solution, due to the partial vapor pressure difference between the air and the desiccant solution. Then, the moisture from the diluted solution is removed in the regenerator.

Many research aspects of the regenerator have been investigated, such as deriving a model for predicting the performance, and experiments to observe the performance. Liu et al. (2011) compared the mass transfer performance of two desiccant solutions, LiCl and LiBr to observe the dehumidification and regeneration performance. Martin and Goswami (2000) showed dehumidification/regeneration and enthalpy effectiveness correlations for the dehumidifier and regenerator functions of design variables. Sultan et al. (2002) proposed a theoretical model and demonstrated the influence of the system parameters on the regeneration process.

Liu et al. (2007) conducted experimental research into the regenerator. This research compared the thermal and regeneration performance between a cross-flow and counter-flow configuration obtained from the literature. Fumo and Goswami (2002) showed the performance of a packed tower absorber and regenerator, using LiCl desiccant solution. Gommed and Grossman (2007) constructed a 16 kW prototype system consist of a dehumidifier and a regenerator, and described the operation of the experimental system and its performance. Zhang et al. (2010) studied mass transfer characteristics of a structured packing dehumidifier/regenerator, using LiCl solution as the desiccant. As shown above, many researchers have conducted experimental research and developed mathematical models of the regenerator; however, few researchers have statistically analyzed the regeneration potential of the regenerator.

The present study developed a statistical model for anticipating the regeneration potential, by using an experimental data pool. In order to obtain the experimental data pool for the regenerator, experimental data were collected from the literature and experiments on the pilot system, and then statistical analysis was conducted using response surface methodology, to evaluate the effects of variables on the regeneration performance.

REGENERATION MODEL

(1) Liquid desiccant system

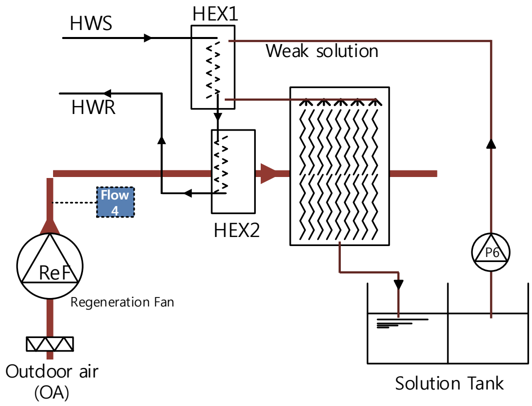

Figure 1. *The configuration of a regenerator*

Fig. 1 shows a schematic of counter flow packed bed regenerator. When the diluted liquid desiccant solution is sprayed into the packed tower, and makes direct contact with the intake air, heat and moisture are transferred between the desiccant solution and intake air by the vapor pressure difference. When the partial vapor pressure of the desiccant solution surface is higher than that of the air, the moisture in the solution moves to the air. Because the partial vapor pressure of the solution responds to the temperature, heat and moisture transfer occur simultaneously between the solution and the air.

(2) Regenerator pilot unit

In this research, a honeycomb structured packed tower is used as a regenerator. The internal diameter of the regenerator is 0.01 m, packed up to a volume of V = 0.315 m, with wood fiber structured packing of a specific surface α = 223 m^2/m^3. The lithium calcium solution used as a desiccant is sprayed at the top of the column from the sump and distributed over the packing.

As shown in Fig. 1, heat from the hot water is reclaimed to the desiccant solution for regeneration, first using a solution-to-water heat exchanger (HEX1), and then the hot water heats the intake air of the air-to-water heat exchanger (HEX2).

The temperature, relative humidity, and flow rate of the air are measured at the inlet and outlet of the regenerator. The temperature and flow rate of the desiccant solution are also measured on the sump, and before spraying the regenerator.

A SIMPLIFIED REGENERATOR MODEL

While a mechanistic model might be used when the relationships between response variable and predictor variables are known exactly, a response surface model, which is an empirical model, consider the more common situation, where these are not fully understood. Response surface methodology (RSM) is a useful tool for investigating the influence of several input variables on the performance of the response. The first order or second order regression model is widely used to approximate the true response surface. The response function (y) is related to factors (x_i and x_j) by a first order regression equation (Equation (1)):

$$y = b_o + \sum b_i x_i + \sum b_i x_j + \sum b_{ij} x_i x_j \qquad (1)$$

where b_o, b_i, b_j, and b_{ij} are a constant, linear coefficients, and an interaction coefficient, respectively (Myers et al. 2009).

In order to estimate the effect of the factors on the regeneration rates as a response, six independent factors (inlet air temperature T_{ai}, inlet air humidity ratio w_{ai}, inlet solution temperature T_{si}, inlet solution concentration X_i, air mass flow rate $\dot{m}_a$, and solution mass flow rate $\dot{m}_s$) are selected. The regeneration effectiveness of the regenerator is the ratio of the actual moisture desorption rate to the maximum desorption rate. The maximum moisture desorption rate of the desiccant solution varies with the equilibrium humidity ratio (w_e) of the air at equilibrium with the desiccant solution.

$$\varepsilon_{reg} = \frac{w_{ai} - w_{ao}}{w_{ai} - w_e} \qquad (2)$$

where, w_{ai} and w_{ao} are the inlet and outlet air humidity ratio, respectively.

In order to generate the experimental data pool for the regenerator, data was collected from four sources (Fumo and Goswami 2002, Gommed et al. 2004, Liu et al. 2011, and Zhang et al. 2010), as shown in Table 1. Table 1 presents minimum and maximum values of experimental data. The experimental data were analyzed using a commercial statistical package, Design Expert version 9 (Stat-Ease Inc., Minneapolis, USA).

Table 1. *Experimental data from the literature*

	T_{ai}	w_{ai}	$\dot{m}_s$	$\dot{m}_a$	T_{si}	X_i	w_{ao}	ε_{reg}
	[°C]	[kg/kg]	[kg/m^{2}s]	[kg/m^{2}s]	[°C]	[-]	[kg/kg]	[-]
Fumo and Goswami (2002)								
Max	40.0	0.021	0.060	0.011	70.0	0.3	0.067	0.88
Min	29.4	0.014	0.041	0.007	60.3	0.3	0.045	0.70
Gommed et al. (2004)								
Max	41.9	0.010	0.014	0.004	55.4	0.4	0.024	0.87
Min	41.2	0.009	0.011	0.004	53.6	0.4	0.018	0.79
Liu et al. (2011)								
Max	36.6	0.020	0.021	0.016	56.8	0.4	0.029	0.42
Min	30.6	0.013	0.016	0.011	48.5	0.3	0.022	0.29
Zhang et al. (2010)								
Max	46.7	0.015	0.003	0.008	55.9	0.4	0.022	0.24
Min	44.1	0.015	0.001	0.004	54.8	0.3	0.016	0.08
Total								

Max	*46.7*	*0.021*	*0.060*	*0.016*	*70.0*	*0.4*	*0.067*	*0.88*
Min	*29.4*	*0.009*	*0.001*	*0.004*	*48.5*	*0.3*	*0.016*	*0.08*

RESULTS AND DISCUSSION

(1) Experimental results

As shown in Table 2, two sets of tests (i.e. TEST 1 and TEST 2) were conducted in the summer condition. During the tests, the outdoor air temperature and relative humidity were 26.5℃~27.4℃ and 62.5%~59.3%, respectively. The inlet hot water temperature to the HEX1 was 52.4℃~55.3℃, and the flow rate was 0.8 kg/s. The regeneration fan was a constant flow at the 4500m^3/h design flow rate.

Table 2. *Experimental results*

	T_{ai}	w_{ai}	$\dot{m}_s$	$\dot{m}_a$	T_{si}	X_i	w_{ao}	e_{reg}
	[℃]	[kg/kg]	[kg/m^{2}s]	[kg/m^{2}s]	[℃]	[-]	[kg/kg]	[-]
TEST 1	39.8	0.014	0.022	0.022	45.8	0.380	0.017	0.714
TEST 2	30.3	0.014	0.016	0.022	48.1	0.384	0.015	0.300

(2) Statistical analysis

The data obtained from 39 runs of the regeneration experiment from the literature and experiments in this paper were statistically analyzed, to recognize the significant terms. Table 3 shows the analysis of variance (ANOVA) results for the quadratic model. The analysis of variance indicates that the 2FI model is significant. Values of less than 0.05 for Prob > F (p-value) indicate that the model terms are significant. In this case C and AC are significant model terms. Table 3 summarizes the ANOVA table after backward elimination regression with adding Hierarchical terms, and shows that the fitted correlation is significant (p-value<0.05). The high values for the predicted and adjusted R^2 indicate that the reduced 2FI model is capable of representing the system. The signal to noise ratio was measured with adequate precision. The desired value was greater than 4; this value was found to be suitable to support the fitness of the model. Moreover, a low value for the coefficient of variation (CV) (less than 10%) indicates that the variation in the mean value and the accuracy are quite good. The data in Table 4 confirm these results.

Table 3*. ANOVA for the 2FI model for regeneration effectiveness*

Source	Sum of Squares	df	Mean Square	F Value	P-value Prob > F
Model	1.887718	21	0.089891	54.04014	<0.0500
A-T_{ai}	0.006366	1	0.006366	3.826814	0.068128
B-w_{ai}	0.002723	1	0.002723	1.636815	0.219006
C-$\dot{m}_s$	0.02422	1	0.02422	14.56034	<0.0500

D- $\dot{m}_a$	0.003722	1	0.003722	2.237374	0.154173
E- T_{si}	0.003706	1	0.003706	2.227687	0.155012
F- X_i	0.00196	1	0.00196	1.178185	0.29381
AB	0.003225	1	0.003225	1.938938	0.182835
AC	0.034098	1	0.034098	20.49894	<0.0500
AD	7.73E-05	1	7.73E-05	0.04649	0.832012
AE	0.000477	1	0.000477	0.286571	0.599788
AF	0.003029	1	0.003029	1.82093	0.195989
BC	0.000924	1	0.000924	0.55576	0.466785
BD	0.001452	1	0.001452	0.872838	0.364057
BE	0.00055	1	0.00055	0.330426	0.573403
BF	0.001002	1	0.001002	0.602489	0.448953
CD	2.91E-06	1	2.91E-06	0.001747	0.967177
CE	0.000862	1	0.000862	0.518091	0.48204
CF	0.003708	1	0.003708	2.22885	0.154911
DE	9.66E-07	1	9.66E-07	0.000581	0.981068
DF	7.23E-05	1	7.23E-05	0.043448	0.837514
EF	0.003659	1	0.003659	2.199716	0.157466
Residual	0.026615	16	0.001663		
Cor Total	1.914333	37			

Table 4. *Statistical results of the ANOVA for hierarchy selection 2FI model*

Response	Correlation in terms of actual significant factors	p-value	R^2	Adj. R^2	Adequate precision	CV %
e_{reg}	Sqrt(e_{reg})=-5.434+0.226 T_{ai} +66.540 w_{ai} -55.699 $\dot{m}_s$ -23.188 $\dot{m}_a$ +0.078 T_{si} +5.084 X_i -2.046 T_{ai} w_{ai} +1.226 T_{ai} $\dot{m}_s$ -0.003 T_{ai} T_{si} -0.123 T_{ai} X_i +0.398 $\dot{m}_s$ T_{si}	< 0.0001	0.98	0.97	29.690	5.692

(3) Comparison of the models

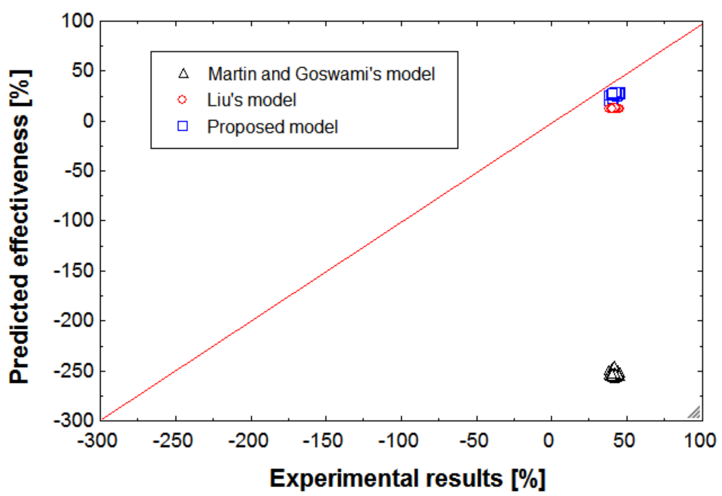

Figure 2. *Correlation comparison of the effectiveness of the regenerator*

The available literature (Liu et al. 2011, Martin and Goswami 2000), presented mass transfer effectiveness models, and Fig. 2 compares their performances with the proposed model for a regenerator using LiCl solution. As shown in Fig. 2, the model derived in this paper predicts the experimental results in TEST 1 within 10%, while Martin and Goswami's model and Liu's model shows over 20% deviation via experimental results. This indicates that the proposed model can predict a wider operable range of regenerators, and much more accurate value than the existing models.

CONCLUSIONS

In this research, a simple first-order polynomial regression model for predicting regeneration effectiveness was proposed via statistical analysis. The proposed model can be used for a packed bed regenerator using LiCl desiccant solution. In order to statistically analyze regenerator performance, a response surface method is used, and a data pool is generated by collecting experimental data from the available literature. A pilot system is also configured, and two set of tests are conducted. By RSM analysis, an improved model can be derived over the existing reported models under a broadened range of operating conditions, by connecting the collected results from the literature and pilot system tests. Comparing the experimental results indicates that the proposed model shows more correct prediction than the existing models.

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REFERENCES

Fumo, N., and Goswami, D.Y. 2002. Study of an aqueous lithium chloride desiccant system: Air dehumidification and desiccant regeneration, *Solar Energy*, Vol.*72*, pp.351–361.

Gommed, K., and Grossman, G. 2007. Experimental investigation of a liquid desiccant system for solar cooling and dehumidification, *Solar Energy*, Vol.*81*, pp.131–138.

Kim, M.H., Park, J.Y., Sung, M.K., Choi, A.S., and Jeong, J.W. 2014. Annual operating energy savings of liquid desiccant and evaporative-cooling-assisted 100% outdoor air system, *Energy and Buildings*, Vol.*76*, pp.538-550.

Langroudi, L. Omidvar, Pahlavanzadeh, H. and Mousavi, S.H. 2013. Statistical evaluation of a liquid desiccant dehumidification system using RSM and theoretical study based on the effectiveness NTU model, *Journal of Industrial and Engineering Chemistry,* Vol.20, pp.2975-2983.

Liu, X.H., Jiang, Y., Chang, X.M., and Yi, X.Q. 2007. Experimental investigation of the heat and mass transfer between air and liquid desiccant in a cross-flow regenerator, *Renewable Energy*, Vol.32, pp.1623–1636.

Liu, X.H., Yi, X.Q., and Jiang, Y. 2011. Mass transfer performance comparison of two commonly used liquid desiccants: LiBr and LiCl aqueous solutions, *Energy Conversion and management*, Vol.52, pp.180-190.

Martin, V. and Goswami, D.Y. 2000. Effectiveness of heat and mass transfer processes in a packed bed liquid desiccant dehumidifier/regenerator, *HVAC&R Research*, Vol.6, pp.21-39.

Myers, R.H., Montgomery, D.C., and Anderson-Cook, C.M. 2009. Response surface methodology: process and product optimization using designed experiments, Vol. 705. John Wiley & Sons.

Pahlavanzadeh, H. and Parisa, N. 2012. Experimental and Theoretical Study of Liquid Desiccant Dehumidification System by Using the Effectiveness Model, *Journal of Thermal Science and Engineering Applications*, Vol.4.

Sultan, G.I., Hamed, A.M., and Sultan, A.A. 2002. The effect of inlet parameters on the performance of packed tower-regenerator.,*Renewable energy, Vol.26*, pp.271-283.

Zhang, L., Hihara, E., Matsuoka, F., and Dang, C. 2010. Experimental analysis of mass transfer in adiabatic structured packing dehumidifier/regenerator with liquid desiccant, *Journal of Heat and Mass Transfer*, Vol.53, pp.2856–2863.

Zurigat, Y.H., Abu-Arabi, M.K., and Abdul-Wahab, S.A. 2004. Air dehumidification by triethylene glycol desiccant in a packed column, *Energy Conversion and Management*, Vol.45, pp.141-155.