# Improvement of Dehumidification Effectiveness Prediction Models

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## Abstract

Dehumidification effectiveness prediction models for packed bed type liquid desiccant systems are important to assess moisture removal rate which is the key performance. Chung (1994) and Martin and Goswami (2000) have proposed models to predict the dehumidification effectiveness as a function of input parameters including flow rate and temperature of the dehumidified air; flow rate, temperature, and concentration of the desiccant solution; and specific area per volume of the packing. Both works used lithium chloride solution and triethylene glycol as the desiccants and the operating condition in terms of the ratio of the desiccant flow rate to the air flow rate (L/G ratio) was between 3.5 and 15.4. An experiment was carried out in Nakhon Pathom, Thailand. Forty percent concentration calcium chloride solution was used as the desiccant and the L/G ratio was within the range of 0.277 to 2.771. The actual moisture removal rates from the experiment were compared with those predicted from 3 cases: 1) using constant effectiveness, 2) using the effectiveness from Chung's and Martin and Goswami's models, and 3) using the effectiveness from Chung's and Martin and Goswami's models with an adjustment of the coefficients in the models to suit the experimental conditions. The results show that using constant effectiveness is possible if it is the average value over the range of actual operating conditions. For the cases of using the models from the literature, after the adjustment of the coefficients the root mean square error (RMSE) and the mean bias difference (MBD) when using Chung's model were improved from 4.491 g/s and 4.376 g/s to 0.629 g/s and 0.522 g/s, respectively. For the case of using Martin and Goswami's model, the RMSE and MBD were improved from 265.475 g/s and 265.377 g/s to 2.178 g/s and 2.072 g/s, respectively. It can be concluded that the coefficients in the models need an adjustment before use to predict the performance accurately and this study has proposed the suitable sets for two models from the literature for the packed bed liquid desiccant dehumidification system using 40% concentration calcium chloride solution within the L/G ratio range of 0.277 to 2.771.

**Keywords**: dehumidification system, liguid desiccant, packed bed, effectiveness prediction model, moisture removal rate prediction

## Introduction

Air conditioning systems are necessary to create thermal comfort in a tropical climate such as Thailand.[1] The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) specifies temperature range of 20 to 27$^{o}$C and relative humidity range of 30 to 60% as the condition at which human beings would feel thermally comfortable.[2]

Vapor compression system is mostly used for air conditioning of which the cooling coil handles both cooling and dehumidification. The cooling coil removes heat from the air causing its temperature to reduce to the dew-point. When the cooling process continues, the moisture in the air passing through the coil will be condensed resulting in the reduction of the humidity level as well as the temperature of the air. In general, the system cuts off when the indoor air temperature reaches the setpoint value at the thermostat regardless of how much moisture left in the air. Excessive humidity in the space can cause uncomfortable feeling to the occupants and also the deterioration of materials or mold and mildew problems.[3]

For the applications that need to control tem-

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perature and humidity simultaneously (e.g., clean rooms in electronic industry, laboratories in pharmaceutical industry), the air conditioning system has to cool the air well below the setpoint temperature to remove moisture to the desired level and then reheat it back to the setpoint value. This scheme, so-called overcool and reheat, requires a large air conditioning system and causes waste heat at the reheating step.[4] A more energy-efficient option is to separate humidity and temperature control by using a dehumidification system to handle the latent load while the sensible load is still handled by the air conditioning system.[5,6] The latent or dehumidification load mainly comes from the ventilation air.[7] Therefore, mitigating its humidity level before introducing into the conditioned space is a proper action that will help reduce the cooling load imposed on the air conditioning system. Past researches reported that the size of the system could be reduced by half resulting in less costs and energy consumption.[8,9]

For the dehumidification system, moisture removal rate is the key performance parameter. A method to predict the moisture removal rate is to use the dehumidification effectiveness model. Thus, an accurate effectiveness model is in need.

This article presents a study conducted to propose suitable sets of coefficients for two dehumidification effectiveness models from the literature to predict the moisture removal rate of an existing liquid desiccant dehumidification system. Comparisons of the results when applying the original and the adjusted models with the proposed sets of coefficients with the actual experimental results are also presented.

## Experimental Setup

The schematic diagram of the liquid desiccant dehumidification system in this work is shown in Figure 1. Calcium chloride ($CaCl_2$) solution was used as the desiccant. The system comprises 3 main parts, i.e., dehumidification, regeneration, and cooling parts.

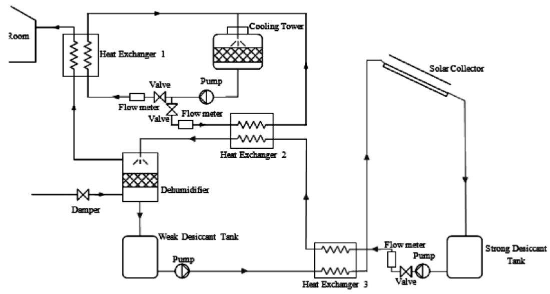


**Figure 1** Liquid Desiccant Dehumidification System in This Study[10]

The dehumidifier is of packed bed type. The air is drawn in from the bottom and directly contacts with the desiccant solution sprayed from the top. The dehumidified air is delivered to a heat exchanger to cool down before being supplied into a conditioned space. The weaker desiccant at the outlet will be transported to the regenerator to evaporate water out by a heat source thus the desiccant becomes stronger and ready to absorb moisture again. However, the temperature of the desiccant will be higher so it needs to be cooled down by cooling water in a heat exchanger before being transferred back to the dehumidifier.

The regenerator in this study is solar parabolic troughs without a sun tracking system. The cooling water is supplied by a 10-ton cooling tower.[10]

## Methodology

The actual experiment mentioned in this study used 40% concentration $CaCl_2$ solution as the desiccant. The regenerating air flow rate was kept constant at 0.0028 kg/s. The dehumidified air flow rate was varied at 0.04, 0.06, and 0.08 kg/s. The desiccant flow rate was varied at 0.02, 0.07, and 0.12 kg/s. The ratio of the desiccant flow rate to the air flow rate (or L/G ratio) was found to be in the range of 0.277 to 2.77. The experiment was carried out during February and March, 2011. The operating data were collected during 8 a.m. to 5 p.m.

The dehumidification effectiveness is defined as the ratio of the actual dehumidifying capacity to the theoretical or maximum one which would occur when the humidity ratio of the outlet air is in equilibrium with the inlet desiccant as shown in Equation 1.

$$\alpha_{ab} = \frac{W_{a,in} - W_{a,out}}{W_{a,in} - W_{s,in}} \quad (1)$$

Where,

$W_{a,in}$ = humidity ratio of inlet air, $kg_w/kg_{da}$

$W_{a,out}$ = humidity ratio of outlet air, $kg_w/kg_{da}$

$W_{s,in}$ = humidity ratio of air in equilibrium with inlet desiccant condition, $kg_w/kg_{da}$.

Chung (1994)[11,12] carried out a study on a liquid desiccant dehumidification system using triethylene glycol (TEG) and lithium chloride (LiCl) solutions. The dehumidifier was of packed bed type. The effectiveness of the equipment has been modeled as a function of flow rates of the fluids, temperature of the fluids at the inlets, size of the packing, and properties of the desiccant as expressed in Equation 2.

$$\alpha_{ab} = \left\{1 - \frac{0.205\left(\frac{G_{a,in}}{G_{s,in}}\right)^{0.174}\exp\left[0.985\left(\frac{T_{a,in}}{T_{s,in}}\right)\right]}{aZ^{0.184}X^{1.680}}\right\} / \left\{1 - \frac{0.152\exp\left[0.686\left(\frac{T_{a,in}}{T_{s,in}}\right)\right]}{X^{3.388}}\right\} \quad (2)$$

Where,

$G_{a,in}$ = flow rate of inlet air, kg/s

$G_{s,in}$ = flow rate of inlet desiccant, kg/s

$T_{a,in}$ = temperature of inlet air, kg/s

$T_{s,in}$ = temperature of inlet desiccant, kg/s

a = area to volume ratio of packing, $m^2/m^3$

X = fraction of the vapor pressure depression of the desiccant solution to the vapor pressure of pure water.

Martin and Goswami (2000)[13] conducted a study on a liquid desiccant dehumidification system using a packed bed dehumidifier and TEG as the desiccant. A mathematical model to predict the dehumidification effectiveness as a function of relevant input parameters was proposed as shown in Equation 3.

$$\alpha_{ab} = 1 - C_1\left(\frac{G_{s,in}}{G_{a,in}}\right)^x\left(\frac{h_{a,in}}{h_{s,in}}\right)^y(aZ)^z \quad (3)$$

Where,

$$x = k_1\frac{\gamma_s}{\gamma_0} + m_1 \quad (4)$$

$$z = k_2\frac{\gamma_s}{\gamma_0} + m_2 \quad (5)$$

and the coefficients are

$C_1$ = 48.3 y = -0.751

$k_1$ = 0.396 $m_1$ = -1.57

$k_2$ = 0.0331 $m_2$ = -0.906.

The L/G ratio in the work of Chung and Martin and Goswami was found to be in the range of 3.5 to 15.4.

The actual experimental data were taken into a regression analysis to search for the new sets of coefficients that would make both models suitable for the desiccant type and the experimental conditions. The adjusted Chung's and Martin and Goswami's models are respectively shown below.

$$\alpha_{ab} = \left\{1 - \frac{4.49\left(\frac{G_{a,in}}{G_{s,in}}\right)^{0.055}\exp\left[0.832\left(\frac{T_{a,in}}{T_{s,in}}\right)\right]}{aZ^{0.838}X^{0.733}}\right\} / \left\{1 - \frac{0.215\exp\left[0.868\left(\frac{T_{a,in}}{T_{s,in}}\right)\right]}{X^{0.326}}\right\} \quad (6)$$

$$\alpha_{ab} = 1 - C_1\left(\frac{G_{s,in}}{G_{a,in}}\right)^x\left(\frac{h_{a,in}}{h_{s,in}}\right)^y(aZ)^z \quad (7)$$

Where,

$$x = k_1\frac{\gamma_s}{\gamma_0} + m_1 \quad (8)$$

$$z = k_2\frac{\gamma_s}{\gamma_0} + m_2 \quad (9)$$

and the coefficients are

$C_1$ = 5,716.96 y = -0.4822

$k_1$ = 1.0034 $m_1$ = -1.647

$k_2$ = 3.9943 $m_2$ = 3.2062.

Once the dehumidification effectiveness is evaluated, the moisture removal rate can then be calculated from Eq. 10.

$$m_{w,ab} = G_{a,in}\alpha_{ab}(W_{a,in} - W_{s,in}) \quad (10)$$

The following section discusses about the comparisons of the moisture removal rates predicted by using the dehumidification effectiveness from 3 cases with the actual experimental results. The first case is that when a constant effectiveness was applied. The second case is that when the original Chung's and Martin and Goswami's models were applied. The last case is that when the adjusted Chung's and Martin and Goswami's models were used.

## Results and Discussion

Figures 2 to 4 show the comparisons of the moisture removal rates predicted by applying a constant effectiveness (case 1) and by Chung's model in cases 2 and 3 with the experimental results. When the dehumidification effectiveness was treated as a constant value, the predicted moisture removal rates were within the error bars of the actual values. This is due to the fact that the constant effectiveness was the average value over the actual operating conditions. The original Chung's model gave the predicted values within the error bars of the actual results only at higher air flow rates as it can be seen in Figures. 3 and 4. The adjusted Chung's model yielded the best outcomes since the predicted values were close to the actual results at all operating conditions.

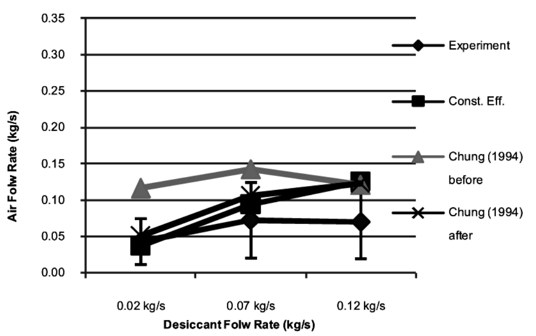


**Figure 2** Moisture Removal Rates When Using Original and Adjusted Chung's Model at Air Flow Rate = 0.04 kg/s

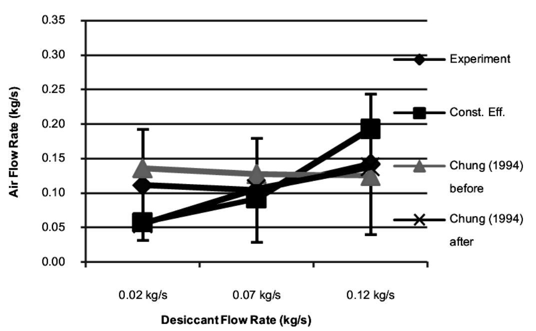


**Figure 3** Moisture Removal Rates When Using Original and Adjusted Chung's Model at Air Flow Rate = 0.06 kg/s

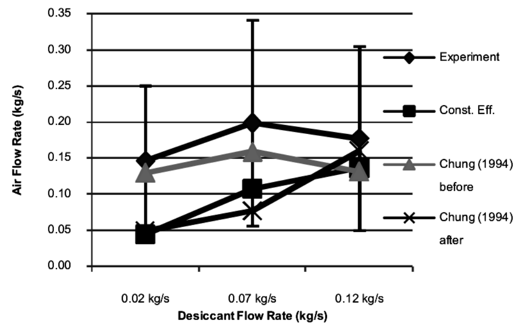


**Figure 4** Moisture Removal Rates When Using Original and Adjusted Chung's Model at Air Flow Rate = 0.08 kg/s

Table 1 shows the root mean square error (RMSE) and the mean bias difference (MBD) of the moisture removal rates predicted by Chung's model before and after the coefficient adjustment and the experimental values. If the values of RMSE and MBD are small and not greater than the measurement errors of the actual results, it is able to say that the model can predict the results accurately. From the table, it is obvious that the RMSE and MBD values were improved significantly when the new set of coefficients for Chung's model was applied. The average RMSE was improved from 4.491 to 0.629 g/s while the average MBD was improved from 4.376 to 0.522 g/s.

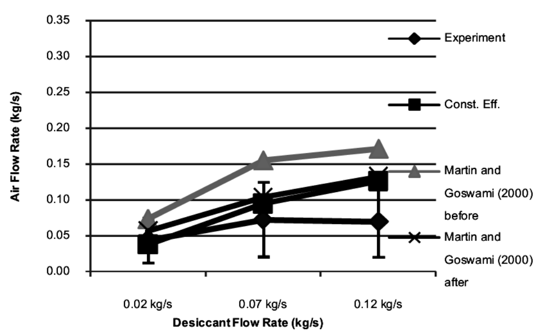


**Figure 5** Moisture Removal Rates When Using Original and Adjusted Martin and oswami's Model at Air Flow Rate = 0.04 kg/s

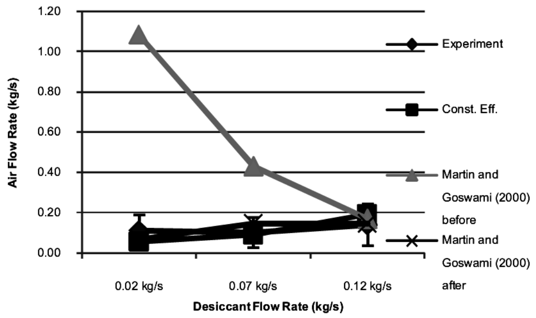


**Figure 6** Moisture Removal Rates When using Original and Adjusted Martin and Goswami's Model at Air Flow Rate = 0.06 kg/s

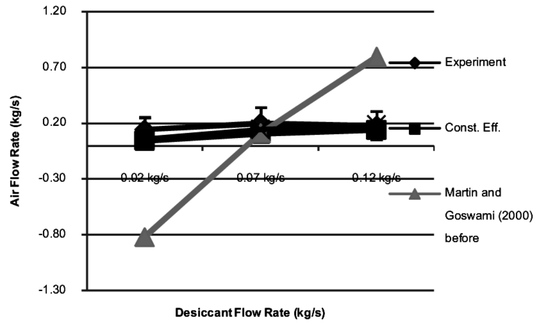


**Figure 7** Moisture Removal Rates When Using Original and Adjusted Martin and Goswami's Model at Air Flow Rate = 0.08 kg/s

Figures 5 to 7 show the comparisons of the moisture removal rates predicted by Martin and

**Table 1** RMSE and MBD of Moisture Removal Rate When Applying Chung's Model before and after the Coefficient Adjustment

| Desiccant flow rate (kg/s) | Air flow rate (kg/s) | Constant effectiveness | | | Chung (1994) before | | | Chung (1994) after | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.04 | 0.06 | 0.08 | 0.04 | 0.06 | 0.08 | 0.04 | 0.06 | 0.08 |
| 0.02 | RMSE | 0.040 | 2.970 | 10.395 | 5.308 | 3.170 | 9.230 | 0.056 | 0.595 | 0.247 |
| | MBD | -3.885 | 2,857.727 | 10,249.301 | 5,264.332 | 3,058.173 | 9,084.541 | 12.413 | 482.808 | 101.233 |
| 0.07 | RMSE | 0.486 | 0.159 | 8.338 | 4.924 | 0.003 | 14.801 | 1.153 | 0.264 | 0.167 |
| | MBD | 414.151 | 54.027 | 8,338.163 | 4,851.600 | -101.604 | 14,633.631 | 1,081.164 | 151.999 | 21.972 |
| 0.12 | RMSE | 3.124 | 2.571 | 1.690 | 2.649 | 0.018 | 0.316 | 2.791 | 0.169 | 0.215 |
| | MBD | 3,054.597 | 2,429.180 | 1,512.782 | 2,579.434 | -124.057 | 139.268 | 2,720.807 | 57.309 | 69.443 |

**Table 2** RMSE and MBD of Moisture Removal Rate When Applying Martin and Goswami's Model before and after the Coefficient Adjustment

| Desiccant flow rate (kg/s) | Air flow rate (kg/s) | Constant effectiveness | | | Martin and Goswami (2000) before | | | Martin and Goswami (2000) after | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.04 | 0.06 | 0.08 | 0.04 | 0.06 | 0.08 | 0.04 | 0.06 | 0.08 |
| 0.02 | RMSE | 0.040 | 2.970 | 10.395 | 0.878 | 951.130 | 933.001 | 0.169 | 1.777 | 8.923 |
| | MBD | -3.885 | 2,857.727 | 10,249.301 | 834.719 | 951,018.348 | 932,855.121 | 125.312 | 1,665.079 | 8,777.673 |
| 0.07 | RMSE | 0.486 | 0.159 | 8.338 | 6.839 | 107.125 | 1.007 | 0.988 | 1.325 | 0.020 |
| | MBD | 414.151 | 54.027 | 8,338.163 | 6,767.098 | 107,020.057 | 986.344 | 915.440 | 1,213.357 | -125.083 |
| 0.12 | RMSE | 3.124 | 2.571 | 1.690 | 10.298 | 0.800 | 378.202 | 3.867 | 1.206 | 1.330 |
| | MBD | 3,054.597 | 2,429.180 | 1,512.782 | 10,228.048 | 657.562 | 378,024.483 | 3,797.686 | 1,094.198 | 1,184.164 |

Goswami's model in cases 2 and 3 with the experimental results. It can be seen that the adjusted model provided the forecast moisture removal rates within the error bars of the actual values at all operating conditions. Therefore, modifying the model's coefficients to suit the actual operating conditions is necessary for accurate prediction.

Table 2 shows the RMSE and MBD values of the moisture removal rates predicted by the original and adjusted Martin and Goswami's model and the experimental values. From the table, it can be seen that the RMSE and MBD values were improved dramatically when the modified Martin and Goswami's model was applied. The average RMSE was improved from 265.475 to 2.178 g/s whereas the average MBD was improved from 265.377 to 2.072 g/s. This confirms the necessity of the adjustment of the model's coefficients to suit the desiccant type and the actual operating conditions.

## Conclusion

This study is about the prediction of the moisture removal rate of a packed bed liquid desiccant dehumidification system using the dehumidification effectiveness models from the literature. When the effectiveness was treated as a constant value, it would be able to give satisfactory results if it is an appropriate value such as the average value over the actual operating conditions. When the effectiveness models with modified coefficients to suit the desiccant type and the experimental conditions were applied, the predicted moisture removal rates were appreciably closer to the actual results implying the importance of the coefficient adjustment. This study has proposed the new sets of coefficients for Chung's and Martin and Goswami's dehumidification effectiveness models suitable for the packed bed dehumidifier using 40% concentration $CaCl_2$ solution as the desiccant (Eqs. 6 and 7). The air and the desiccant flow rates should be in the range of 0.04 to 0.08 kg/s and 0.02 to 0.12 kg/s, respectively, which yields the L/G ratio range of 0.277 to 2.77.

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