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A Statistical Analysis of a Liquid Desiccant Dehumidifier/Regenerator in an Air Conditioning System

Abdulrahman T. Mohammad[*], Sohif Bin Mat, M.Y. Sulaiman, K. Sopian, Abduljalil A. Al-Abidi
Solar Energy Research Institute, University Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

Abstract

A packed bed is the most common technology employed today as a dehumidifier or a regenerator in a liquid desiccant air conditioning system. During the experiments, the inlet and outlet parameters in the dehumidifier and regenerator can be easily measured, however, in the theoretical analysis it is difficult to predict the relationship between these parameters because of the complexity of the combined heat and mass transfer process in the dehumidifier or regenerator. In this paper statistical analysis using (SPSS) software was used to predict the functional relationships between the input and output parameters in the dehumidifier/regenerator. The analysis of variance (ANOVA) was investigated to analyze the effect of inlet operating variables (independent) on the water condensation rate in the dehumidifier and the water evaporation rate in the regenerator. Statistical analysis shows that the inlet air humidity ratio, inlet air mass flow rate, and inlet solution temperature cause good significant variation ($P<0.01$) in the water condensation rate. The inlet air mass flow rate, and inlet solution temperature cause also good significant variation ($P<0.01$) in the water evaporation rate in the regenerator. Experimental results for a counter dehumidifier and regenerator were taken from previous study.

Keywords: *Statistical, Dehumidifier, Regenerator, SPSS, ANOV.*

1. Introduction

Liquid desiccant systems consist of two main components: an absorber for dehumidifying the air and a regenerator for regenerating the solution. In the dehumidifier, Kumar et al [1] said the air comes in direct contact with the desiccant solution and attracts it moisture because of the lower water vapor pressure of the desiccant solution. Liu et al [2] showed that the process of heat and mass transfer in the dehumidifier and regenerator are the same but the difference is in the heat and mass transfer direction. Regression performance analysis was used by Liu et al [3] to predict the effect of the air and desiccant inlet parameters on the regenerator performance. Fumo and Goswami [4,5] assessed the rate of dehumidification and the water evaporation as well as the effectiveness of the dehumidifier and the effectiveness of the regenerator respectively, under the effect of variables such as the air and desiccant flow rate, air and desiccant temperature, air humidity, and desiccant concentration.

Yin et al [6] developed the correlations of the heat and mass transfer coefficients by using regression analysis. Yin et al [7] correlated the average mass transfer coefficient of a packed tower in terms of liquid desiccant concentration and heating temperature. McDonald et al [8] predicted a simple functional relationship for the packed tower dehumidifier using statistical analysis software. Abdul-Wahab et al [9] studied the effects of several influencing design factors on the performance of the structured liquid desiccant air dehumidifier, where the multiple regression method was used to predict the water condensation rate and the dehumidification effectiveness in terms of these design factors. Additional experimental data provided by Oberg and Goswami [10] to carried out the effect of the air and desiccant variables and the area of heat and mass transfer on the performance of the desiccant system. El-Shafei et al [11] predicted the performance of the regenerator in a solar liquid desiccant dehumidification/regeneration system using artificial neural network(ANN). The results showed that the outputs of ANN investigate good agreement with the experimental results.

In this paper, regression analysis is used to predict the outlet parameters of the dehumidifier and regenerator (outlet air temperature, outlet air humidity ratio, outlet liquid desiccant temperature, outlet liquid desiccant concentration, and water condensation and evaporation rate) as a function of the inlets parameters (air mass flow rate, air temperature, air humidity ratio, solution mass flow rate, solution temperature, and solution concentration). The height of the dehumidifier and the regenerator is a constant according to the experimental facility.

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[*] Corresponding Author. Tel.: + 60173672679
Fax: + 60389214593; E-mail: abdtm_1972@yahoo.ca

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2. Materials and Methods

2.1 Experimental facility

The schematic of the system is shown in Fig. 1. The dimensions of the packed bed absorption tower as constructed by [12] were (25.4 cm diameter and 60 cm height), the packing material used polypropylene Rauschert Hiflow Rings with a diameter of (1 inch); lithium chloride was used as a liquid desiccant and stored in a tank; and cold or hot water was circulated through coils to adjust the temperature of the solution. An air heater or a cooling coil was used to adjust the air temperature and relative humidity before entering the packed tower.

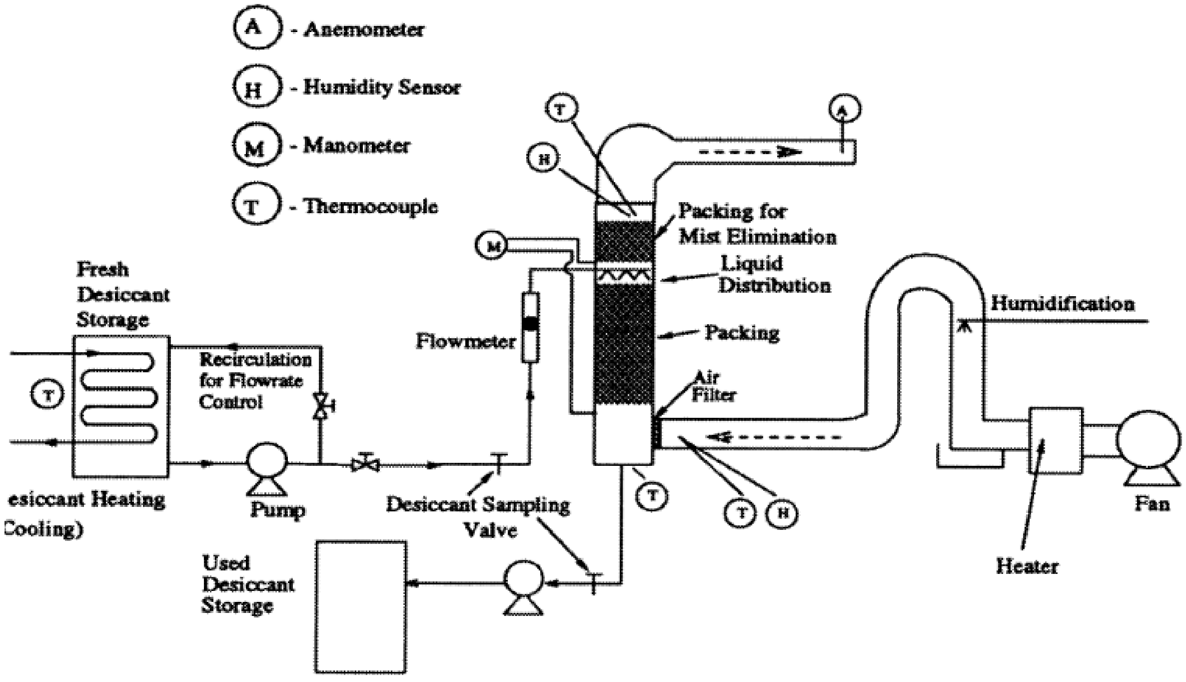

Fig.1. Experimental facility

2.2 Input and output experimental data

Inlet and outlet parameters were measured by PC-based data acquisition; these measurement devices included: (1) Copper constantan thermocouples were used to measure the inlet and outlet temperature of the desiccant and the air. (2) Humidity props were used to measure the relative humidity of the inlet and outlet air. (3) Karl Fischer titration was used to analyze the water content in the desiccant. Table 1 and Table 2 present the experimental results for the counter flow dehumidifier and regenerator respectively.

3. The multiple linear regression models

Regression analysis is a statistical technique for modeling and investigating the relationship between two or more variables. A simple linear regression model has only one independent variable. However, there are many applications where there is more than one independent factor that affects the outcome of a process [13]. In this situation, a multiple regression model is required:

$$y=\beta_0+\sum_{j=i}^{k}\beta_j x_j \qquad (1)$$

k represents the independent variables and the β_j from j=0 to *k* are the regression coefficients. The analysis of variance (ANOVA) is a common statistical technique to determine the percent contribution of each parameter for:

1-The total sum of squares:

$$\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2 \qquad (2)$$

is a chi-squared random variable with *n-1* degrees of freedom

2-The sum of squares due to regression:

$$\sum_{i=1}^{n}\left(\hat{y}_i-\bar{y}\right)^2 \qquad (3)$$

is a chi-squared random variable with 1 degree of freedom.

3-The error sum of squares:

$$\sum_{i=1}^{n}\left(y_i-\hat{y}_i\right)^2 \qquad (4)$$

is a chi-squared random variable with *n-2* degrees of freedom.

4-The sums squares $\sum_{i=1}^{n}\left(\hat{y}_i-\bar{y}\right)^2$ and $\sum_{i=1}^{n}\left(y_i-\hat{y}_i\right)^2$

are independently distributed.

5-The ratio between the mean square for regression and the mean square for error

$$\sum_{i=1}^{n}\left(\hat{y}_i-\bar{y}\right)^2 \Bigg/ \sum_{i=1}^{n}\left(y_i-\hat{y}_i\right)^2 \Bigg/ n-2 \tag{5}$$

follows the *F* (*1, n-2*) distribution[14].

According to the experimental facility the height of the dehumidifier and regenerator is a constant throughout the experimental tests. From the experimental data tables, the independent variables are(inlet air and solution temperature, inlet air and solution flow rate, inlet air humidity ratio, and inlet solution concentration) and dependent variables are (P<0.05) with *F* ratio between 25.225 and 274.638. Table 3 presents the comparison of the statistical coefficients values for the dependent variables. The values of R^2 considered between 0.416 and 1.0 for the dehumidifier and between 0.722 and 0.989 for the regenerator, this means a very good accuracy of

(outlet air and solution temperature, outlet air humidity ratio, and outlet solution concentration).

4. Results and discussion

The multiple linear regression model type for each dependent variable in the dehumidifier and regenerator was analyzed by its R^2 value, F ratio, and P value. The value of R^2describes the accuracy of the curve fit, where R^2 =1 is the optimum fit and R^2=0.9 to 0.99 is a very good fit. The F ratio is a measure of the error of the regression, where its values are usually more than 50, while P-value is used to assess the degree of response affected by factors, its values can be divided into five ranges (1) P-value≤0.001, extremely significant (2) 0.001< P-value≤0.01, very significant (3) 0.01< P-value≤0.005, significant (4) 0.05< P-value≤0.1, slightly significant (5) P-value>0.1, insignificant. The results of the ANOVA test indicated that the independent effective factors of inlet air mass flow rate, inlet air temperature, inlet air humidity ratio, inlet desiccant mass flow rate, inlet desiccant temperature, and inlet desiccant concentration on the outlet air temperature, outlet air humidity ratio, outlet desiccant temperature, and outlet desiccant concentration were very significant in the range of

the curve fit between the predicted regression curve and the actual value for each of the dependent variables in the dehumidifier and regenerator.

Table1. Air dehumidification experimental results by [12]

Inlet						Outlet				
Ma Kg/m^{2}sec	*Tai* C^0	*Wai* Kg/Kg dry	*Ms* Kg/m^{2}sec	*Tsi* C^0	*Xi* %	*Tao* C^0	*Wao* Kg/Kg dry	*Tso* C^0	*Xo* %	m_{con} g/sec
0.890	30.1	0.0180	6.124	30.1	34.6	31.3	0.0104	32.3	34.5	0.32
1.180	30.1	0.0181	6.227	30.3	34.7	32.2	0.0108	32.6	34.6	0.40
1.513	30.2	0.0181	6.113	30.0	34.3	32.2	0.0108	32.7	34.1	0.52
1.189	35.5	0.0188	6.290	30.3	34.5	32.8	0.0112	32.6	33.7	0.42
1.183	40.1	0.0180	6.287	30.5	34.4	33.1	0.0115	32.9	34.3	0.36
1.214	30.3	0.0142	6.273	30.1	33.9	31.1	0.0103	31.5	33.8	0.23
1.187	29.9	0.0215	6.272	30.3	33.9	33.4	0.0120	33.1	33.7	0.53
1.190	30.1	0.0180	5.019	30.2	34.4	32.2	0.0113	32.7	34.2	0.38
1.182	30.2	0.0181	7.420	30.2	34.4	32.0	0.0110	32.5	34.3	0.39
1.198	29.9	0.0177	6.269	25	34.7	28.2	0.0088	28.4	34.5	0.50
1.176	29.9	0.0178	6.309	35.2	34.9	35.7	0.0140	36.2	34.8	0.21
1.182	29.9	0.0179	6.164	30.1	33.1	32.4	0.0114	32.2	33.0	0.36
1.192	29.9	0.0179	6.267	30.2	33.8	32.5	0.0112	32.6	33.7	0.38
1.176	30	0.0181	6.206	30.2	34.8	32.0	0.0107	32.5	34.7	0.41

Table2. Air regeneration experimental results by[12]

Inlet						Outlet				
Ma Kg/m^{2}sec	*Tai* C^0	*Wai* Kg/Kg dry	*Ms* Kg/m^{2}sec	*Tsi* C^0	*Xi* %	*Tao* C^0	*Wao* Kg/Kg dry	*Tso* C^0	*Xo* %	m_{eva} g/sec
0.833	30.4	0.0183	6.463	65.0	34.0	58.9	0.0579	58.6	34.5	1.55
1.098	30.1	0.0180	6.206	65.1	34.1	59.3	0.0532	57.8	34.8	1.81
1.438	29.8	0.0177	6.479	65.1	34.5	57.5	0.0488	56.6	35.2	2.10
1.097	35.1	0.0180	6.349	65.1	33.4	58.5	0.0551	57.4	34.1	1.91
1.102	40.0	0.0178	6.354	65.0	33.6	58.9	0.0548	57.6	34.2	1.91
1.132	30.2	0.0143	6.370	65.2	34.0	57.6	0.0513	57.2	34.7	1.97
1.097	29.4	0.0210	6.440	65.5	33.6	58.5	0.0541	58.3	34.2	1.70
1.116	30.3	0.0182	5.185	65.4	34.4	57.6	0.0507	57.0	34.9	1.71
1.101	29.9	00.180	7.541	65.2	34.3	59.0	0.0556	57.9	34.9	1.95
1.111	30.0	0.0187	6.245	60.3	34.4	55.8	0.0447	54.2	34.8	1.36
1.084	29.7	0.0184	6.315	70.0	34.5	62.6	0.0666	60.0	35.3	2.45
1.099	29.7	0.0177	6.400	64.8	32.8	57.6	0.0542	56.8	33.4	1.89
1.116	30.3	0.0182	6.428	65.0	34.9	57.9	0.0501	57.5	35.4	1.67

Table 3. Main statistical values

Dependent	Dehumidifier		
	R^2	F-value	Sig.
Tao	0.877-0.9922	192.052	$P<0.01$
Wao	0.846-0.941	58.2380	$P<0.01$
Tso	0.966-1.00	339.834	$P<0.01$
Xo	0.8660	77.6990	$P<0.01$
m_{con}	0.416-0.967	99.210	$P<0.05$
Dependent	Regenerator		
	R^2	F-value	Sig.
Tao	0.791	41.653	$P<0.01$
Wao	0.722-0.872	28.522	$P<0.01$
Tso	0.814-0.914	47.414	$P<0.01$
Xo	0.961-0.989	274.638	$P<0.01$
m_{evap}	0.82-0.914	25.225	$P<0.01$

4.1 Statistical analysis of the dehumidifier

Figure 2 shows the normal P-P plot of regression standardized residual for the dehumidifier. All these plots show a reasonably good fit between the predicted and actual value falling well within the 95% confidence level. Only, the measuring error of the outlet solution concentration in the dehumidifier (Fig.2, curve d) exceeds 5%, which was attributed to the small range of inlet solution concentration, such as the outlet solution concentration as a function of the inlet solution concentration. The 95% confidence interval is a measure of error that provides assurance that the data from repeated experiments would fall within this interval 95% of the time.

The statistical analysis of the results in the dehumidifier shows the main functional relationships of the dependent variables represented by: $Tao=f\ (Tsi, Wai, Tai, Xi, Ma)$, $Wao=f\ (Tsi, Wai)$, $Tso=f\ (Tsi, Wai)$, $Xo=f\ (Xi)$, $m_{con}=f\ (Wai, Tsi, Ma)$. The outlet air temperature is expected to be greatly affected by the inlet air mass flow rate, inlet solution temperature, and inlet solution concentration, while the outlet air humidity ratio and outlet solution temperature were strong function of the inlet solution temperature. Furthermore, the outlet solution concentration was found to be mainly a function of the inlet solution concentration. A summary of the functional relationships is given in Table 4. The condensation water rate in the dehumidifier as shown in Fig.3 was increased through an increase in the airflow rate. Statistically, the P-value was ($P<0.01$). The results demonstrate that the effect of changing the airflow rate was highly significant for the condensation water rate. Comparing this with the solution flow rate, the water condensation rate does not vary by changing the value of the solution flow rate. A higher desiccant temperature causes a lower potential for mass transfer in the dehumidifier, this means a lower condensation rate.

4.2 Statistical analysis of the regenerator

Figure 4 shows the normal P-P plot of regression standardized residual for the dehumidifier. All these plots show a reasonably good fit between the predicted and actual value falling well within the 95% confidence level.

The main functional relationships of the dependent variables are represented by: $Tao=f\ (Tsi)$, $Wao=f\ (Tsi)$, $Tso=f\ (Tsi)$, $Xo=f\ (Xi, Ma)$, $m_{con}=f\ (Tsi,Ma)$ as shown in Table5. The outlet air temperature, humidity ratio, and outlet solution temperature are affected by the inlet solution temperature. The outlet concentration of the solution was found to be a function for two independents variable, inlet solution concentration and inlet air mass flow rate. The water evaporation rate increases with the inlet solution temperature and air flow rate as shown in Fig. 5. Since, the vapor pressure of the desiccant is dependent on the inlet temperature of desiccant, the higher the temperature, the higher the vapor pressure and then the greater the potential for mass transfer.

Table4. Final regression functions

Dependent Variables	Dehumidifier	Regenerator
Outlet air temperature	$Tao=11.929+0.743*Tsi+0.299*Wai$ $0.076*Tai+0.333*Xi+1.308*Ma$	$Tao = 13.101 + 0.696 * Tsi$
Outlet air humidity ratio	$Wao = -7.873 + 0.508*Tsi+0.201*Wai$	$_{Wao} = -70.667 + 2.186 * Tsi$ $-16.274 * Ma$
Outlet solution temperature	$Tso = 5.86 + 0.763 * Tsi + 0.199 * Wai$	$Tso=22.69+0.591*Tsi-3.364*Ma$
Outlet solution concentration	$Xo = 1.309 + 0.957 * Xi$	$Xo = - 0.651 + 0.943 * Xi$ $+0.043*Tsi+0.368*Ma$
Condensation and evaporation water rate	$m_{con}= 0.079 + 0.044 * Wai$ $-0.028*Tsi+0.312*Ma$	$m_{eva}=6.439+0.112*Tsi+0.865*Ma$

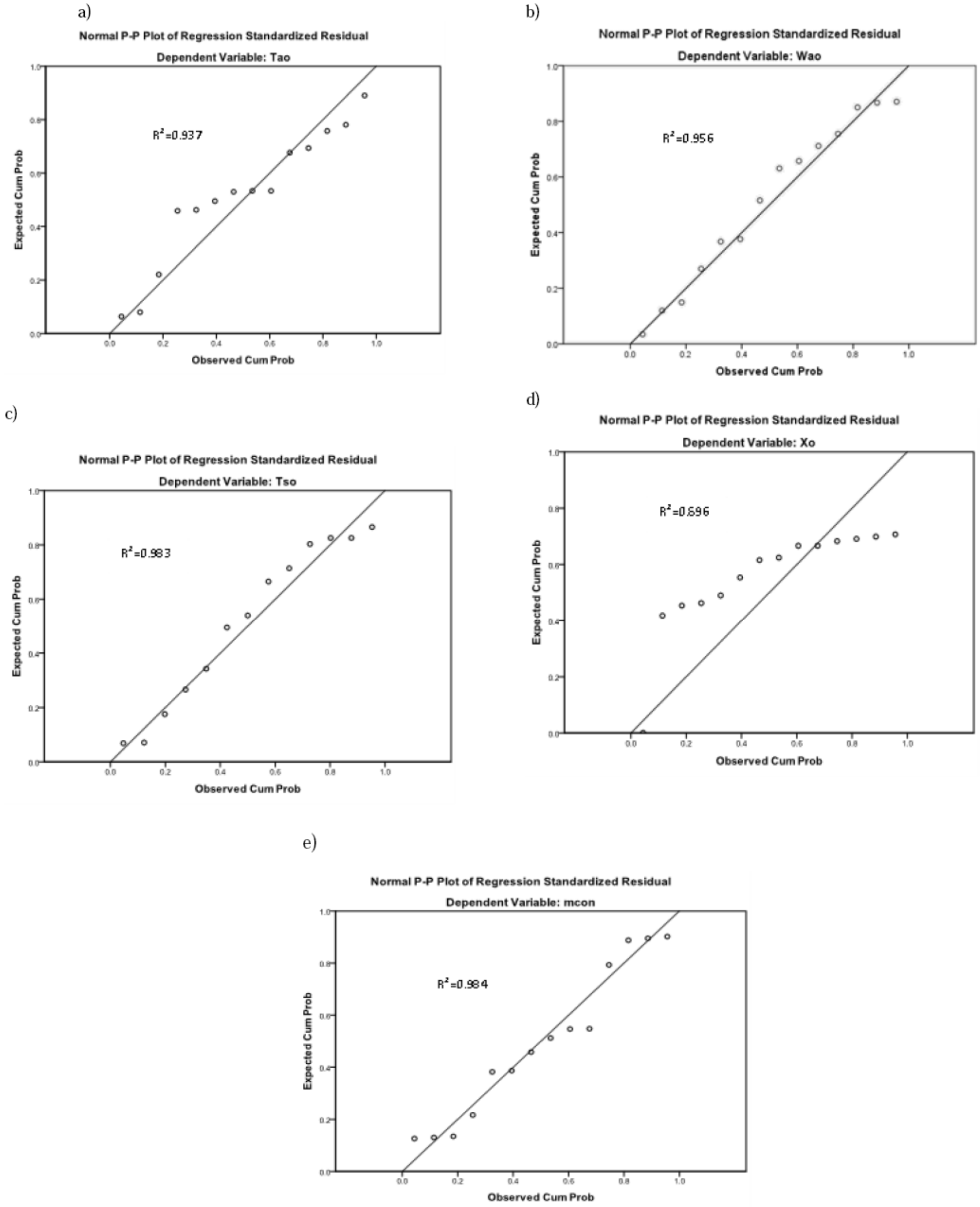

Fig.2. Curves (a, b, c, d, e) the relationships between the actual and the predictor value in dehumidifier

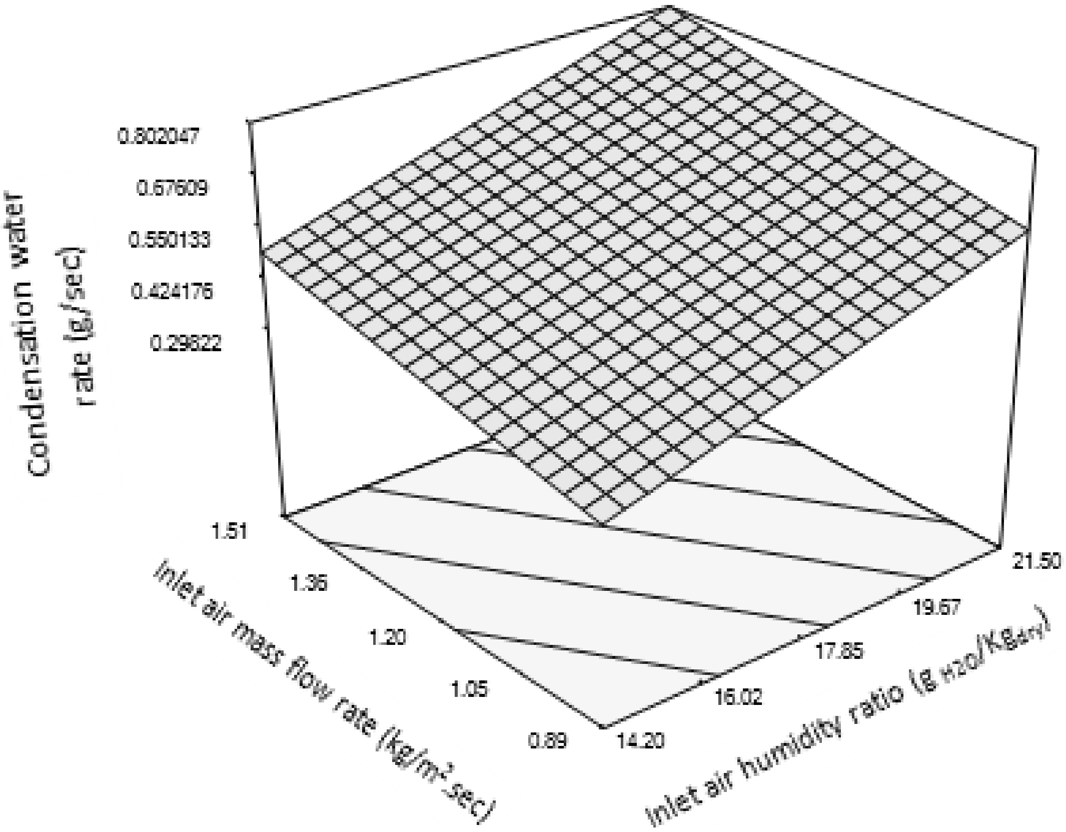

Fig.3. Effect of the inlet air mass flow rate and humidity ratio on the condensation rate in dehumidifier

5. Conclusions

A multiple linear regression model was used to determine the functional relationship between the inlet and outlet parameters for the counter flow dehumidifier and regenerator. This model was performed on a counter flow dehumidifier and regenerator in an air conditioning system tested by [12] in a solar energy and energy conversion laboratory, in the USA, 2002. From the results of this work, the main conclusions can be summarized by: (1) The effect of inlet air and desiccant variables were very significant in the range of $P<0.01$; (2) The values of R^2 are considered to be between 0.416 and 1.00 for the dehumidifier and between 0.722 and 0.989 for the regenerator; (3) Very good accuracy of the curve fit between the predicted regression curve and the actual value for each dependent variables in the dehumidifier and the regenerator; (4) Higher air flow rate would result in increasing of the water condensation rate from the air and evaporation rate from the desiccant. (5) Higher desiccant temperature can provide more regeneration rate in the regenerator and provide less condensation rate in the dehumidifier.

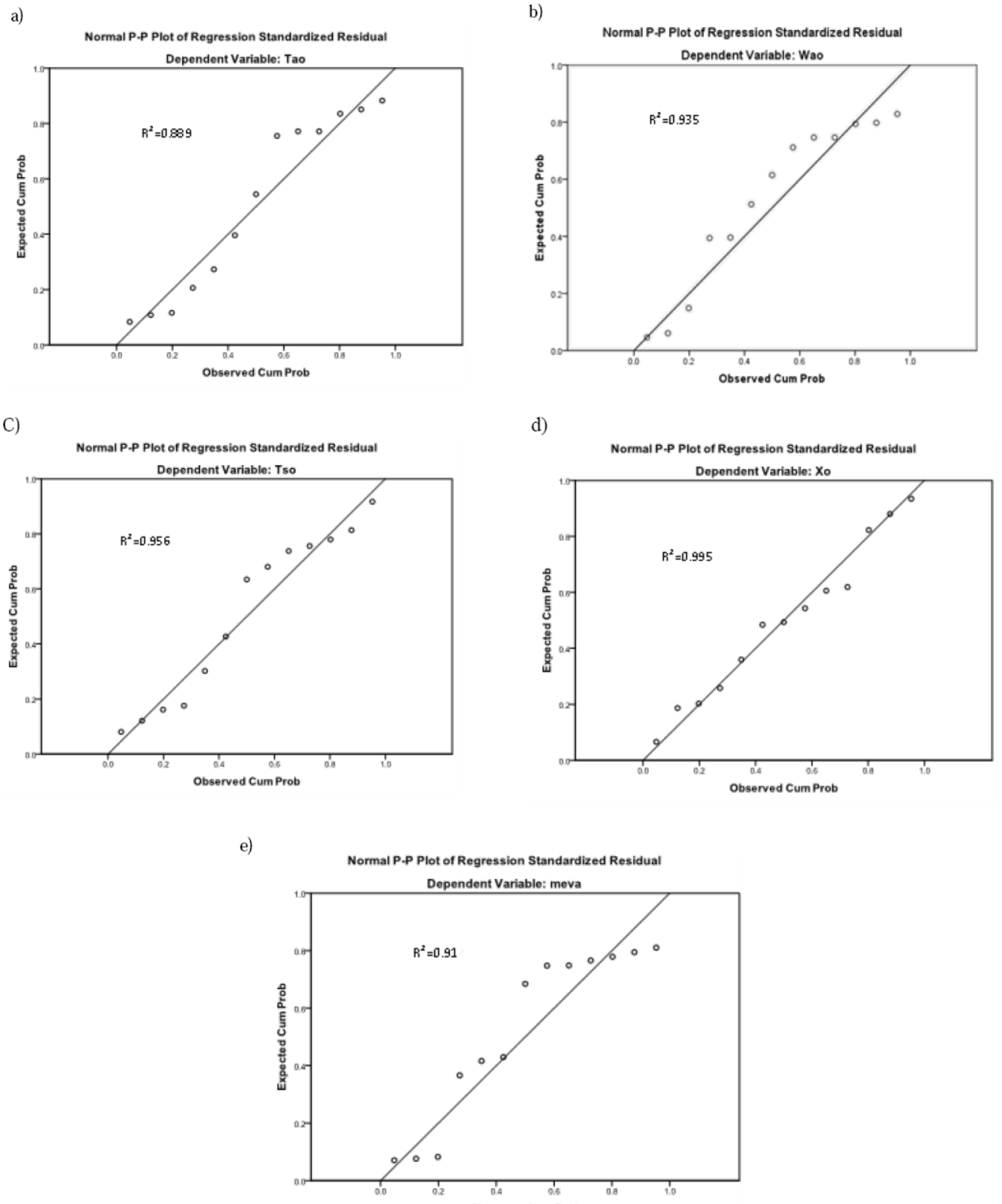

Fig.4. Curves (a, b, c, d, e) the relationships between the actual and the predictor value in regenerator

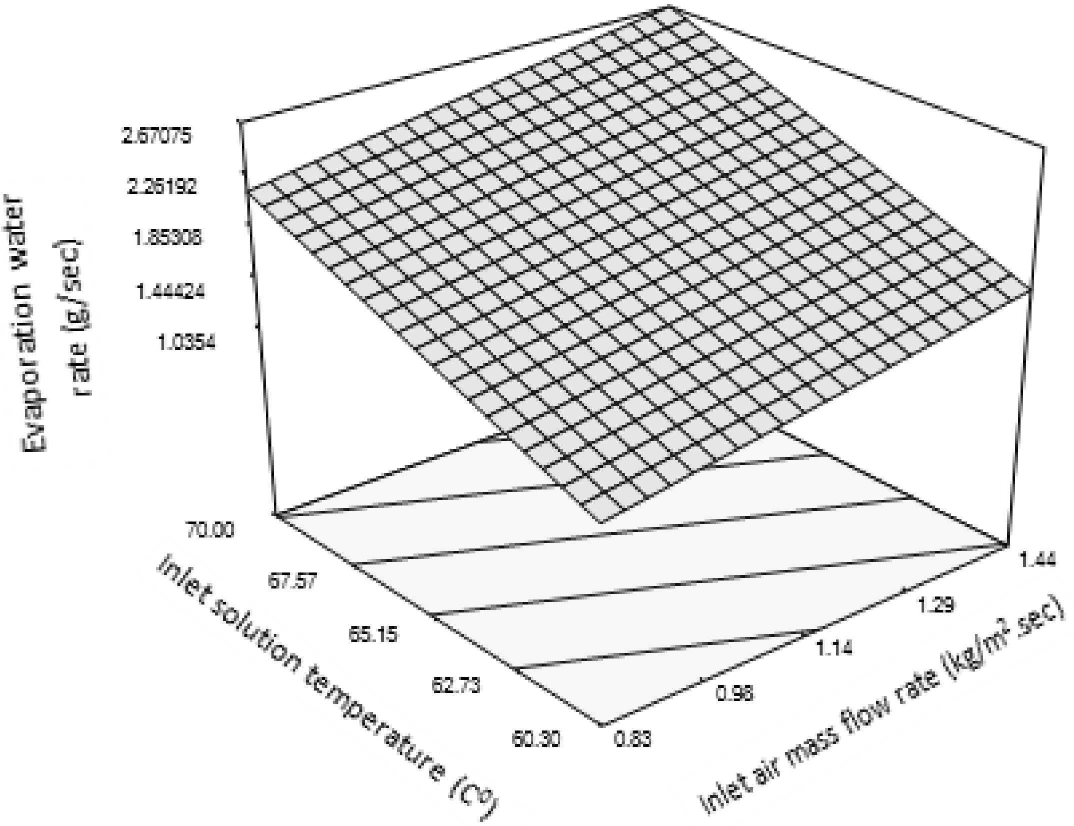

Fig.5. Effect of the inlet air mass flow rate and humidity ratio on the evaporation rate in regenerator

Nomenclature

F	ratio of mean square model to the mean square error
Ma	air inlet mass flow rate, kg/m^{2}sec
m_{con}	condensation water rate , g/sec
m_{evap}	evaporation water rate, g/sec
Ms	solution inlet mass flow rate, kg/m^{2}sec
P	significant coefficient
R	accuracy of the curve fit
Tai	inlet air temperature, ^{o}C
Tao	outlet air temperature, ^{o}C
Tsi	Inlet solution temperature, ^{o}C
Tso	Outlet solution temperature, ^{o}C

Wai	inlet air humidity ratio, kg$_{H2O}$/ kg $_{dry\ air}$
Wao	outlet air humidity ratio, kg$_{H2O}$/kg $_{dry\ air}$
Xsi	inlet solution concentration ,%
Xso	outlet solution concentration,%

Subscripts

ANOVA	analysis of variance
SPSS	statistical Package for the Social Sciences

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References

[1] N. Kumar, G. Srivastava and B. Gangil. Heat and mass transfer study of liquid desiccant with heat exchange by solar cooling technology. Int. J. Eng. Studies 2010; 2: 105-118.

[2] X. H. Liu, Y. Jiang, X. M. Chang and X. Q. Yi. Experimental investigation of the heat and mass transfer between air and liquid desiccant in a cross-flow regenerator. Renewable Energy 2007; 32 :1623-1636. http://dx.doi.org/10.1016/j.renene.2006.07.002

[3] X. H. Liu, Y. Jiang and K. Y. Qu. Heat and mass transfer model of cross flow liquid desiccant air dehumidifier /regenerator. Energy Convers. Manage. 2005; 48: 546-554. http://dx.doi.org/10.1016/j.enconman.2006.06.002

[4] N. Fumo and Y. Goswami. Study of the Aqueous Lithium Chloride Desiccant System, Part II: Desiccant Regeneration. Proc. of Millennium Solar Forum 2000, C. A. Estrada, ed., Asociacion Nacional de Energia Solar 2000; 313-318.

[5] N. Fumo and Y. Goswami. Study of the Aqueous Lithium Chloride Desiccant System, Part I: Air Dehumidification. Proc. of Millennium Solar Forum 2000, C. A. Estrada, ed., Asociacion Nacional de Energia Solar 2000; 307-312.

[6] Y. Yin and X. Zhang. A new method for determing coupled heat and mass transfer coefficient between air and liquid desiccant. Int. J. Heat Mass Transfer 2008; 51 : 3287- 3297. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2007.11.040

[7] Y. Yin, X. Zhang, Z. Chen. Experimental study on dehumidifier and regenerator of liquid desiccant cooling air conditioning system. Build. Environ. 2007; 42: 2505-2511. http://dx.doi.org/10.1016/j.buildenv.2006.07.009

[8] B. McDonald, D. G. Wagaman, C. F. Kettleborough. A statistical analysis of a packed tower dehumidifier. Drying Technol. 1992; 10 : 223-237. http://dx.doi.org/10.1080/07373939208916423

[9] S. A. Abdul-Wahab, Y. H. Zurigat and M. K. Abu-Arabi. Predictions of moisture removalrate and dehumidification effectiveness for structured liquid desiccant air dehumidifier. Energy 2004; 29 : 19-34. http://dx.doi.org/10.1016/j.energy.2003.08.001

[10] V. Oberg and D. Y. Goswami. Experimental study of the heat and mass transfer in a packed bed liquid desiccant air dehumidifier. J. Sol. Energy Eng. 1998; 120: 289-297. http://dx.doi.org/10.1115/1.2888133

[11] El-Shafei B. Zeidan, Ayman A. Aly and Ahmed M. Hamed. Investigation on the effect of operating parameters of solar desiccant cooling system using artificial neural networks. International Journal of Thermal & Environmental Engineering 2010; 1: 91-98. http://dx.doi.org/10.5383/ijtee.01.02.005 .

[12] N. Fumo and Y. Goswami. Study of an aqueous lithium chloride desiccant system: air dehumidification and desiccant regeneration. Sol. Energy 2002; 72: 351-361. http://dx.doi.org/10.1016/S0038-092X(02)00013-0

[13] E. B. Magrab, S. Azarm, B. Balachandran, J. Duncan, K. Herold and G. Walsh. An Engineers Guide to MATLAB. Prentic Hall, New Jersey; 2000.

[14] J. Kinny. Statistics for science and engineering. Rose Hulman Insititute of Technology. United State of America; 2002.