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Mathematical modeling of a packed-bed air dehumidifier: The impact of empirical correlations

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ABSTRACT

Applying empirical correlations to estimate various parameters used in a mathematical model is inevitable. In this study, a mathematical model is developed for a packed-bed air dehumidifier and the impact of some well-known empirical correlations available in literature is evaluated on the model's predictions and accuracy. The results reveal that in designing an air dehumidifier, using different empirical correlations may lead to very different predictions for the required bed height. The equations of Onda et al. (1968) and Rocha et al. (1996) to calculate the effective interfacial area, the equation of Treybal (1981) to calculate the heat transfer coefficient, and the equations of Chung et al. (1996) to calculate the mass transfer coefficient show precise results and increase the reliability of the mathematical models.

1. Introduction

Dehumidification is a separation process for removing moisture from a gasiform stream. This process is particularly used for the drying of natural gas in the oil and gas industries to reduce the water content of a natural gas to levels suitable for gas transport in subsea pipelines (Yaling, 2006; Parks and Amin, 2012). It is also used for dehumidification of the utility air in oil and gas industries located in humid and sultry areas. Dehumidification could be achieved either by cooling of air/increasing its pressure or absorption/adsorption of moisture by a solid or liquid material named as desiccants. Desiccants are materials with a high affinity for water. The moisture removal from the air depends on the vapor pressure gradient between the desiccant and the air. Conventional solid desiccants are silica gel, activated alumina, lithium chloride salt, molecular sieves, titanium silicate and synthetic polymers. Liquid desiccants include lithium chloride (LiCl), lithium bromide, calcium chloride and triethyleneglycol (TEG).

Pecked-bed operating systems have received special attention for reducing the moisture content of a humid air stream. These kinds of equipment are well known for their compactness, high efficiency, large contact area, and large contact time. Table 1 lists some recent investigations that have been conducted on the packed-bed air dehumidifiers (PBAD).

Two types of packings are generally used namely random packing (such as Berl Saddles, Rasching rings and Intalox Saddles) and structured packing (such as cellulose rigid media pads, wood grids, expanded metal lash packing, double spiral rings). Although, random packing provides greater contact area between the air and desiccant, in this kind of packing the required desiccant flow rates for proper wetting as well as the air-side pressure drop are generally high. In recent years, the researchers intend to use structured packing in counter flow or in some cross flow configurations (Raynal and Royon-Lebeaud, 2007; Marcia et al., 2009).

Similar to other conventional operating systems, many empirical correlations are required to design and model a liquid desiccant dehumidification system. A proposed mathematical model may lead to different results depending on the accuracy of the empirical correlations applied. Comparison of the results of a proposed non-isothermal model with experimental data may be a useful technique to evaluate the precision of the applied empirical correlations.

Several researchers performed studies in evaluating different empirical correlations (Ali, 1991; Al-Fattah and Al-Marhoun, 1994; Lide et al., 2007; Asadisaghandi and Tahmasebi, 2011); Lide et al. (2007) compared different correlations used for Venturi wet gas metering in oil and gas industry and showed that some correlations do not fit the experimental data very well. In the area of liquid desiccant dehumidification systems, literature reviews show a great drawback in evaluating the impact of different empirical correlations presented on the performance predictions of these systems.

In this paper, for the first time, the impact of different correlations in determining a number of important parameters required for modeling packed bed dehumidification towers is evaluated. For this purpose, a non-isothermal model is developed for liquid desiccant dehumidification systems. The studied parameters are the effective interfacial area, and the heat and mass transfer

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Nomenclature

a_W	interfacial surface area (m^2/m^3)
A	column cross-sectional are (m^2)
C_p	specific heat (J/kg K)
d_p	normal size of packing (m)
d_{eq}	equivalent diameter of packing (m)
F	mass transfer coefficient (mol/m^2 s)
Fr	Froude number (dimensionless)
G	superficial gas flow rate (kg/m^2 s)
G_S	superficial air flow rate (kg dry air/m^2 s)
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K)
h'	modified heat transfer coefficient
k	heat conduction coefficient (W/m K)
k_g	gas phase mass transfer coefficient (J/m^2 Pa s)
L	superficial desiccant flow rate (kg/m^2 s)
M	molecular weight (kg/mol)
N	molar mass transfer flux (mol/m^2 s)
P	pressure (Pa)
Pr	Prandtl number (dimensionless)
Re	Reynolds number (dimensionless)
R	universal gas constant (J/mol K)
Sc	Schmidt number (dimensionless)
Sh	Sherwood number (dimensionless)
T	temperature (K)
We	Weber number (dimensionless)
X	desiccant concentration (kg LiCl/kg solution)
y'	air humidity (kg water vapor/kg dry air)
y	water mole fraction (mol water/mol air)
z	tower height (m)

Greek letters

λ	latent heat of condensation (J/kg)
ε	void fraction of packing (dimensionless)
ν	viscosity (N/m^2)
ρ	density (kg/m^3)

Subscripts

a	air
c	critical
g	gas
i	interface
l	liquid
m	mixture
P	packing
V	vapor
w	wetted
0	reference state

Abbreviations

LiCl	lithium chloride
PBAD	packed-bed air dehumidifier
TEG	triethyleneglycol

coefficients. An attempt is made here to demonstrate the difficulties that may be raised for a designer when several correlations give different results.

2. Mathematical model

A control volume from a typical counter-flow dehumidification tower and the flow directions are shown in Fig. 1. The model is developed based on the following assumptions: (1) steady state operation; (2) negligible thermal resistance in the liquid phase in comparison with the gas phase; (3) no heat exchange with the surroundings; and (4) negligible vaporization of desiccant.

2.1. Water vapor in the gas phase

Water is vaporized into the gas across the tower length. Applying the mass balance for vapor in the selected differential control volume of the tower (Fig. 1) the equations for water vapor in the gas phase is derived as follows:

$$\frac{dy'}{dz} = -\frac{N_V M_V a_W}{G_S} \tag{1}$$

where y' is the absolute humidity of air, G_S is the superficial gas mass flow rate, and N_V is the flux of mass transfer which is obtained by the following relation (Treybal, 1981):

$$N_V = F_G \ln\left(\frac{1-y_i}{1-y}\right) = F_G \ln\left(\frac{1+y'}{1+y'_i}\right) \tag{2}$$

Substituting Eq. (2) into Eq. (1), a differential equation for air humidity is obtained as follows:

$$\frac{dy'}{dz} = -\frac{M_V F_G a_W}{G_S} \ln\left(\frac{1+y'}{1+y'_i}\right) \tag{3}$$

2.2. Mass balance for desiccant in solution

If X is defined as desiccant concentration which is the mass of pure LiCl per unit mass of LiCl solution, the variation of X through the column length is given by

$$\frac{d(LX)}{dz} = 0 \tag{4}$$

2.3. Mass balance for water in solution

As water is vaporized, the mass flow rate of liquid is changed. The mass balance for water in the solution yields to the following equation:

$$\frac{d}{dz}[L(1-X)] = -G_S \frac{dy'}{dz} \tag{5}$$

By substituting Eq. (4) in Eq. (5), the following equation is obtained:

$$\frac{dX}{dz} = -\frac{G_S}{L} X \frac{dy'}{dz} \tag{6}$$

2.4. Energy balance for gas phase

The gas flow exchanges heat with the liquid. The energy balance for gas phase will result in (Niksiar and Rahimi, 2009; Rahimi et al., 2011)

$$\frac{dT_g}{dz} = -\frac{h' a_P (T_g - T_l)}{G_S (C_{pa} + y' C_{pv})} \tag{7}$$

where h' is the heat transfer coefficient which is modified for considering simultaneous heat and mass transfer (see Table 3).