CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 9

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 9*. Department of Civil Engineering, Aalborg University.

Statistical analysis of the liquid desiccant system operation parameters in hot and humid climates

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Abstract

The aim of this research is to propose a simplified prediction model for liquid desiccant system performance in hot and humid climates. The liquid desiccant pilot system used in this research was designed 2000m^3/h process air and 35kw air-cooled chiller provides cooling water at any given temperature. The lithium-chloride (LiCl) is used as the liquid desiccant solution. (The experiment data is collected from the liquid desiccant pilot system operation.) The dehumidification performance test is conducted during the summer in Seoul, South Korea when the outdoor air (i.e. process air) is hot and humid. The liquid desiccant system performance data was statistically analyzed using the response surface methodology (RSM). The impact of each operation parameters on the liquid desiccant system performance were estimated by analysis of variance provided from Design expert 9.0 tool. After analyzing process, the simplified linear prediction model was derived as a function of six operation parameters which have significant impact on the system performance (e.g. air mass flow rate, solution mass flow rate, ambient air dry-bulb temperature, ambient air humidity ratio, solution inlet temperature and solution concentration). Finally, to verify the reliability of the proposed model, a comparison of the response values predicted by the proposed model and the experimental data is conducted. The proposed model predictions are within 10% of the experimental values.

Keywords – Liquid desiccant system (LD), Statistical analysis, Response surface methodology (RSM), Prediction model

1. Introduction

A conventional vapor compression (e.g. CFC, HCFC) type HVAC systems can remov the latent heat load of process air by generating condensation. It occurs by maintaining the cooling coil temperature below the dew-point temperature of the process air. For this reason, conventional

HVAC systems (i.e. vapor compression) must to use a reheat coil to meet the target supply air temperature (SA), which makes inefficient energy consumption. In addition, the material used as a refrigerant is associated with the depletion of the ozone layer, which is a problem of environmental destruction.

In order to overcome this problem, many energy-efficient systems have been proposed to replace conventional HVAC systems. (Among them, decoupling systems as dedicated outdoor air system (DOAS) is a system that introduces outdoor air (OA) as supply air, it separates latent heat and sensible heat and proposes as more energy-efficient system than the conventional HVAC system [1].) As similar with DOAS, many researches have studied desiccant air-conditioning system using the desiccant absorption material (e.g. solid type, liquid type). In particular, the liquid desiccant air-conditioning system is attracting more interests than before [2].

Currently, researches related to liquid desiccant cooling system effectiveness are mostly oriented to experiments. Chung et al. [3, 4] proposed a dehumidification effectiveness model through experimental studies of a liquid desiccant system. Martin and Goswami [5] analyzed system effectiveness according to the temperature conditions of the solution within the absorber and regenerator by considering the physical variables of the system. Liu et al. [6, 7] calculated the mass transfer efficiency of desiccant solutions according to the moisture removal rate in dehumidification and regeneration. Thus, existing studies have primarily proposed models that use numerical or analytical methods to consider complex heat and mass transfer equations to predict the dehumidification effectiveness of a liquid desiccant system.

To reduce the complexity and hassles of the existing prediction models, this study offers a prediction model that is both reliable and simple. In this study, experimental data have obtained through the long-term operation of an actual liquid desiccant system. Using statistical method, contribution between dehumidification effectiveness and operation parameters were analyzed through accumulated experimental data. Also, this selected parameters influenced significantly through statistical analysis, and finally proposed the linear equation comprised of selected parameters. Finally, in order to obtain validity of dehumidification effectiveness prediction model proposed in this study, this research verified the reliability through comparing with experimental data and prediction value within 10% of deviation.

2. Liquid desiccant system overview

The liquid desiccant system can effectively remove latent heat loads by removing moisture included in OA using the desiccant solution (e.g. lithium chloride (LiCl), lithium bromide (LiBr) and triethylene glycol (TEG) etc.). The dehumidification process in a liquid desiccant absorber is generated by a partial pressure difference between the process air and desiccant solution. Any change in that partial pressure difference caused by the temperature of the desiccant solution affects the dehumidification performance. Desiccant solution that has removed moisture from outdoor air in the absorber becomes diluted and goes through a regeneration process in the regenerator. The maintenance temperature of the regenerator is generally 40-80℃, which makes a low-temperature heat source practical [8, 9].

The pilot system used in this study is designed for a maximum supply air (SA) flow of 2000m^3/h and uses LiCl solution as a desiccant material. Unlike commonly used liquid desiccant systems that handle only latent cooling, the pilot system can simultaneously treat sensible cooling of the process air.

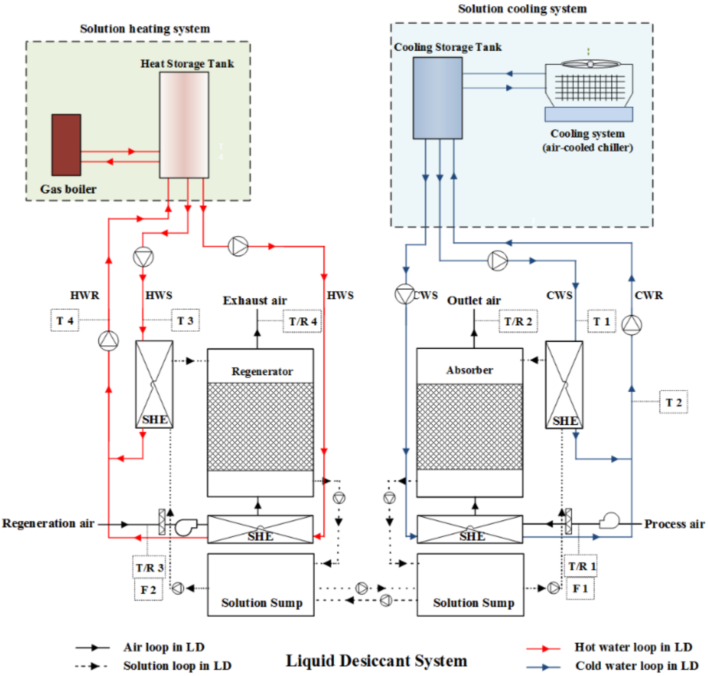


Fig. 1 Schematic diagram of the liquid desiccant pilot system

The pilot system is located on the 4th floor of a building in Incheon, Korea. A heat exchanger and a packed tower are installed in the absorber and regenerator, each supplied with cold and hot water. It controls the supply temperature of the desiccant solution through the entire process of introducing outdoor air and performing the heat exchange. To adjust the supply temperature of cold water needed for absorber in the system, an air cooled chiller with capacity of 35kW is installed. A liquefied petroleum gas

(LPG) condensing boiler with a capacity of 55.8kW controls the hot water temperature supplied to the regenerator. This system has a dehumidification capacity of 12.3g/kg and a sensible cooling capacity of 14.0kW simultaneously.

As shown in Fig. 1, the sensors confirm the status of the process air and desiccant solution in each part of the liquid desiccant system. To monitor the temperature and humidity, 4 temperature and humidity sensors are installed on the inlet/outlet of the absorber and regenerator, along with 2 air-flow meters to verify the process air flow induced on the system inlet. In addition, four temperature sensors verify temperature changes in the cold and hot water. A concentration of desiccant solution supplied to the absorber was measured by using a portable measurement device. The measured values from all sensors are connected to the automatic control system for operation of the pilot system in real time. Those are also programmed to store the measured values every 1 minute.

3. Experiment of pilot system

The pilot system experiment was conducted under the summer OA conditions when the cooling load is mostly high. The dehumidification performance was evaluated through the system operation during the summer in Korea (e.g. June - August) in 2013 to 2015. In Korea, the summer climate is hot and humid. Therefore, the weather is appropriate for evaluating the latent cooling (i.e. dehumidification performance) of a liquid desiccant system.

The experiment was conducted to measure changes in the system performance (i.e. dehumidification effectiveness) according to the variation of the system parameters, such as a process air mass flow, desiccant solution mass flow, OA conditions (e.g. temperature and humidity ratio) and desiccant solution conditions (e.g. temperature and concentration).

Table 1. Operating condition of the liquid desiccant pilot system

Operation parameter	Low value	High value	Average
Air mass flow ($\dot{m}_{ai}$)	1.55g/m^{2}s	6.57g/m^{2}s	3.88g/m^{2}s
Solution mass flow ($\dot{m}_{si}$)	6.01g/m^{2}s	19.85g/m^{2}s	13.35g/m^{2}s
OA temperature (T_{oa})	20.42℃	35.46℃	27.49℃
OA humidity ratio (ω_{oa})	7.27g/kg	22.37g/kg	14.0g/kg
Solution temperature (T_{si})	9.44℃	32.55℃	20.59℃
Solution concentration (C_{si})	36.80%	39.04%	37.61%

The obtained experiment data measured after operating the system at least 30 minutes in order to stabilize according to the changes of experimental parameters. The ambient air considered includes various summer outdoor conditions. The system performance (i.e. dehumidification effectiveness) was measured through at least three repetitions of the parameter adjustments using the 1-minute-interval data stored in the automatic control system. The Table 1 shows the operating range of the liquid desiccant system parameters.

Normally, the dehumidification performance can be evaluated by calculation of the performance index (e.g. dehumidification effectiveness, moisture removal rate and mass transfer coefficient). In this study, dehumidification effectiveness is used as a performance index. The dehumidification effectiveness depends on the humidity ratio, which is the ratio of changes in air humidity before and after the absorber. In other words, it used the difference between the humidity ratio of the process air entering the absorber and the equilibrium humidity ratio of the desiccant solution (1).

$$\varepsilon_{\mathrm{deh}} = (\omega_{\mathrm{in}} - \omega_{\mathrm{out}})/(\omega_{\mathrm{in}} - \omega_{\mathrm{equ}}) \tag{1}$$

Where, the solution equilibrium humidity ratio is as follows (2).

$$\omega_{equ} = 0.622 \times P_{si}/(B - P_{si}) \tag{2}$$

From the experimental result, a total 20 types of test sets are derived with average value based on the 160 types of operational data. During the experiment, a system parameters, the OA conditions and the desiccant solution conditions are estimated with the quantitative range of the operating conditions (Table 1.). Based on the experimental results, the dehumidification effectiveness of the system, calculated using (1), ranged from a minimum of 51.7% to a maximum of 90.3%.

The uncertainty analysis [10] of the dehumidification effectiveness was estimated by using the ASHRAE guidelines [11]. The overall uncertainty of the experimental data was determined by using basis ($\mathrm{b}_{\varepsilon_{deh}}$) and precision ($p_{\varepsilon_{deh}}$) uncertainty calculated on the experimental operating parameters (X_i) (3), (4), (5). The uncertainty analysis was carried out by using the Monte Carlo method via the Engineering Equation Solver (EES), a commercial equation solver [12]. Table 2 summarizes the uncertainty analysis of the experimental data.

$$\mathrm{U}\varepsilon_{deh} = (\mathrm{b}_{\varepsilon_{deh}}^2 + P_{\varepsilon_{deh}}^2)^{1/2} \tag{3}$$

$$\mathrm{b}_{\varepsilon_{deh}} = \left[\sum_{i=1}^{n} \left(\frac{\partial \varepsilon_{deh}}{\partial X_i} b_{X_i}\right)^2\right]^{1/2} \tag{4}$$

$$p_{\varepsilon_{deh}} = \frac{2S_r}{\sqrt{M}} \tag{5}$$

Table 2. Overall uncertainty value of the experimental data

	$\dot{m}_{ai}$	$\dot{m}_{si}$	T_{oa}	ω_{oa}	T_{si}	C_{si}	ε_{deh}
Uncertainty [%]	1.82	1.29	0.15	0.21	2.31	1.53	4.82

4. Statistical analysis of system praremers

Based on the experimental data obtained from the liquid desiccant system operation, a linear equation is proposed by using the response surface methodology (RSM) [13]. The proposed model derived a prediction model for the dehumidification effectiveness value according to system operating parameters (i.e. system parameters, OA conditions and desiccant solution conditions). The RSM is useful in statistically analyzing correlations between dehumidification effectiveness and system operating parameters. The system operating parameters that influenced the dehumidification effectiveness are presented in (6). From the 160 types operating data of the pilot system operation, contribution between dehumidification effectiveness and system operating parameters are analyzed by using the RSM of Design expert 9.0 [14], which is a statistical analysis program tool. After then, a linear equation is derived for 2FI model that considers interactions with system operating parameters. The response dependent parameter y is related to independent factors x_i and x_j by a first-order regression (7).

$$\varepsilon_{\mathrm{deh}} = f(\dot{m}_{ai},\ \dot{m}_{si}, T_{oa},\ \omega_{oa}, T_{si},\ C_{si}) \tag{6}$$

$$y = b_o + \sum b_i x_i + \sum b_j x_j + \sum b_{ij} x_i x_j \tag{7}$$

Where, b_o is a constant, b_i and b_j are linear coefficients, and b_{ij} is an interaction coefficient [13].

The prediction model for the dehumidification effectiveness was proposed for the liquid desiccant system used in this experiments that is defined 6 system operating parameters in the 2FI linear correlation (6), (7). The each parameter and its combination of the dehumidification effectiveness was analyzed by the analysis of variance (ANOVA) of the RSM. Table 3 presents the ANOVA results for 2FI model of the dehumidification effectiveness.

As shown in Table 3, the ANOVA results indicate that the two-factor interaction model (i.e. 2FI) is significant. In this research, A, B, C, D, E, F, AB, AC, AD, AE, BD, BE, CD, CE, DE, DF, and EF, as indicated by values of less than 0.05 for Prob > F (e.g. p-values). It means, those parameters have significant impact on the proposed model terms. The values for R^2 (0.945) and adjusted R^2 (0.936) give a low value for the coefficient variation (1.92%).

Table 3. ANOVA results for 2FI model of dehumidification effectiveness

Source	Sum of squares	df	Mean squares	F-value	P-value (prob > F)
Model	0.472348	21	0.022494	90.0717	< 0.0001
A: $\dot{m}_{ai}$	0.133322	1	0.133322	533.849	< 0.0001
B: $\dot{m}_{si}$	0.068704	1	0.068704	275.104	< 0.0001
C: T_{ai}	0.027022	1	0.027022	108.200	< 0.0001
D: ω_{ai}	0.033496	1	0.033496	134.126	< 0.0001
E: T_{si}	0.023076	1	0.023076	92.4029	< 0.0001
F: C_{si}	0.001156	1	0.001156	4.62751	0.03367
AB	0.010040	1	0.010040	40.2043	< 0.0001
AC	0.003034	1	0.003034	12.1489	0.00071
AD	0.009020	1	0.009020	36.1165	< 0.0001
AE	0.031338	1	0.031338	125.485	< 0.0001
AF	0.000051	1	5.129E-05	0.20536	0.65133
BC	0.000008	1	8.277E-06	0.03314	0.85588
BD	0.002845	1	0.002845	11.3929	0.00102
BE	0.005611	1	0.005611	22.4678	< 0.0001
BF	1.531E-08	1	1.531E-08	6.13E-05	0.99377
CD	0.016785	1	0.016785	67.2123	< 0.0001
CE	0.019519	1	0.019519	78.1574	< 0.0001
CF	0.000316	1	0.000316	1.26729	0.26274
DE	0.019351	1	0.019351	77.4846	< 0.0001
DF	0.017672	1	0.017672	70.7625	< 0.0001
EF	0.029506	1	0.029506	118.150	< 0.0001
Residual	0.027221	109	2.49E-04		
Cor Total	0.499599	130			

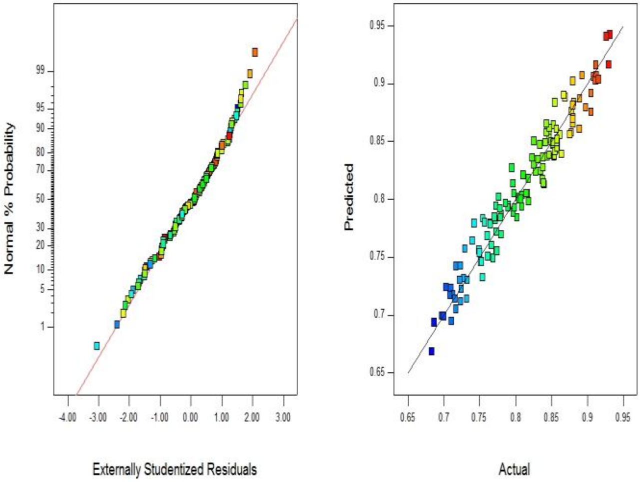
Equation (8) shows that the 2FI prediction model of this research, it has 17 significant terms from the ANOVA results as a model parameters. The symbol ‘α’ is the model coefficient, and the following Table 4 gives the model coefficients.

$$\begin{aligned}\varepsilon_{\mathrm{deh}} = \alpha_0 + \alpha_1 \cdot \dot{m}_{ai} + \alpha_2 \cdot \dot{m}_{si} + \alpha_3 \cdot T_{oa} \\ + \alpha_4 \cdot \omega_{oa} + \alpha_5 \cdot T_{si} + \alpha_6 \cdot C_{si} + \alpha_7 \cdot \dot{m}_{ai} \cdot \dot{m}_{si} \\ + \alpha_8 \cdot \dot{m}_{ai} \cdot T_{ai} + \alpha_9 \cdot \dot{m}_{ai} \cdot \omega_{ai} + \alpha_{10} \cdot \dot{m}_{ai} \cdot T_{si} \\ + \alpha_{11} \cdot \dot{m}_{si} \cdot \omega_{ai} + \alpha_{12} \cdot \dot{m}_{si} \cdot T_{si} + \alpha_{13} \cdot T_{ai} \cdot \omega_{ai} \\ + \alpha_{14} \cdot T_{ai} \cdot T_{si} + \alpha_{15} \cdot \omega_{ai} \cdot T_{si} + \alpha_{16} \cdot \omega_{ai} \cdot C_{si} \\ + \alpha_{17} \cdot T_{\mathrm{si}} \cdot C_{si}\end{aligned} \qquad (8)$$

Table 4. Coefficients of dehumidification effectiveness model

α_0	α_1	α_2	α_3	α_4	α_5
+1.3906	-0.0473	-0.0045	+0.0427	-0.5539	+0.3870
α_6	α_7	α_8	α_9	α_{10}	α_{11}
-2.8714	-0.0016	+0.0021	+0.0048	-0.0051	+0.0005
α_{12}	α_{13}	α_{14}	α_{15}	α_{16}	α_{17}
+0.0006	-0.0018	-0.0016	+0.0019	+1.4589	-0.9721

As shown in Fig. 2, the dehumidification effectiveness prediction model given in (8) well reflects the characteristics of the experimental data used in the process of deriving the prediction model. A comparison of the response values predicted by the proposed model and the experimental data is shown in Fig. 3. The proposed model predictions are within 10% of the experimental values.



(a) Normal probability plot (b) Predicted and actual plot of experiments

Fig. 2 Normal probability of statistical analysis

To verify the reliability of the experimental data and the prediction value of the proposed model, EES is used to calculate the prediction value of the proposed models based on the operating condition of the system operating parameters. The prediction value of the proposed model agrees well with the measurement experimental data within 10% error bound.

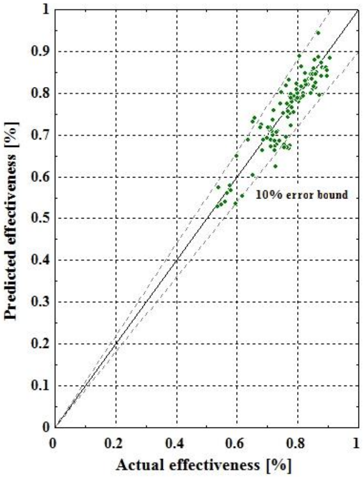


Fig. 3 Comparision between precited values and experimental data

5. Conclusions

In this paper, the experimental study is conducted on the liquid desiccant system operation. To propose a prediction model for dehumidification effectiveness, the experiment results are statistically analyzed by using the response surface methodology (RSM). The proposed model can predict the dehumidification effectiveness value of the absorber tower when is using an aqueous LiCl solution under the practical operation conditions.

According to the results of ANOVA, the two-factor interaction model (2FI) is indicated significant. The R^2 value shows 0.945 with low value for the coefficient variation (CV) was presented 1.92%. The prediction model of this research has 17 significant terms from the ANOVA results as a model parameters.

To verify the reliability of the proposed model, the obtained experimental data was compared with prediction value of the proposed model. It has considered operating condition based on the actual system operating parameters. The prediction value of the proposed model agrees well with the measured experimental data within 10% error bound.

Result of comparison prediction value was closed to actual system operation conditions. So, the proposed model can be used for predicting the performance of the practical operating condition. Further research integrated comparison of both proposed model and prediction model from the open literature [3-7]. The practicality and accuracy of the predicted value of the proposed model are achieved through the comparative analysis with the open literature [3-7].

Acknowledgment

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (No. 2015R1A2A1A05001726).

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