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Experimental investigation on the performance of packed tower for regeneration of liquid desiccant

دراسة تجريبية حول آداء برج مضغوط لإعادة توليد محلول ماص للرطوبه

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KEYWORDS:
Desiccant, Regenerator, Packed tower, Calcium chloride, Packing of burned clay.

الملخص العربي:- **يعتبر المولد (Regenerator) من المكونات الأساسية في أنظمة التكييف باستخدام محلول ماص للرطوبة، وفعاليتة تؤثر مباشرة على آداء النظام. تم عمل دراسة تجريبية حول آداء نظام إعادة توليد محلول ماص في مهد مضغوط، وتم تصميم وتركيب وحدة الاختبار التجريبية في معمل الاحتراق بكلية الهندسة جامعة المنصورة. تم استخدام محلول كلوريد الكالسيوم كمحلول ماص في وجود حشوة من قطع الطين المحروق ذات شكل عشوائي مساميتها 0.22 ومتوسط حجم ووزن القطعة منها هو ($90.25\ cm^3$, 88.4 gram) على الترتيب. المدخلات المتغيرة في هذه التجربة هي درجة حرارة الهواء الداخل، معدل سريان الهواء الداخل ومعدل سريان المحلول الماص. المخرجات المقاسة أو المستنتجة رياضيا من النتائج في هذه التجربة هي درجة حرارة الهواء الخارج، نسبة الرطوبة في الهواء الخارج وتركيز ودرجة حرارة خروج المحلول الماص. تمت دراسة النتائج ورسمها بيانيا لتوضيح تأثير المدخلات المتغيرة للهواء والمحلول الماص على المخرجات، وتبين من هذه النتائج أنه بزيادة درجة حرارة الهواء الداخل (60, 80, 100 and 120 °C) حيث نسبة الرطوبة للهواء الداخل ($0.0127, 0.0123, 0.0114$ and $0.0130\ kg/kg_{da}$) تزداد نسبة الرطوبة للهواء الخارج ($0.0206, 0.0232, 0.0249$ and $0.0334\ kg/kg_{da}$) وكذلك يزداد التغير في التركيز للمحلول الماص (0.63, 1.13, 1.95 and 2.25 %) على الترتيب ، كما تبين أنه بزيادة معدل سريان الهواء الداخل ($0.0252, 0.0529, 0.0659$ and $0.0683\ m^3/s$) حيث نسبة الرطوبة للهواء الداخل ($0.0147, 0.0177, 0.0178$ and $0.0184\ kg/kg_{da}$) تزداد نسبة الرطوبة للهواء الخارج ($0.0245, 0.0293, 0.0302$ and $0.0312\ kg/kg_{da}$) وكذلك يزداد التغير في التركيز للمحلول الماص (0.78, 2.21, 2.57 and 3.01 %) على الترتيب وعلى عكس ذلك فإنه بزيادة معدل سريان المحلول الماص (1, 2 and 3 LPM) حيث نسبة الرطوبة للهواء الداخل ($0.0175, 0.0151$ and $0.0148\ kg/kg_{da}$) تقل نسبة الرطوبة للهواء الخارج ($0.0278, 0.0274$ and $0.0267\ kg/kg_{da}$) وكذلك يقل التغير في التركيز للمحلول الماص (2.86, 2.58 and 2.23 %) على الترتيب.**

***Abstract*— In a liquid desiccant air conditioning system the regenerator is one of the essential components. The effectiveness of the regenerator directly influences the system performance. An experimental investigation on the performance of packed tower for regeneration of liquid desiccant is carried out. The experimental test unit has been designed and installed in the combustion Lab., Faculty of Engineering, Mansoura University, Egypt. A solution of calcium chloride is used as a working desiccant with a packing of burned clay pieces with a random shape, its porosity is about 0.22 and the average size and weight of the piece are about ($90.25\ cm^3$, 88.4 gram) respectively. The input variables used in the experiment are air inlet temperature, air flow rate and solution flow rate. The outlet parameters which are measured or calculated from the experimental results are air outlet temperature, air humidity ratio, desiccant solution outlet temperature and concentration. To illustrate the effect of air and liquid desiccant parameters on the outlet variables the**

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experimental results are plotted. Based on these results, higher air inlet temperature (Tai = 60, 80, 100 and 120 °C) where the air inlet humidity ratio (0.0127, 0.0123, 0.0114 and 0.0130 kg/kg$_{da}$) results in higher average air humidity ratio (0.0206, 0.0232, 0.0249 and 0.0334 kg/kg$_{da}$) and the %age change of desiccant solution concentration (0.63, 1.13, 1.95 and 2.25 %) respectively. And higher air flow rate (Ma = 0.0252, 0.0529, 0.0659 and 0.0683 m^3/s) where the air inlet humidity ratio (0.0147, 0.0177, 0.0178 and 0.0184 kg/kg$_{da}$) results in higher average air humidity ratio (0.0245, 0.0293, 0.0302 and 0.0312 kg/kg$_{da}$) and the %age change of desiccant solution concentration (0.78, 2.21, 2.57 and 3.01 %) respectively. Increase in solution flow rate (Ms = 1, 2 and 3 LPM) where the air inlet humidity ratio (0.0175, 0.0151 and 0.0148 kg/kg$_{da}$) results in lower average air humidity ratio (0.0278, 0.0274 and 0.0267 kg/kg$_{da}$) and the %age change of desiccant solution concentration (2.86, 2.58 and 2.23 %) respectively.

I. INTRODUCTION

DEHUMIDIFICATION is the process of removal/decreasing of water vapor from moist air. It can be achieved by either cooling or absorption/adsorption of moisture by solid or liquid desiccants. The liquid desiccant air-conditioning system has been proposed as an alternative to the conventional vapor compression cooling systems to control air humidity, especially in hot and humid areas, due to its advantage in removing the latent load as well as the potential to remove number of pollutants from the air stream [1-11]. Liquid desiccant generally has a lower water vapor partial pressure than air at the same temperature, as a result of this; desiccants can absorb moisture from air when they are brought into contact. The desiccant is diluted during the dehumidification process and needs to be regenerated before being reused. Packed columns or towers are widely used for gas absorption or liquid regeneration. The regenerator is one of the most significant heat and mass transfer elements in a liquid desiccant system. The heat for regeneration purpose is supplied either as hot air or hot desiccant.

In the experimental study due to Lof et al [12] and Patnaik et al [13], heat source for regeneration is hot air at 80~110˚C with LiCl as desiccant at 40˚C in counter flow packed bed regenerator. Other researchers [14-16] tested the performance of hot desiccant type regenerators. Fumo and Goswami [14] tested the counter flow regenerator performance. They found that air flow rate, desiccant temperature and concentration had the greatest impact on the regenerator performance. Liu et al. [15] used LiBr with cross flow configuration. They showed the effects of air inlet humidity ratio, inlet temperature and flow rate and desiccant inlet temperature, inlet concentration and flow rate on the moisture removal rate and regenerator effectiveness. Yin et al. [16] used LiCl and tested the counter flow regenerator performance with desiccant inlet temperature higher by 40˚C than inlet air. They found that the average mass transfer coefficient of the packing regenerator is 4 g/ (m^2 s) and the dehumidifier and regenerator are the key components of the new type of healthy air conditioning liquid desiccant evaporation cooling system. Each researcher has used different types of desiccants at different temperatures of air and desiccants for counter, cross or parallel flow between air & desiccant. Sultan et al. [17] studied the effect of inlet parameters on the performance of packed tower regenerator. They found that the regeneration rate decreases with an increase in humidity ratio of inlet air and solution inlet concentration for the given range of operation for inlet parameters. Salarian et al. [18] studied the size and performance of a dehumidification tower by simulating various operating conditions and presented the performance of a packed tower absorber for a lithium chloride desiccant dehumidification system. They showed the effects of the main variables such as air flow rate, liquid desiccant flow rate and inlet air temperature on the rate of dehumidification. Ani et al. [19] tested the performance of a hybrid liquid desiccant system for various packing heights. They concluded that 1000 mm packing height is found to be the most suitable among the tested range and the one which result in 17.9–48.5% improvement of the coefficient of performance. Gandhidasan et al. [20] investigated the heat and mass transfer in a gauze-type structured packing liquid desiccant dehumidifier. They showed the effect of various independent variables such as air inlet absolute humidity, desiccant flow rate and its concentration on the performance of a liquid desiccant dehumidifier. Elsarrg [21] investigated the effect of varying various design parameters such as air and liquid flow rates, humidity ratio and packing height on the removal rate. It is found that the liquid flow rate has no significant effect on the moisture removal rate when the liquid to air flow ratio has exceeded the value of 2. Kumar et al. [22] studied the effect of solution flow rate and air inlet temperature on different outlet parameter; the evaporation rate, regenerator effectiveness, out let dry bulb temperature of the air, %age change in the concentration and solution outlet temperature. They found that the performance parameter evaporation rate and the effectiveness of the regenerator are increased as we increase the mass flow rate and the inlet dry bulb temperature of the air. The % change in the concentration is increases for the both cases. But the temperature of the solution is increased as we increases the mass flow rate but decreases as we increase the inlet dry bulb temperature. The outlet dry bulb temperature is increases for the both cases. Asati et al. [23] studied the effect of inlet process parameters on the effectiveness of dehumidifier and regenerator of liquid desiccant cooling system. They found that the effectiveness of dehumidifier increases with solution flow rate, inlet specific humidity while decreases with increasing mass flow rate of air, inlet temperature of air and desiccant, temperature and concentration of desiccant solution. The effectiveness of regenerator increases with increasing solution flow rate and inlet desiccant concentration and it decreases with increasing inlet air temperature, air flow rate and inlet solution temperature.

There are several parameters that affect the performance of packed tower regenerator. In the present investigation the effect of air flow rate, solution flow rate and air inlet temperature upon the outlet parameters are studied.

II. EXPERIMENTAL STUDY

To study the effect of operating parameters on the performance of desiccant regenerator, an experimental test unit has been designed and installed. A schematic diagram as well as view of the experimental unit is given in Figs. 1 and 2 respectively. The experimental set-up consists mainly of air blower (1), square steel duct (2), air damper (3), Electric heater (4), desiccant solution tank (5), submersible pump (6), ball valve (7), rotameter (8), pipe and rubber hose (9), liquid distributor (10), packed tower (11), packing of burned clay (12), sampling valve (13), vane type anemometer (14) and Thermocouple (T).

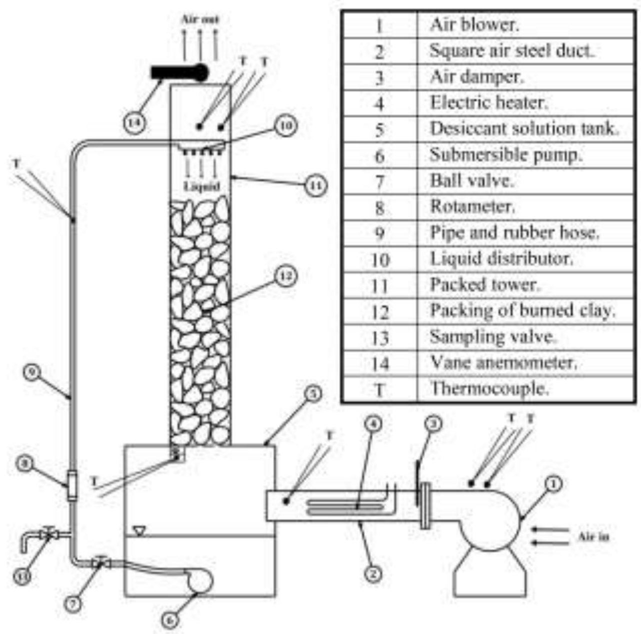

Fig.1. Schematic diagram of the experimental study.

For visual observation, desiccant solution tank is made of plexyglass and its dimensions are (30cm×30cm) cross section and (40cm) height. This tank contains calcium chloride as liquid desiccant solution. Submersible pump, made of plastic from a material that resists liquid desiccant solution is immersed in desiccant solution tank to transfer liquid desiccant through the pipe and rubber hose to the liquid distributor at the top of the packed tower. To control the solution flow rate, a ball valve is fitted through the pipe and rubber hose. A square steel duct of (7cm×7cm) cross section is used to carry the atmospheric air from the blower to the bottom of the packed tower. The liquid desiccant solution and atmospheric air are flowing through the packing of burned clay in counter flow in the packed tower. The porosity of the used packing of burned clay is evaluated be measuring the total value of the burned clay after covering the outside surface by a thin layer of plastic stretch. Then the porous material is impregnated with water and the value is measured. The difference between these two values represents porosity. The packing height is 1m. To control the air flow rate an air damper is designed and fitted at the blower discharge. An electric heater is fitted through the air duct to control the air temperature at tower inlet. The heater was connected to the A.C. supply through a voltage regulator. A glass wool layer is used to insulate the square steel duct to minimize heat loss.

Fig.2. View of the experimental study.

To measure the solution flow rate a rotameter is fitted through the pipe and rubber hose after the ball valve. The rotameter was calibrated by using water and also by using desiccant solution, it is found that there is a little difference between them. K-type thermocouples are located at the positions as shown in Fig.1 to measure the inlet and outlet temperatures of both the air and liquid desiccant streams. Humidity ratio of air at inlet and outlet is evaluated by measuring the air wet and dry bulb temperature. The air stream velocity is measured by using a vane type anemometer. To evaluate the desiccant solution concentration at the tank the solution density and temperature are measured. The solution concentration is given as a function of measured density and temperature [24]. The density of the solution is evaluated by taking a sample from liquid desiccant solution in a vessel of 1000 cm^3 and its weight is measured by using a digital balance of 1gram resolution.

III. EXPERIMENTAL PROCEDURE

A calcium chloride desiccant solution of desired concentration is put in solution tank. The submersible pump and air blower and heater are started and the operation starts. The inlet and outlet parameters of air and solution are recorded. The liquid desiccant flows through the pipe and rubber hose to the liquid distributor. The liquid distributor distributes the solution uniformly over the packing. The desiccant flows in the downward direction through the packing. The air blower sucks the atmospheric air. The air enters the square air steel duct passing through the heater. The hot air enters the packed tower at the bottom and flows upward. The air comes in contact with the desiccant due to which the desiccant losses moisture to the air. The humidified air comes out at the top of the packed tower. The desiccant solution is collected at the bottom of the packed tower in a desiccant tank and its concentration is measured. Different air and solution inlet and outlet temperature, air inlet and outlet humidity ratio are recorded.

The data collected for each experiment were:

- Air stream velocity using a vane anemometer that is located at the top of the backed tower.
- Desiccant solution flow rate using a rotameter.
- Air inlet temperature using a thermocouple that is located after air heater.
- Wet and dry air inlet temperature using two thermocouples that are located beside the air blower.
- Wet and dry air outlet temperature using two thermocouples that are located at the top of the packed tower.
- Desiccant solution inlet temperature using a thermocouple that is located inside the top of rubber hose.
- Desiccant solution outlet temperature using a thermocouple that is located at the bottom of the backed tower
- The weight of a desiccant solution sample in a vessel of 1000 cm^3 using digital balance to evaluate the density of the solution.

Three groups of experiments have been performed to study the following:

A. Effect of air inlet temperature on the outlet parameters

In these tests the effect of air inlet temperature change (T_{ai} = 60, 80, 100 and 120 ˚C)±1˚C respectively on the outlet parameters at constant air flow rate of 0.0252 m^3/s and solution flow rate of 2 LPM has been studied.

B. Effect of air flow rate on the outlet parameters

In this test group, the effect of air flow rate change (M_a = 0.0252, 0.0529, 0.0659 and 0.0683 m^3/s) respectively on the outlet parameters at constant air inlet temperature of 80 ˚C and solution flow rate of 2 LPM has been studied.

C. Effect of solution flow rate on the outlet parameters

In this group, the effect of desiccant solution flow rate change (M_s = 1, 2 and 3 LPM) respectively on the outlet parameters at constant air inlet temperature of 80 ˚C and air flow rate of 0.0714 m^3/s has been studied.

The ranges of the operating conditions employed in this experimental study are listed in Table1.

TABLE I
RANGES OF OPERATING CONDITIONS

Parameter	Range
Air inlet temperature (˚C)	49.8 – 120.7
Solution inlet temperature (˚C)	28.7 – 42.3
Air stream velocity (m/s)	0.41 – 1.20
Air flow rate (m^3/s)	0.0252 – 0.0739
Solution flow rate (LPM)	1 – 3
Solution concentration (%)	25.32 – 30.46
Air inlet humidity ratio (kg/kg_{da})	0.0105 – 0.0358

IV. PERFORMANCE ANALYSIS

Referring to the regenerator control volume shown in Fig.3, the energy balance equation can be written as follows:

$$\dot{m}_{s.i}h_{s.i} + \dot{m}_{a.i}h_{a.i} = \dot{m}_{s.o}h_{s.o} + \dot{m}_{a.o}h_{a.o} \qquad (1-a)$$

Where:

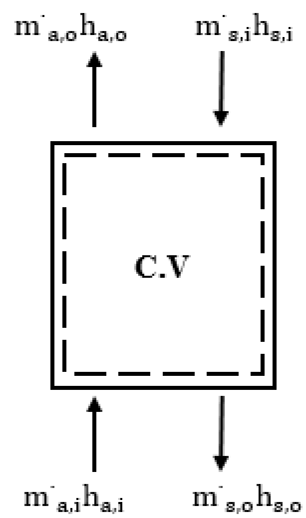

Fig. 3. Control volume of regenerator.

$$\dot{m}_{s.o} = \dot{m}_{s.i} = \dot{m}_{s} \qquad \dot{m}_{a.o} = \dot{m}_{a.i} + (MRR)$$

Equation (1 – a) becomes:

$$\dot{m}_{s}h_{s.i} + \dot{m}_{a.i}h_{a.i} = \dot{m}_{s}h_{s.o} + \dot{m}_{a.i}h_{a.o} + (MRR)h_{a.o} \qquad (1-b)$$

$$\dot{m}_{s}(h_{s.i} - h_{s.o}) = \dot{m}_{a.i}(h_{a.o} - h_{a.i}) + (MRR)h_{a.o} \qquad (1-c)$$

In the present work, some important parameters are used for evaluating the performance of the regenerator as follows:

A. Moisture removal rate (MRR)

The MRR is defined as the rate of which moisture is removed from desiccant solution into process air.

$$MRR = \dot{m}_{a}(HR_o - HR_i) \qquad (2)$$

B. Regeneration effectiveness (ε_{reg})

The regeneration effectiveness is defined as the actual HR drop of the process air to the maximum possible drop, it is calculated as:

$$\varepsilon_{\mathrm{reg}} = \frac{\mathrm{HR_o} - \mathrm{HR_i}}{\mathrm{HR_{eq}} - \mathrm{HR_i}} \tag{3}$$

Where HR_{eq} is the HR of air in equilibrium with $CaCl_2$ solution at the interfacial area, it is calculated from the following equation:

$$\mathrm{HR_{eq}} = \frac{0.622\mathrm{p_{vs}}}{1.013 \times 10^5 - \mathrm{p_{vs}}} \tag{4}$$

Where P_{vs} is the partial vapor pressure on the desiccant solution surface. The partial vapor pressure of the desiccant solution is given as a function of measured temperature and evaluated concentration.

C. Average mass transfer coefficient (K_{av})

The average mass transfer coefficient is defined as the rate of moisture flux passing through a unit area (kg/m^2.s). It can be obtained from the measured data as follows:

$$\mathrm{K_{av}} = \frac{(\mathrm{MRR})}{\mathrm{A}\left(\mathrm{HR_{av}} - \mathrm{HR_{eq}}\right)} \tag{5}$$

Where A is the interfacial area of contact between liquid desiccant and air inside the regenerator, $HR_{av}=(HR_{in}+HR_{out})/2$ is the average process air HR across the regenerator.

V. RESULTS AND DISCUSSION

Three sets of experiments have been performed. Figure 4 shows the effect of air inlet temperature on the air outlet humidity ratio. From this figure, it can be seen that increase in air inlet temperature leads to increase in air outlet humidity ratio. The increase of air outlet humidity ratio with the increase of air inlet temperature is due to increase in air vapour pressure. The driving potential for the mass transfer of the system is the vapour pressure difference between desiccant solution and hot air.

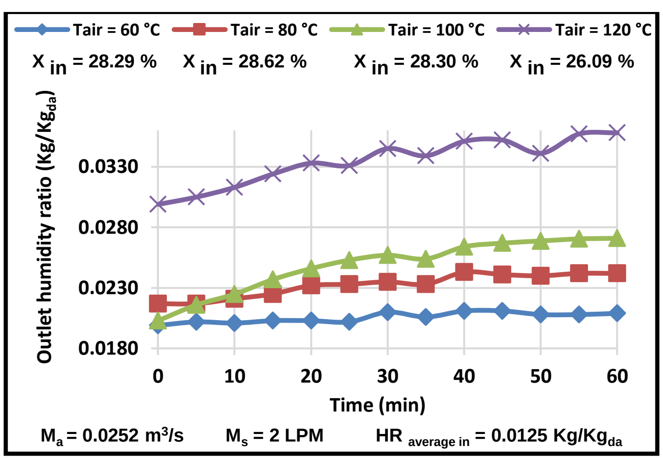

Fig.4. The effect of air inlet temperature on the air outlet humidity ratio.

Figure 5 shows the effect of air inlet temperature on the change of solution concentration. From this figure, it can be seen that increase in air inlet temperature leads to increase in the change of solution concentration. The increase of change of solution concentration with the increase of air inlet temperature is due to increase in vapour pressure on the solution surface. As discussed before the driving potential for the mass transfer of the system is the vapour pressure difference between desiccant solution and hot air. Therefore, an increase in vapour pressure on the solution surface increases the evaporation rate, which results in an increase in solution output concentration xo.

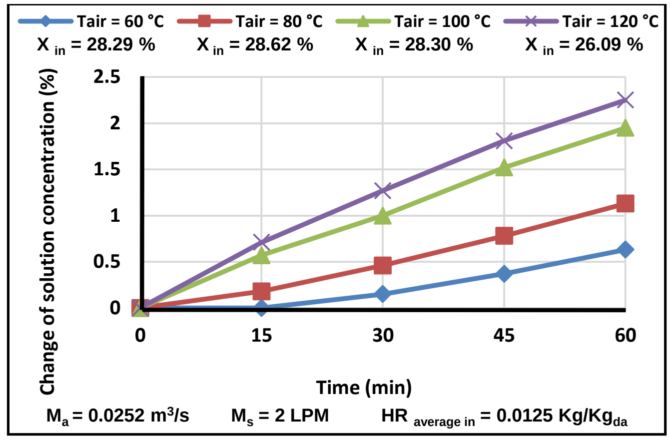

Fig.5. The effect of air inlet temperature on the change of solution concentration.

In the other set of experiments, fig.6 shows the effect of air flow rate on the solution vapour pressure. From this figure, it can be seen that increase in air flow rate leads to increase in solution vapour pressure. The increase of solution vapour pressure with the increase of air flow rate is due to the increase of mass transfer coefficient from the solution surface which leads to increase in the water evaporation rate. Rate of heat transfer from air stream to liquid solution also increases which consequently raises the solution temperature.

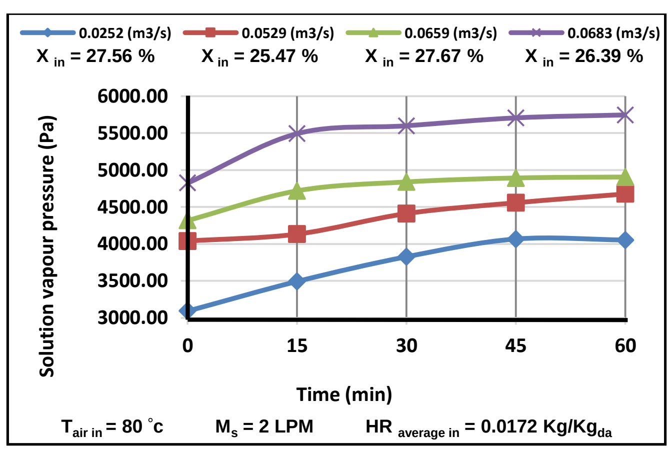

Fig.6. The effect of air flow rate on the solution vapour pressure.

Figure 7 shows the effect of air flow rate on the air outlet humidity ratio. From this figure, it can be seen that increase in air flow rate leads to increase in air outlet humidity ratio. The increase of air outlet humidity ratio with the increase of air flow rate is due to increase in the rate of heat transfer from air stream to liquid solution which leads to increase in air vapour pressure.

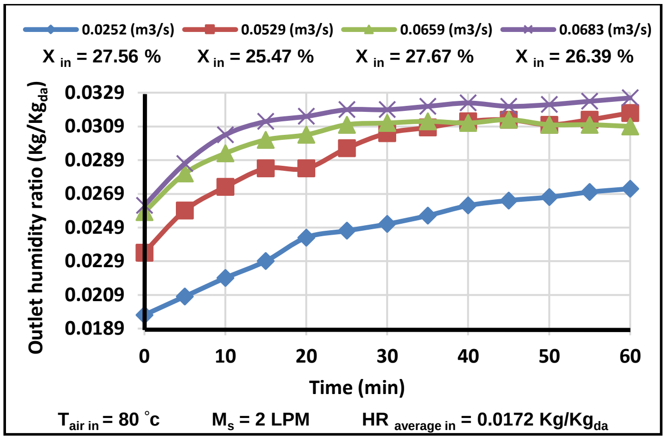

Fig.7. The effect of air flow rate on the air outlet humidity ratio.

Figure 8 shows the effect of air flow rate on the change of solution concentration. From this figure, it can be seen that increase in air flow rate leads to increase in the change of solution concentration. The increase of solution concentration with the increase of air flow rate is due to the increase of mass transfer coefficient from the solution surface which leads to increase in the water evaporation rate as a result of the vapour pressure difference between desiccant solution and air, which results in an increase in solution concentration.

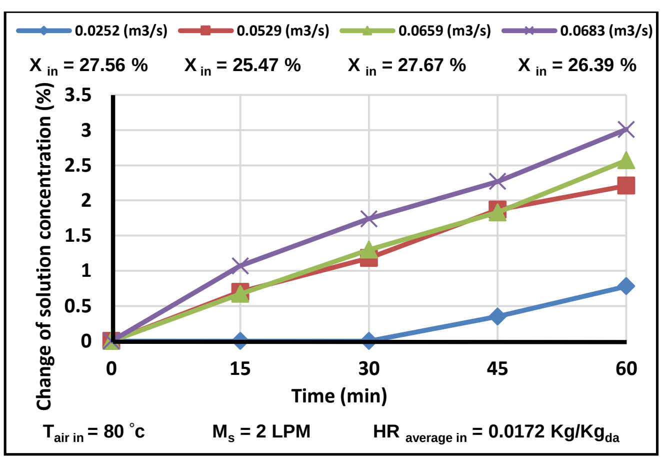

Fig.8. The effect of air flow rate on the change of solution concentration.

Furthermore, fig.9 shows the effect of solution flow rate on the solution vapour pressure. From this figure, it can be seen that increase in solution flow rate leads to decrease in solution vapour pressure. The decrease of solution vapour pressure with the increase of solution flow rate is due to decrease in outlet solution temperature. Although the heat transferred to the desiccant increases with an increase in the liquid flow rate, the outlet solution temperature may decrease and consequently the vapour pressure on the liquid surface decreases.

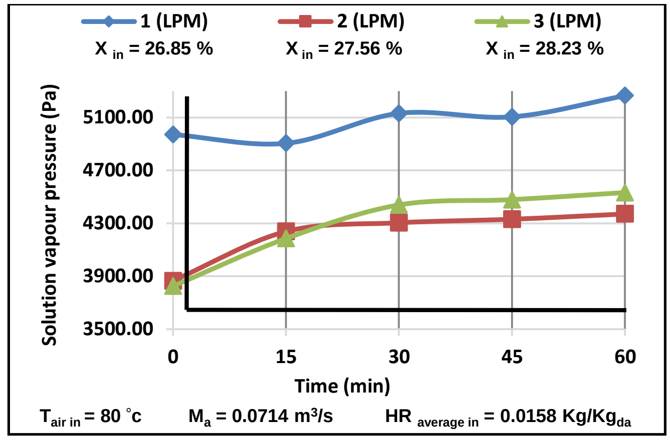

Fig.9. The effect of solution flow rate on the solution vapour pressure.

Figure 10 shows the effect of solution flow rate on the air outlet humidity ratio. From this figure, it can be seen that increase in solution flow rate leads to decrease in air outlet humidity ratio. The decrease of air outlet humidity ratio with the increase of solution flow rate is due to increase the heat transfer from heating stream of air. Increase in solution flow rate lead to increase the heat transfer from heating stream of air, so air temperature decreases. Therefore, a decrease in air temperature decreases the air vapour pressure which leads to decrease the outlet humidity ratio of the air.

Figure 11 shows the effect of solution flow rate on the change of solution concentration. From this figure, it can be seen that increase in solution flow rate leads to decrease in the change of solution concentration. The decrease of change of solution concentration with the increase of solution flow rate is due to decrease in outlet solution temperature. As discussed before increase in the liquid flow rate leads to increase in the heat transferred to the desiccant, but the outlet solution temperature may decrease and consequently the vapour pressure on the liquid surface, which results in a decrease in solution concentration.

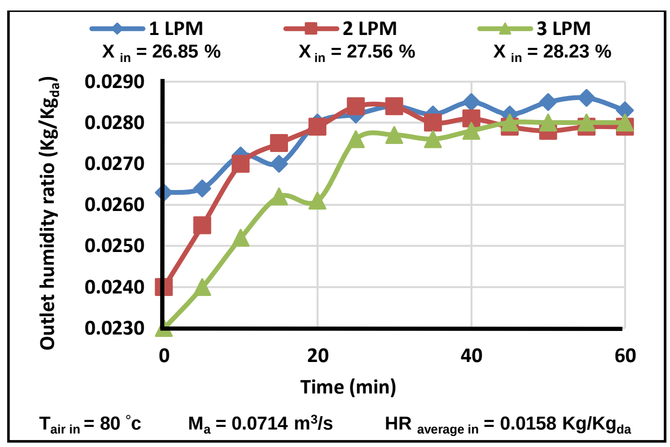

Fig.10. The effect of solution flow rate on the air outlet humidity ratio.

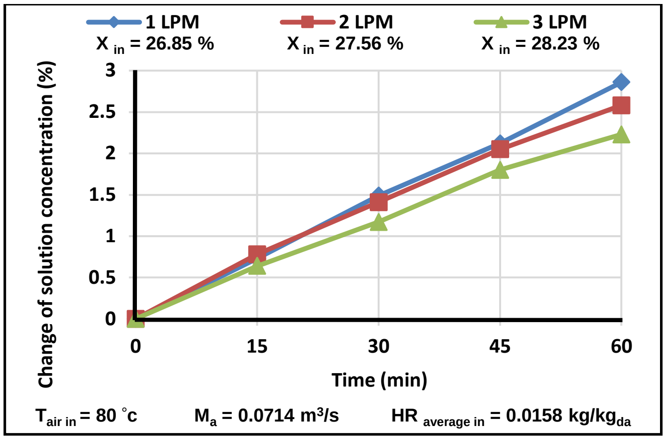

Fig.11. The effect of solution flow rate on the change of solution concentration.

Effect of operating parameters on the regenerator effectiveness

Table 2 shows the effect of input parameters on the regenerator effectiveness.

TABLE 2
EFFECT OF INPUT PARAMETERS ON THE REGENERATOR EFFECTIVENESS

Parameter	Effectiveness
Air inlet temperature	
60 (ºC)	1.0152
80 (ºC)	0.9020
100 (ºC)	0.7920
120 (ºC)	0.9199
Air flow rate	
0.0252 (m3/s)	1.0693
0.0529 (m3/s)	1.0855
0.0659 (m3/s)	0.9410
0.0683 (m3/s)	0.7175
Solution flow rate	
1 (LPM)	0.6623
2 (LPM)	1.0035
3 (LPM)	0.9218

VI. CONCLUSION

The operation of the regenerator of liquid desiccant packed tower using packing of burned clay is studied experimentally. From this study, the following conclusions have been obtained:

1. An increase in air inlet temperature leads to increase the air vapour pressure which increases the outlet humidity ratio of the air.
2. An increase in outlet solution temperature leads to increase the vapour pressure on the solution surface which increases the solution outlet concentration.
3. Increase in the air flow rate leads to quick removal of the moisture from the solution surface which increases the water evaporation rate.

NOMENCLATURE

A	Interfacial area of contact (m3).
HR	Air humidity ratio (kgv/kgda).
H	Enthalpy (kj/kg).
K	Mass transfer coefficient (kg/m2.s).
M	Volume flow rate (m3/s), (L/min).
m·	Mass flow rate (kg/s).
Pv	Vapor pressure on desiccant surface (Pa).
T	Temperature (°C).
X	Desiccant solution concentration (%).
ΔX	Change of desiccant solution concentration (Xo-Xi) (%).
Greek symbol	
ε	Effectiveness.

Subscripts

A	Process air.
S	Desiccant solution.
I	Inlet.
O	Outlet.
V	Vapor.
da	Dry air.
reg	Regeneration.
av	Average.
eq	Equilibrium.

Abbreviations

MRR	Moisture removal rate (kg/s).
LPM	Liter per minute.
min	Minute.

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