycomb is made of aluminum wire which is welded together to gave honeycomb cross section. A thick layer of cloth around the honeycomb was used as a bed carrying the desiccant solution $CaCL_2$.

Each cell of the bed is weighed and then impregnated in the desiccant solution. During the absorption and regeneration process, the mass of each cell is recorded every 5 minutes in order to evaluate the mass of absorbed water during this time interval. The experiments were carried out at different values of air flow rate (0.00324, 0.029, 0.0389, 0.04536, .06395 Kg/s) and at different inlet temperatures (21, 22, 23, 25, 27 $^0$C). The air stream velocity is measured as average value across the bed inlet and exit by a hot wire anemometer. Temperatures at inlet and outlet section are measured at different points using thermocouples and the average value is evaluated.

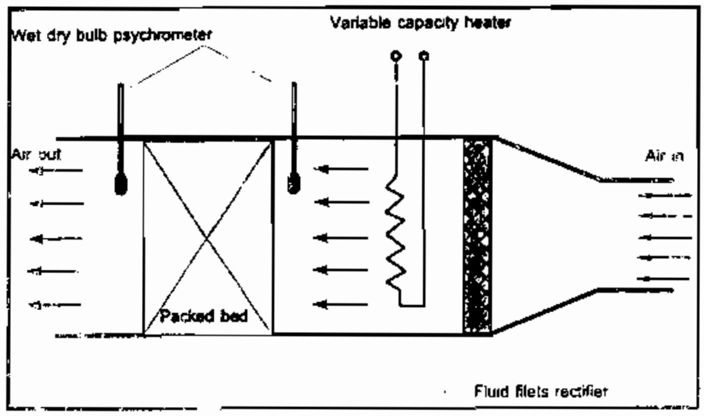


**Fig. 1: Experimental set up**

## ANALYSIS OF EXPERIMENTAL MEASUREMENTS

Since $Ca\ Cl_2$ salt is not volatile, the concentration of the solution can be calculated from the following equation:

$$Xo\ M_o = X_i\ M_i \tag{12}$$

where:
$M$ is the mass of solution and $X$ is the solution concentration in the bed, subscripts o and i refers to initial and instantaneous conditions

$$M_i = M_t - M_b \tag{13}$$

where $M_b$ is the mass of the dry bed, $M_t$ is the total mass of bed and solution.

The humidity ratio of air can be calculated at the bed exit section from the following equation.

$$W_o = W_i \pm \frac{\Delta m}{\Delta \tau . m_a} \quad \text{(+ sign for regeneration and - sign for absorption)} \tag{14}$$

$\Delta m$ is mass of absorbed water and $\Delta \tau$ is the absorption period and $m_a$ is the mass flow rate of flowing air..

The vapour pressure in the air $P_v$ can be calculated from this equation:

$$P_v = \frac{W_o P}{0.622 + W_o} \tag{15}$$

where $W_o$ is the humidity ratio of air at exit section and $P$ is the ambient air pressure.
The mass transfer coefficient β can be evaluated from the following relation,

$$\beta = \frac{\Delta m}{\Delta \tau \, \Delta P \, A} \tag{16}$$

and $\Delta P = P_v - P_s$ (17)

where $P_s$ is the water vapour pressure on the bed surfaee

$$t_r = \frac{t_i}{t_{max}} \tag{18}$$

where $t_{max}$ is the saturation time at ambient temperature for practical lowest flow rate

$$M_r = \frac{M}{M_c} \tag{19}$$

$M_c$ is the mass of elothes in the bed.

The power ratio ( $P_r$ ) is calculated from the following relation:

$$P_r = \frac{P_i}{P_{max}} \tag{20}$$

where , $P_i$ , $P_{max}$ are the instantaneous power and maximum power respectively.

## RESULTS AND DISCUSSION

The experimental tests are carried out at different inlet air temperatures and different air flow rate. The aim of the experiments is to study the effect of air cooling and air flow rate on the absorption and regeneration processes of a honeycomb bed impregnated with liquid desiccant of $CaCL_2$.

Figures (2,3 and 4) show the mass ratio (Mr) variation with time ratio (Tr) at different temperatures and at constant air flow rate through the honeycomb bed. The mass ratio (Mr) in absorption process is the ratio between the mass of water in the bed to the mass of the clothes in the bed. The mass of clothes in the bed cquals 17 gm. The mass ratio increases with decreasing the temperature of inlet air. The time ratio ($T_r$) in absorption process is the ratio between the instantaneous absorption time and the maximum time for saturation. The maximum saturation time is the saturation time at ambient temperature for practical lowest flow rate. In the present work the maximum saturation time is about 100 minutes in absorption process and 60 minutes in regeneration process. The practical lowest flow rate in the present work equals 0.00324 kg/s. The mass ratio reached to maximum value 1.8 at a time ratio of 1 for the middle honeycomb bed cell, 1.4 for the dowoward honeyeomb bed and 1.6 for the upward honeycomb bed.

The variation of mass ratio versus time ratio for different flow rates at constant inlet air temperature to the cells is presented in Figures ( 5, 6 and 7). The mass ratio increases with the increase of the air flow rate. The maximum value of the mass ratio is 1.8 at a time ratio equals 1, at maximum value of flow rate (0.06395 kg/s).

Figures from (8 to 13) show the regeneration process. Figures (8, 9 and 10) show the variation of the mass ratio (Mr) and the time ratio (Tr) at constant temperature and different air flow rates 0.029, 0.0389 , 0.04536 and 0.06395 kg/s. The mass ratio (Mr) in the regeneration process is the ratio between the mass of solution regeneration from the bed to the mass of the clothes in the bed. The time ratio in the regeneration process is the ratio between the time during the experiment and maximum saturation time, the maximum saturation time is the saturation time for the practical lowest flow rate. The variation of the mass ratio versus time ratio for different temperatures 35 , 40, 45, 49 C at constant flow rate are presented in Fig 11, 12 and 13. The mass ratio increases with the decrease flow temperature at constant flow rate.

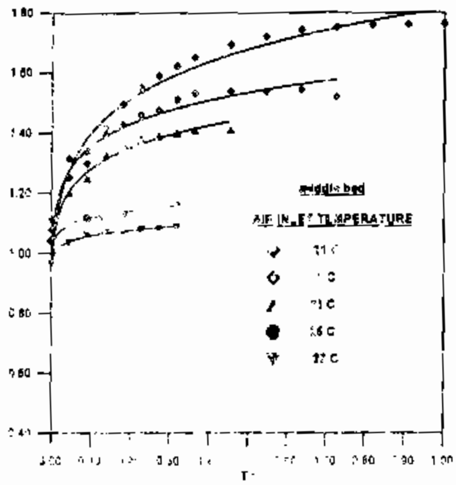


Fig 2: Variation of the mass ratio versus time ratio for [illegible] honeycomb bed at constant mass flow rate 0.0639 kg/s

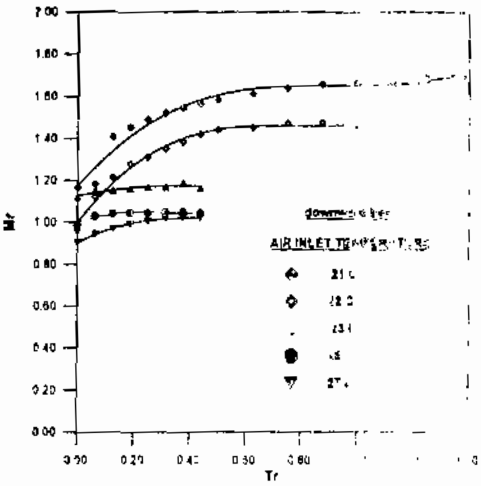


Fig 3: Variation of the mass ratio versus time ratio for the downward honeycomb bed at constant mass flow rate 0.0639 kg/s

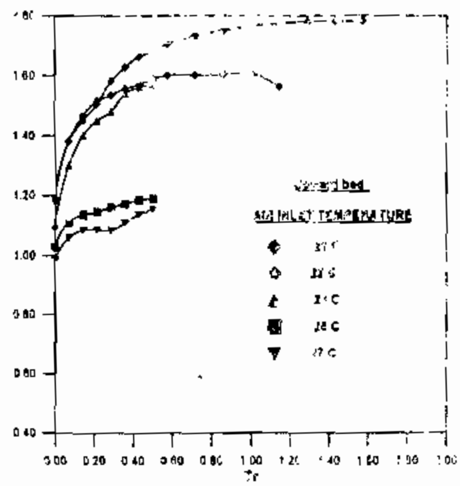


Fig 4: Variation of the mass ratio versus time ratio for the upward honeycomb bed at constant mass flow rate 0.0639 kg/s

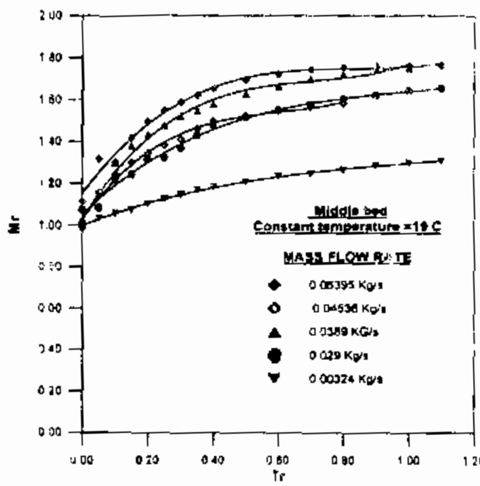


Fig 5: Variation of the mass ratio versus time ratio for middle honeycomb bed at constant temperature 19 c.

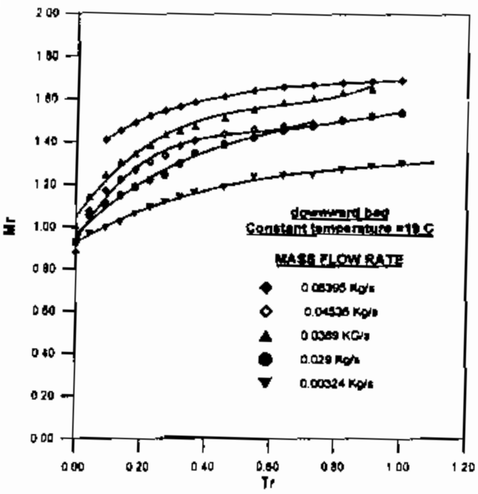


Fig 6: Variation of the mass ratio versus time ratio for downward honeycomb bed at constant temperature 19 C.

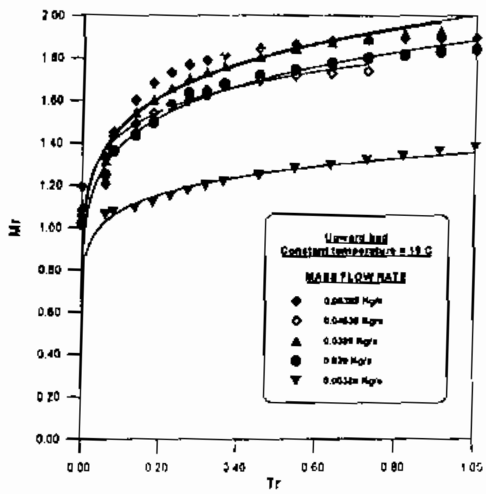


Fig 7: Variation of the mass ratio versus time ratio for upward honeycomb bed at constant temperature 19 C.

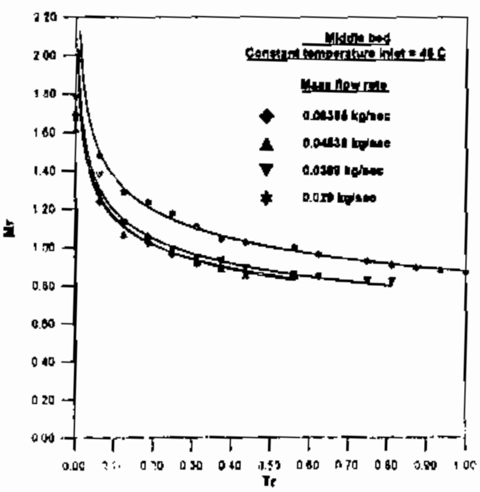


Fig 8: Variation of the mass ratio of bed versus time ratio for middle honeycomb bed at constant temperature

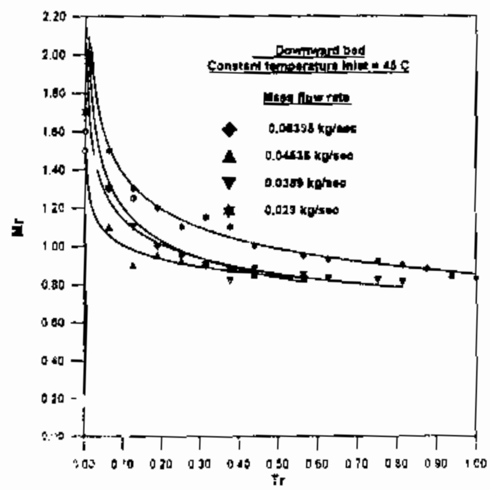


Fig 9: Variation of the mass ratio of bed versus time ratio for downward honeycomb bed at constant temperature

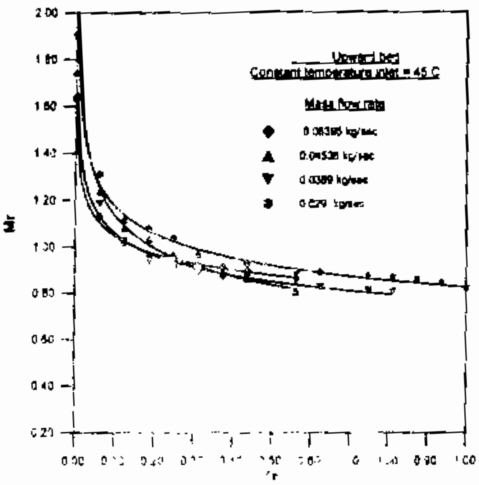


Fig 10: Variation of the mass ratio bed versus time ratio for upward honeycomb bed at constant temperature

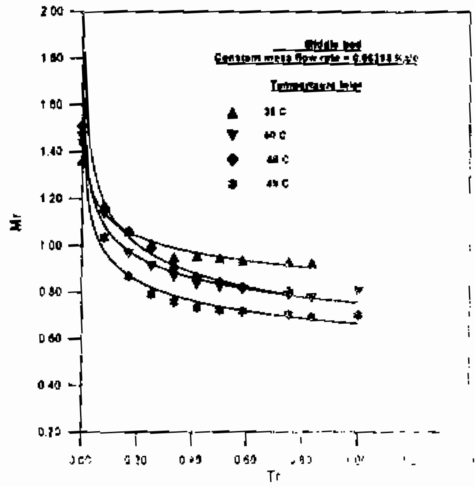


Fig 11: Variation of the mass ratio versus time ratio for middle honeycomb bed at constant air flow rate

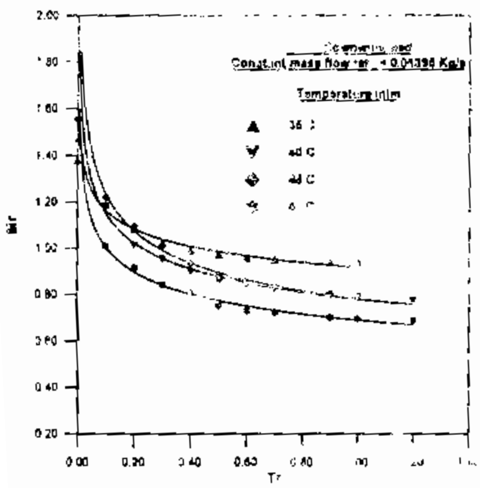


Fig 12: Variation of the mass ratio versus time ratio for downward honeycomb bed at constant air flow rate .

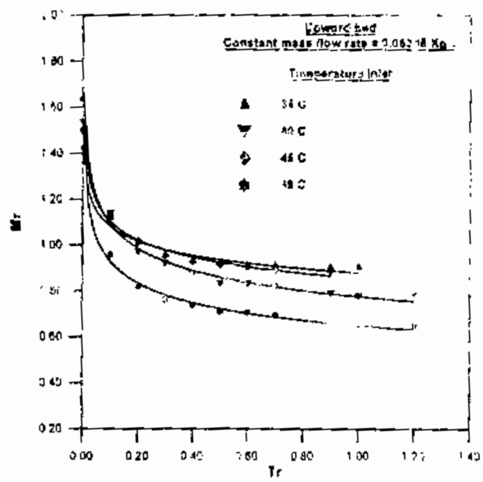


Fig 13: Variation of the mass ratio versus time ratio for upward honeycomb bed at constant air flow rate .

Figure 14 shows the variation of power ratio versus mass ratio for both absorption and regeneration. The absorbed (regenerated) mass ratio is higher due temperature change, than that due to flow rate change. However, the mass ratio for the absorption process is higher than that of regeneration process either for temperature or mass flow rate change. For example, at a power ratio of unity the mass ratio during the absorption process is equal to 1 for temperature change, but it equals to 0.45 during regeneration process. For flow rate change ( at the same power ratio), the mass ratio is 0.7 for the absorption process and 0.45 for regeneration process.

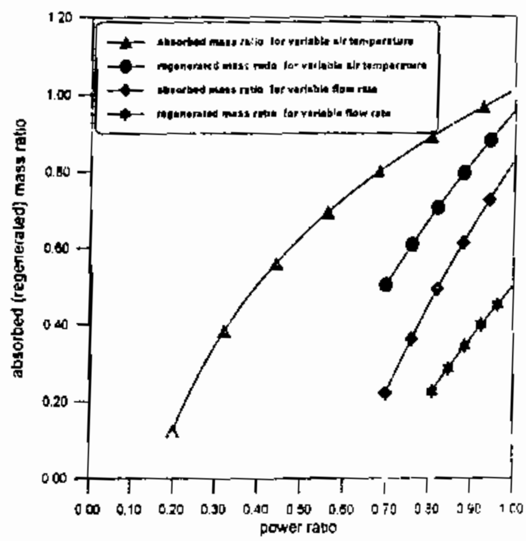


Fig. 14: variation of absorption (regeneration) mass ratio versus power ratio

The mass transfer coefficient is ealculated from equation (16) for the absorption and regeneration at variation of flow rate and its temperatures. Results are shown that the average value of mass transfer coefficient ranged from 0.04 to 0.05 kg/s.m. mm$^2$ .Hg.

## CONCLUSIONS

- In this work, the absorption of moisture from atmospheric air to produce fresh water is investigated. The effect of air flow rate and its temperature on the absorption and regeneration processes for a honeycomb packed bed saturated with Calcium Chloride (Ca $Cl_2$) as a desiccant is experimentally tested. The power consumed in heating or cooling the air, and the blowing power are considered. For this purpose, an experimental setup is designed and constructed. A honeycomb packed bed saturated with Ca $Cl_2$ as a desiccant is employed. The power consumption is calculated according to the measured data. Results have shown that, during the absorption process, the change of inlet air temperature is more effective in vapour absorption than increasing the flow rate. Increasing the inlet air temperature is also more effective in the regeneration process. In all cases ( temperature change and flow rate change ) the mass exchange is higher in absorption process than that of regeneration process.

## NOMENCLATURE

dimensionless constant, Eq. (3)

specific heat of air, kJ/kg. k

the coefficient of performance for heat pump

the coefficient of performance for cooling cycle.

specific flow resistance coefficient, Eq (5)

the permeability, m$^2$

the bed thickness, m

the mass of water in the bed, gm

the air flow rate, kg/s

the mass of the dry bed, gm

the mass of clothes in the bed, gm

the ratio between the mass of water in the bed to the mass of the clothes in the bed

| | |
|---|---|
| $M_t$ | the total mass of bed and solution, gm. |
| o, i | initial and instantaneous condition |
| $P_c$ | the consumed power for cooling, W |
| $P_h$ | heat pump consumed power, W |
| $P_i$ | the instantaneous power, W |
| $P_{max}$ | the maximum power supplied, W |
| $P_r$ | the power ratio. |
| $P_s$ | the water vapour pressure on the bed surface, mm Hg |
| $P_v$ | the vapour pressure in the air, mm Hg |
| $Q$ | the heat consumed, W |
| $T_c$ | the cold temperature, K |
| $T_h$ | the hot temperature, K |
| $t_i$ | the instantaneous absorption time, s |
| $t_{max}$ | the saturation time at ambient temperature for practieal lowest flow rate, s |
| $t_r$ | the ratio between the instantaneous absorption time and the maximum time for saturation |
| v | the air velocity, m/s |
| $V$ | the volume flow rate, $m^3/s$ |
| $F$ | the inertia coefficient of the porous medium |
| $W_o$ | the humidity ratio of air at exit section. |
| $X_o$ | the initial concentration |
| $\Delta P$ | the pressure drop through the honeycomb bed, $N/m^2$ |
| $\Delta T$ | the temperature difference (rise or drop), K. |
| $\Delta m$ | mass of absorbed water, gm |
| $\Delta \tau$ | the absorption period, sec |
| $\mu$ | the dynamic viscosity of the air flow rate, $N.s.m^2$ |
| $\beta$ | the mass transfer coefficient, $kg/sec.^2mm$ Hg |
| $\rho$ | the air flow rate density, $kg/m^3$ |
| $\eta_c$ | the Carnot efficiency |

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