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# General correlations for the heat and mass transfer coefficients in an air-solution contactor of a liquid desiccant system and an experimental case application

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## ABSTRACT

This paper presents general types of correlation for the heat and mass transfer coefficients inside an air-solution contactor as expressions of Reynolds-Prandtl numbers and Reynolds-Schmidt numbers, respectively. These general equations summarize the physical and thermophysical properties of the air, the solution, and the contactor, which make them capable to be used for parametric studies provided they are fitted in a wide range of experimental data that include all the properties involved. In this work, a liquid desiccant system with an adiabatic structured packed bed as contactor and an aqueous lithium chloride as solution was constructed. The experimental data taken at various air superficial velocities and solution flow rates were fitted to the general correlations, and comparisons between the predicted and experimental results for both coefficients are within ±10%, for both dehumidification and regeneration processes. In addition, the calculated values of the outlet air humidity ratio and temperature agree well with the experimental data for both processes. The particular equations for the heat and mass transfer coefficients can be used to perform parametric studies at different air superficial velocities and solution flow rates with very good accuracy. Results from this study can help improve the system design and operation methods of air-solution contactors.

## 1. Introduction

Vapor Compression Systems (VCS) and Desiccant Cooling Systems (DCS) are two of the numerous types of air conditioning systems being used nowadays. Compared to the VCS, the latter is still a developing technology and shares a small portion in the market in terms of deployment and actual application. However, VCS have been facing several challenges due to a number of problems, namely performance and environmental issues. On the other hand, DCS are being extensively studied and have been suggested by researchers as an alternative to conventional VCS due to their ability to perform more efficiently and their capability to provide better indoor air quality. The two types of DCS are the solid desiccant system (SDS) [1–3] and the liquid desiccant system (LDS) [4,5]. In a LDS, the major component is the air-solution contactor; this is used to improve the heat and mass transfer between the air and the liquid desiccant solution. Air-solution contactors act as either dehumidifiers when they are used to remove water vapor from the air or as regenerators when they are used to reject water content from the solution. These contactors are categorized as either adiabatic (random or structured) or internally cooled and the type of flows between the air and the solution inside these are classified as either counter, cross, or parallel flow configuration. This study uses a structured packed bed contactor with the air and solution under cross flow configuration.

Due to the complex simultaneous heat and mass transfer phenomena inside the air-solution contactor, several models have been developed by different researchers to predict its performance. There are two sets of performance predictors commonly used to calculate the heat and mass transfer rates inside the contactor, these are the heat and mass transfer coefficients and the enthalpy

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## Nomenclature

| | |
|---|---|
| $C$ | surface contact area per unit volume |
| $d_h$ | hydraulic diameter |
| $d_p$ | diameter (or nominal size) of packing |
| $D$ | mass diffusivity |
| $G$ | mass flux |
| $h$ | enthalpy |
| $h_v$ | enthalpy of vaporization |
| $q_{sens}$ | sensible heat flux |
| $j_w$ | diffusion mass flux, latent heat flux |
| $K$ | transfer coefficient |
| $m$ | solution mass flow rate |
| $M_t$ | molecular weight of water |
| $Nu$ | Nusselt number |
| $Pr$ | Prandtl number |
| $Re$ | Reynolds number |
| $Sc$ | Schmidt number |
| $Sh$ | Sherwood number |
| $T$ | temperature |
| $u$ | air superficial velocity |
| $x$ | humidity ratio |
| $X$ | concentration |

*Greek symbols*

| | |
|---|---|
| $\lambda$ | thermal conductivity |
| $\rho$ | density |

*Subscripts*

| | |
|---|---|
| a | air |
| b | bulk |
| e | equilibrium |
| i | inlet, interface |
| h | heat |
| m | mass |
| o | outlet |
| s | solution |

and moisture effectiveness. To date, there is still no agreement on the general correlations for these performance predictors. Thus, a generalized methodology based on the significant parameters involved and the fundamental principles of heat and mass transfer, able to characterize the thermo-fluid-dynamic behavior of the air and solution is needed in order to optimize the use of the contactor.

Liu et al. [6] developed general correlations for the enthalpy and moisture effectiveness through experimental data analysis of the effects of both air and solution inlet parameters on both effectiveness. They fitted their experimental data to their correlations and provided particular equations for each effectiveness, which predicted the experimental data within deviations of ±20%. Similarly, Gao et al. [7] formulated empirical equations for the enthalpy and moisture effectiveness based on the performance trend of both effectiveness with the inlet air and solution parameters. The general form of their equations is the same with that of reference [6] but they fitted their own experimental data to the general correlations and derived different values for the coefficients and exponents. The predicted values from both of their correlations agreed with the experimental results within ±18%. Moon et al. [8] calculated the humidity effectiveness using the equations of Liu et al. [9] and Chung [10] and compared the calculated values to their experimental results, but they found that the calculated values from both equations do not fit well with their experimental data. Hence, they fitted their experimental data to the general form of the dehumidifier effectiveness from Refs. [9,10] and compared the predicted values from their equations with their experimental data, which resulted to within ±10% deviations. Liu et al. [11,12] utilized analytical solution to derive equations for the enthalpy and moisture effectiveness. Comparison between the predicted and experimental results from both studies showed deviations mostly within ±20%. Chung et al. [13] developed correlations for the heat and mass transfer coefficients as expressions of Reynolds-Prandtl numbers *Re-Pr* and Reynolds-Schmidt numbers *Re-Sc* of the air, respectively, including the solution concentration and the air-solution flow ratio. They fitted their experimental data to their general correlations and obtained particular equations, which predicted the experimental data within ±10%. In another study, Liu et al. [14] adopted the correlation of Sherwood number *Sh* from reference [13] and fitted their experimental data to the correlation. Their equation was used to solve for the number of transfer units *NTU*, which was then used to estimate the outlet conditions needed to calculate the enthalpy and moisture effectiveness. Comparison between the predicted and experimental results from both effectiveness showed that most of the values agree within ±20%. Yin and Zhang [15] pointed out that traditional Nusselt number *Nu* and Sherwood number *Sh* that include only the *Re-Pr* and *Re-Sc* of the air, respectively, are not comprehensive enough to define the heat and mass transfer coefficients, as they cannot indicate the effects of the solution temperature and concentration. This assertion is fundamentally correct, which is probably why Chung et al. [13] included the solution concentration and air-solution flow ratio on their correlations for the heat and mass transfer coefficients. Nevertheless, even these correlations have the limitation of not including the effect of the solution temperature. In reference [15], new correlations for the heat and mass transfer coefficients as functions of the inlet air velocity, inlet air humidity ratio and temperature, and inlet solution temperature and concentration were developed. However, one drawback of these correlations is that the influence of the solution flow rate was ignored, which is found to greatly affect both coefficients. A possible solution to the inability of the previous representations of *Nu* and *Sh* to indicate the effects of the physical properties of the solution is to include the *Re-Pr* and *Re-Sc* of the solution in the expression of *Nu* and *Sh*, respectively. This type of correlation for the *Sh* was obtained by Zhang et al. [16] from a dimensional analysis that includes both physical properties of the air and solution in the mass transfer coefficient model. They fitted their experimental data to their correlation and predicted results agreed with their experimental data approximately within ±20%. So far, the relationships of the heat and mass transfer coefficients to the *Re-Pr* and *Re-Sc*, respectively, of the air and solution are yet to be clarified and a better understanding of both coefficients as expressions of these dimensionless numbers is necessary to fully utilize the coefficients with greater accuracy and to improve the performance prediction of air-solution contactors.

This study addresses the problem by correlating the heat and mass transfer coefficients as expressions of *Re-Pr* and *Re-Sc*, respectively, involving both physical properties of the air and solution. The experiments present new data on the variation of the heat and mass transfer coefficients within typical range of applications for the air superficial velocities and solution flow rates. The validity of the particular equations are confirmed by the experimental data,