Roughness Surface Methodology for Predicting the Performance of Heat and Mass Transfer Process in Liquid Desiccant Dehumidifier

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Abstract. The heat and mass transfer process in liquid desiccant dehumidification system (LDDS) is very complicated because it is affected by a combination of input parameters. In this paper, the numerical optimization method is applied to optimize the performance of LDDS depending on experiment data taken from previous study for authors. The input data includes air temperature (Ta), humidity ratio (Wa) and solution temperature (Ts) and ranged between (27 to 34.5°C), (20.5 to 25 g/kg), and (27.5 to 38.5°C) respectively. Whereas the responses are the rate of moisture removal (MRR) and effectiveness (ε). The statistical analysis shows that the (Wa) has the most considerable effect on MRR while the (Wa) and (Ts) have the most considerable effect on ε. The optimization analysis for MRR and ε are found to be 0.54 g/s and 0.50 with minimum desirability 0.92 and 1 respectively.

1. Introduction

Liquid desiccant dehumidification process used to remove the moisture from the humid air due to the vapor pressure difference between the air and the solution. After the solution becomes weak, it can be regenerated at low temperatures using solar energy, waste heat, or geothermal power. The performance of dehumidification process is evaluated in terms of two indicators: MRR and ε. In the last three decades, many liquid desiccant dehumidification systems have been designed and developed to increase the efficiency of traditional air conditioning system. Different models were used to introduce the performance of dehumidifier and regenerator performance including theoretical and experimental models [1-3]. A modular simulation program with first and second laws of thermodynamics have been proposed by [4] to analyze the effect of several key variables on the performance of a novel hybrid air-conditioning system with lithium chloride as a desiccant in the system. The main results of simulation show that the increasing of the Ts in regenerator can improve the system’s performance. In [5], one dimensional non-equilibrium models developed to analyze the heat and mass transfer process in liquid desiccant system at low flow conditions. Some of experimental studies are conducted to justify the models. The experimental models show that the accumulating time of solution in packing investigates achievement of steady state. In the study of [6], lithium bromide (Li Br) and lithium chloride (LiCl) were used to compare the heat and mass transfer
performance. As reported in the results, the dehumidification performance of Li Br solution is a little better as compared with LiCl2 solution, while the regeneration performance of Li Br solution is better. Experimental work with different structured packing densities was investigated by [7] to evaluate the performance of air dehumidifiers using triethylene glycol as desiccant. Six design factors were taken to express the performance of air dehumidifier in terms of MRR and ε. These factors include; flow rate and inlet temperature of air and desiccant, inlet air humidity and desiccant concentration. An experimental study on liquid desiccant air conditioning system was investigated by [8]. The experiments include the performance of the dehumidification and regeneration rates and mass transfer coefficient (Cm). According to the experimental results, the mean Cm of the regenerator was 4 g/(m².s). In the current paper, optimization design is investigated to optimize the performance of the LDD, and to predict any significant effect of the input variables on MRR and ε.

2. Performance of Dehumidifier

The dehumidifier performance is evaluated in two indexes: The MRR and ε and defined by [8, 9] as:

\[ \Delta m_{\text{evap}} = m_a \times (w_{\text{out}} - w_{\text{in}}) \] (1)

\[ \varepsilon = \frac{w_{\text{out}} - w_{\text{in}}}{w_{\text{out-eq}} - w_{\text{in}}} \] (2)

Where \( m_a \), \( w_{\text{in}} \), \( w_{\text{out}} \) and \( w_{\text{out-eq}} \) are the air mass flow rate, inlet humidity ratio, outlet humidity ratio and air humidity ratio in equilibrium case with the solution [10]:

\[ w_{\text{out-eq}} = 0.62185 \times \frac{P_{wz}}{P - P_{wz}} \] (3)

Where \( P \) and \( P_{wz} \) are the total and partial pressures of air and water vapor in the solution.

3. D-Optimal Design

A quadratic polynomial model is assumed to predict the output \( Y \) [11, 12].

\[ Y = \beta_0 + \sum \beta_i z_i + \sum \beta_{ij} z_i z_j + \sum \sum \beta_{ijk} z_i z_j \] (4)

As shown in Table 1, Z1, Z2, and Z3 are the (Ta), (Wa) and (Ts) respectively. The settings for the independent variables are as follows: Ta (27 and 34) °C; Wa (20 and 25) g/kg and Ts (27 and 38) °C. Table 2 shows the values of \( Y \) responses for coding.

| Table 1: Levels of independent variables |
|------------------------------------------|
| Independent variables | levels  |
|------------------------|---------|
| Ta (°C)                | X1      |
|                        | -1 27   |
|                        | 0 30    |
|                        | +1 34   |
| Wa (g/kg)              | X2      |
|                        | 20 22   |
|                        | 25      |
| Ts (°C)                | X3      |
|                        | 27 33   |
|                        | 38      |
Table 2: Optimization of MRR and ε

| Run No. | Z variable | Y response |
|---------|------------|------------|
|         | Z1  | Z2  | Z3  | MRR(g/s) | ε    |
| 1       | 27.00 | 20.50 | 38.50 | 0.450    | 0.456 |
| 2       | 34.50 | 25.00 | 38.50 | 0.341    | 0.482 |
| 3       | 34.50 | 20.50 | 38.50 | 0.336    | 0.423 |
| 4       | 27.00 | 25.00 | 33.00 | 0.542    | 0.513 |
| 5       | 27.00 | 25.00 | 38.50 | 0.540    | 0.532 |
| 6       | 27.00 | 22.75 | 27.50 | 0.490    | 0.451 |
| 7       | 34.50 | 22.75 | 33.00 | 0.389    | 0.416 |
| 8       | 27.00 | 20.50 | 27.50 | 0.473    | 0.417 |
| 9       | 27.00 | 25.00 | 27.50 | 0.577    | 0.461 |
| 10      | 34.50 | 20.50 | 27.50 | 0.358    | 0.321 |
| 11      | 34.50 | 20.00 | 27.50 | 0.485    | 0.405 |
| 12      | 34.50 | 20.50 | 27.50 | 0.399    | 0.318 |
| 13      | 30.75 | 23.88 | 27.50 | 0.387    | 0.415 |
| 14      | 34.50 | 20.50 | 38.50 | 0.351    | 0.494 |
| 15      | 27.00 | 20.50 | 38.50 | 0.354    | 0.431 |
| 16      | 30.75 | 20.50 | 33.00 | 0.387    | 0.435 |
| 17      | 34.50 | 20.50 | 38.50 | 0.259    | 0.429 |
| 18      | 30.75 | 22.75 | 38.50 | 0.318    | 0.430 |

4. Optimization

Desirability (D) is an objective function used in Design-Expert under numerical optimization and defined as a desirabilities (di) that range from 0 to 1[12].

\[
D = \left( \prod_{i=1}^{n} d_i \right)^{1/n}
\]

(5)

5. System Description and Measured Data

According to Fig.1, the system consists of three subsystems: Dehumidification, regeneration and vapor compression (VCS). The VCS used to dehumidify and regenerate the solution before entering the dehumidifier and regenerator respectively. Each dehumidification and regeneration subsystems consists of centrifugal fan, pump, valves, filter, eliminator, flow meter.
The two pumps used to circulate the solution between the dehumidifier and evaporator from one side and between the regenerator and condenser in other side. Two centrifugal fans used to circulate the ambient air into the bottom of the dehumidifier and regenerator.

To measure the air and solution temperature, nine thermocouples with an accuracy ±0.1 °C were installed. Five TR-RH2W humidity sensors with accuracy of ± 3% RH were installed to measure the relative humidity at inlet and outlet of air flows. All these sensors coupled with data acquisition logger to collect and transfer the record data to the PC system. One flow meter with accuracy ±2 l/h was installed to control the mass flow rate of desiccant solution. Experimental runs have been conducted to evaluate the performance of the liquid desiccant dehumidification unit with the following parameter ranges as in Table 3.

Table 3: Characteristic measured data

| Description                                      | Value                      |
|--------------------------------------------------|----------------------------|
| Air flow rate in dehumidifier/regenerator        | 0.125 kg/s                 |
| Dehumidifier/regenerator inlet solution flow rate| 0.1 kg/s                   |
| Dehumidifier/regenerator air inlet temperature   | 27-34.5 °C / 39-57 °C      |
| Dehumidifier/regenerator air inlet humidity ratio| 20.5-25 g/kg / 18.9-21.8 g/kg |
| Dehumidifier/regenerator inlet solution temperature| 27.5-38.5 °C / 42-73 °C    |
| Desiccant concentration                          | 36.8%wt                    |

Fig.1: The diagram of system and experimental rig
6. Results and Analysis

6.1. Response surface analysis

The relationship for the response characteristic as a function of the three inputs in these experiments is considered as quadratic regression equations:

\[
MRR = +0.38 \cdot 0.057 \cdot Z1 + 0.043Z2 + 0.039 \cdot Z3 + 0.052 \cdot Z12 \\
+ 0.028 \cdot Z22 - 0.022 \cdot Z32 + 0.009419 \cdot Z1 \cdot Z2 - 0.00364 \\
\times Z1 \cdot Z3 \cdot 0.00364 \cdot Z2 \cdot Z3
\]  

\[
\varepsilon = +0.43 - 0.029 \cdot Z1 + 0.032 \cdot Z2 + 0.033 \cdot Z3 + 0.016 \cdot Z12 \\
+ 0.016 \cdot Z22 - 0.027 \cdot Z32 + 0.001879 \cdot Z1 \cdot Z2 + 0.016 \\
\times Z1 \cdot Z3 - 0.001883 \cdot Z2 \cdot Z3
\]  

It is clear that the (Ta and Ts) have a negative influence while (Wa) has a positive influence on MRR. On the other side, the effectiveness is affected in a positive with the (Wa and Ts) and in negative with the (Ta). As shown in Figure 2, the model values were found to be similar to the experimental values and fell on a straight line. The significance of the model was assessed using equation 4 by fitting to the experimental data to determine the F-value at a probability (P) of 0.01. The ANOVA results of different runs of experiment showed in Tables 4 and 5. As shown in table 4, the probability (P) is less than 0.01 which demonstrates that the model is important in a linear model and has considerable effect on the responses. As listed in Table 4, the lack of fit and pure error for MMR and \(\varepsilon\) are the lowest, with the sum of squares error of \(4.712 \times 10^{-3}\) and \(8.502 \times 10^{-3}\), and \(2.129 \times 10^{-3}\) and \(3.928 \times 10^{-4}\), respectively. This explains that the model is a suitable to indicate the experiment data with \(R^2\) being higher than 0.90 and 0.95 for the MRR and the \(\varepsilon\) models respectively.
b)

![Fig. 2: Predicted vs. Actual](image)

**Fig. 2:** Predicted and actual values of MRR and $\varepsilon$

**Table 4: Regression coefficients for MRR and $\varepsilon$**

| Predictors | Coefficients (β) MRR (g/s) | T | Probability (P) | Notability | Coefficients (β) $\varepsilon$ | T | Probability (P) | Notability |
|------------|-----------------------------|---|-----------------|------------|------------------------------|---|-----------------|------------|
| Intercept  | +0.38                        | 8.01 | 0.0037         | *          | +0.43                       | 17.2 | 0.0003         | *          |
| Linear     |                             |     |                |            |                            |     |                |            |
| X1         | -0.057                       | 27.5 | 0.0008         | *          | -0.029                      | 36.6 | 0.0003         | *          |
|            | X2                           | 14.3 | 0.0053         | *          | +0.032                      | 40.4 | 0.0002         | *          |
|            | X3                           | 12.0 | 0.0084         | *          | +0.033                      | 45.3 | 0.0001         | *          |
| Quadratic  |                             |     |                |            |                            |     |                |            |
| X11        | +0.052                       | 2.83 | 0.1308         | *          | +0.016                      | 1.35 | 0.2795         | *          |
| X22        | +0.028                       | 1.00 | 0.3477         | *          | +0.016                      | 1.61 | 0.2404         | *          |
| X33        | -0.023                       | 0.60 | 0.4594         | *          | -0.027                      | 4.83 | 0.0591         | *          |
| Interaction|                             |     |                |            |                            |     |                |            |
| X12        | +0.009                       | 0.65 | 0.4424         | *          | +0.001                      | 0.14 | 0.7217         | *          |
| X13        | -0.012                       | 1.05 | 0.3359         | *          | +0.016                      | 9.61 | 0.0147         | *          |
| X23        | -0.003                       | 0.09 | 0.7723         | *          | -0.001                      | 0.13 | 0.7321         | *          |
| $R^2$      | 0.90                         |      | 0.95           |            |                            |     |                |            |

* ***P<0.01; **P<0.05; *P<0.1; T: F test value; F=0.01, 0.05 and 0.1*
Table 5: ANOVA table of optimum responses

| Variable and source | df | Sum of squares | F-value | P-value |
|---------------------|----|----------------|---------|---------|
| MRR (g/s)           |    |                |         |         |
| Model               | 9  | 0.12           | 8.01    | 0.0037  |
| Residual            | 8  | 0.013          |         |         |
| Lack of fit         | 4  | 4.712×10⁻³     | 1.55    | 0.7092  |
| Pure error          | 4  | 8.502×10⁻³     |         |         |
| R²                  | 0.90| 9.82           |         |         |
| CV, %               |    |                |         |         |
| η                   |    |                |         |         |
| Model               | 9  | 0.049          | 17.27   | 0.0003  |
| Residual            | 8  | 2.521×10⁻³     |         |         |
| Lack of fit         | 4  | 2.129×10⁻³     | 5.42    | 0.0653  |
| Pure error          | 4  | 3.928×10⁻⁴     |         |         |
| R²                  | 0.95| 4.08           |         |         |
| CV, %               |    |                |         |         |

6.2. Behavior of MRR and ε

Figures (3-8) represent the 3D surface and contour graphs of behavior of MRR and ε under the (Ta, Wa and Ts). From Figures (3-5), it is clear that MRR increases with decreasing Ta to its minimum level (27°C), the MRR increased when the Wa was increased from 20 to 25 g/kg and at Wa of 25 g/kg, the MRR was achieved at 0.577 g/s. This may be discussed as that the mass transfer potential increases with increase in the humidity ratio of air. This result indicates that the air humidity ratio is an important factor in the liquid desiccant dehumidification.

Figures (6-8) indicated that the (ε) increased with the decrease in the air temperature and it is change slightly with the increase the inlet air humidity ratio. The above behavior as a results that the increasing of the inlet air temperature lead to rise the pressure of the solution. Hence, the effectiveness is reduced. On the other side, when the solution temperature increases, the equilibrium humidity ratio on the solution surface increase. Further, the effectiveness of the dehumidifier increased slightly as a result of equation (2).
Fig. 3: (a) Behavior of MRR and (b) Contour plots solution temperature 27.5 °C

Fig. 4: (a) Behavior of MRR and (b) Contour plots at inlet air humidity ratio 25 g/kg
Fig.5: (a) Behavior of MRR and (b) Contour plots at inlet air temperature 27 °C
Fig. 6: (a) Behavior of $\varepsilon$ and (b) Contour at solution temperature 33.2 °C

Fig. 7: (a) Behavior of $\varepsilon$ and (b) Contour at air humidity ratio 25 g/kg
6.3 Optimization of MRR and $\varepsilon$

The numerical optimization method used to optimize the maximum values of MRR and $\varepsilon$ while kept the input conditions within the operating range. The optimum conditions of MRR and $\varepsilon$ were (27.4°C, 24.5 g/kg, and 27.5°C) and (27.4°C, 24.8 g/kg, and 38.5°C) respectively while the optimum responses of MRR and $\varepsilon$ found to be 0.54 g/s and 0.5 with a minimum desirability of 0.992 and 1.00, respectively.

7. Conclusions

The numerical optimization method in expert design software was effectively used to optimize the inlet parameters on the dehumidification process performance. Depending on the model results, two main conclusions can be drawn:

1. Depending on the variance analysis, the (Wa) has the most considerable effect on MRR, while the (Wa and Ts) have the most considerable effect on $\varepsilon$.
2. According to the optimization model, the maximum MRR was (0.54 g/s) under optimum levels of (Ta =27.4°C), (Wa =24.5 g/kg) and (Ts = 27.5°C). Additionally, the maximum $\varepsilon$ was (0.50) under optimum levels for (Ta =27.4°C), (Wa=24.8 g/kg) and (Ts =38.5°C).
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