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Procedia Computer Science 109C (2017) 817–824

Procedia
Computer Science

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The 7th International Conference on Sustainable Energy Information Technology
(SEIT 2017)

Experimental investigation on vapor pressure of desiccant for air conditioning application

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Abstract

Recently, the rapid development of desiccant air conditioning technology, without using refrigerant fluids, energy saving and environmental protection, has expanded natural fluid to a broader niche applications. An experimental study is carried out to calculate the vapor pressure of $CaCl_2$ using regression dependent parameters and evaluate the mass transfer coefficient. The effect of relevant operating parameters, such as air temperature, humidity and air velocity on the mass transfer processes between the air and the desiccant $CaCl_2$ is analyzed. For a detailed study of the dehumidification process and desiccant regeneration, a "DVS", a "Dryer" and "climatic chamber" equipment are used. Several measurements were made in a relatively large range of operating conditions. It was found that the absorption mass rate increased linearly with increasing air humidity. After 6 hour of absorption the mass transfer becomes slow. The mass transfer coefficient is affected by the climatic condition variation. The decrease in mass transfer potential with time is mainly due to vapour pressure rise on the desiccant surface during absorption. The vapor pressure is significantly affected by the air humidity variation. At higher humidity, the concentration decreases while the vapor pressure increases. The mass transfer process duration decreased with increasing the air velocity during the desiccant regeneration. It can be pointed out that the $CaCl_2$ is able to absorb moisture and can be regenerated at low temperature then; solar collector can be used in liquid desiccant cooling system. This study allows selecting the best desiccant for use in LDAC system.

Peer-review under responsibility of the Conference Program Chairs.

Keywords: Desiccant, Vapor pressure, Evaporative cooling system, Mass transfer coefficient.

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Peer-review under responsibility of the Conference Program Chairs.
10.1016/j.procs.2017.05.338

1. **Introduction**

Desiccants are chemical substances that have strong attraction for water vapor. They can be broadly classified as solid or liquid desiccants. Solid desiccants such as silica gel, activated alumina adsorb water vapor physically or chemically with no chemical change. Liquid desiccants such as calcium chloride, triethylene glycol, lithium bromide or chloride remove water vapor by absorption. They change chemically when they absorb moisture. However, desiccants used for space conditioning must be able to hold much larger amounts of water. The vapor pressure is the most important parameter of liquid desiccants.

In recent years, more and more attention of researchers has been attracted to desiccants and alternatives of the conventional vapor compression system due to depleting energy resources and serious environmental pollution. Furthermore, the traditional commercial, non-natural working fluids, like CFC, HCFC and HFC result in both ozone depletion and global warming. Under the increasingly austere situation of energy sources and environment problems, solar energy-driven liquid desiccant air-conditioning systems, Fig.1 (LDAC) that can reduce electrical energy consumption by utilizing solar energy and avoid ozone depletion by employing natural working fluids have been developed as an alternative to vapor compression cooling devices for air-conditioning applications.

The use of liquid desiccant enhances the indoor air quality, reduces energy consumption, and produces an environmentally safe product. Liquid desiccant is brought into contact with air at a low temperature to dehumidify the air. Liquid desiccant is brought again into contact with air at high temperature to regenerate the liquid desiccant. Dehumidification is one of the most important processes in the liquid desiccant cooling system Fig.1. Liquid desiccant dehumidification was proved to be an effective method to extract the moisture from air with a relatively less energy. The mass transfer is driven by the difference between the partial pressure of water vapour in the air stream and the vapour pressure associated with the solution. This pressure difference allows the desiccant solution to absorb moisture from air whenever the vapour pressure of air is greater than that of the desiccant solution.

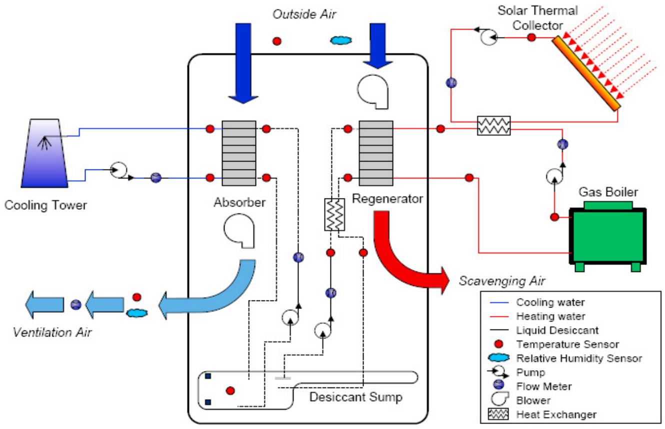

Fig. 1. Schematic representation of (LDCS) [1]

Liquid desiccants can absorb even more. Desiccants can be subjected to hundreds of thousands of adsorption/ desorption cycles over their useful life. Both adsorption and desorption are actually a heat and mass transfer process between moist air and desiccants. Desiccants are widely used in many solar applications such as (LDAC) system. In the dehumidification process, the strong desiccant that has been brought into direct contact with the air to absorb the moisture and during this process it gets diluted. In order to reuse the same desiccant in the process, the desiccant has to be regenerated to an acceptable level of concentration. The driving potential for the absorption of moisture is the difference in the partial pressure of water in the air and the vapor pressure of water above the desiccant solution. A cool, dry desiccant has a very low surface vapor pressure compared with the vapor pressure of humid air. Many attempts have been made to use desiccants, such as lithium bromide, lithium chloride, calcium chloride, triethylene glycol, in solar applications. Calcium chloride is the cheapest and most readily available desiccant but it has the disadvantage of being unstable. In addition, the regeneration temperature required for the (LDAC) system by solar energy is about 50–65°C and thus any low grade thermal energy can be effectively used for regenerating the weak desiccant solution.

In order to analyze the performance of the system using desiccant technology, the thermophysical properties of desiccants are essential. In particular, the vapor pressure of the desiccant is one of the important properties in air dehumidification.

Gandhidasan[2] has developed a new approach based on artificial neural networks (ANNs) to determine the vapor pressure of three widely used inorganic desiccant solutions, namely, calcium chloride, lithium chloride, and lithium bromide. Neural networks were trained to predict vapor pressure of desiccant solutions with a reasonable accuracy without mathematical formula. Results showed potential of using ANNs for the prediction of vapor pressure of desiccant solution for cooling applications. Ahmed[3] has presented an investigation on the absorption/regeneration mass transfer through parallel plates of cloth layers impregnated with $CaCl_2$ solution and contacting with an air stream. The concentration range of desiccant is 0.2-0.5. Experimental measurements are used to evaluate the vapor pressure, the mass transfer coefficient. Empirical equations are used to predict vapor pressure. Kabeel[4] has carried out an experimental study on liquid desiccant system using an injected air through the desiccant $CaCl_2$. The vapor pressure of desiccant at the bed surface is calculated as a function of the solution temperature, concentration and dependent parameters which are expressed as a linear function of the concentration. The mass transfer coefficient is obtained by the equation in function of the vapor pressure difference between the ambient air and the desiccant surface. Bassuoni [5] has made an experimental investigation and the mass transfer coefficient is evaluated using the partial vapor pressure on the desiccant solution surface which is calculated using the correlations introduced with regression constants, which can be expressed as linear function of concentration.

In this work, the regression constants depending on the solution concentration and temperature are used to calculate the vapor pressure of $CaCl_2$ solution in a stationary state and to evaluate the mass transfer coefficient. Also, a study is performed to analyse is the effects of the relevant operating parameters, such as air temperature, humidity and air velocity, on the mass transfer processes between the air and desiccant during absorption/ regeneration process. The air is in forced convection in regeneration process.

2. **Vapor pressure**

Vapor pressure of desiccant solution is an important property since its difference with air–water vapor pressure determines the mass transfer for air dehumidification. To analyze the performance of the (LDAC) system the partial vapor pressure of desiccant solution must be known. The vapor pressure curve for each substance is unique, but each exhibits generally a similar shaped characteristic curve. The vapor pressure allows comparison and selection of desiccant.

The absorption equilibrium relation of the calcium chloride, which is used as a working absorbent in this study, is correlated by Manuel R. Conde-Petit[6]. The actual mathematical relationship between the equilibrium thermophysical properties (vapor pressure, temperature and concentration) is complex. However, when the concentration x is constant, the relation between vapor pressure and solution temperature is given by the following equation:

$$\ln P = a - \frac{b}{T} + c \ln T + dT \tag{1}$$

and the approximate form of Eq. (1) can be written as:

$$\ln P = a' - \frac{b'}{T} \tag{2}$$

where a, b, c, d, a' and b' are empirically determined constants for the ranges of temperature and concentration of interest.

During the isothermal absorption in the (LDAC) system, vapour pressure and solution concentration varies over a wide range. Therefore, a mathematical relationship between vapour pressure and concentration is required. On the other hand, during the regeneration process, temperature and concentration are also varied, consequently. In the light of Eq. (2), with the help of $CaCl_2$ data, the following correlation is obtained as a result of treatment of the available data.

$$\ln P_S = A(x) - \frac{B(x)}{T_S + 111.96} \tag{3}$$

where *Ps* is the vapor pressure in mm Hg, Ts is the solution temperature in °C, A(*x*) and B(*x*) are regression dependent parameters, which can be expressed as a linear function of the concentration according to the following relations:

$$A(x) = a_0 + a_1 x \tag{4}$$

$$B(x) = b_0 + b_1 x \tag{5}$$

where a_0, a_1, b_0 and b_1 are the regression constants and their values are given as follow[6]:
$a_0 = 10.0624$, $a_1 = 4.4674$, $b_0 = 739.828$, $b_1 = 1450.96$.

The vapor pressure of calcium chloride solution at the bed surface, *Ps*, can be calculated as a function of the solution temperature. This value is within a temperature range of 10–65°C and a concentration range of 20–50%, according to the Eq.(3).

Interphase transport from the air stream to the absorbing surface (during absorption) or from the desiccant to flowing air (during regeneration) obeys a rate law, which is based on departure from the equilibrium state. The problem of convective mass transfer can be solved with an appropriate formulation. This formulation relates the mass transfer flux (to or from an interfacial surface) to the difference of density, concentration or vapour pressure across the main bed of exchange area. The local mass transfer coefficient is considered on the basis of the difference in vapor pressure and its local value can be expressed as given as follow:

$$\beta = \frac{\dot{m}_v}{A \cdot (P_a - P_s)} \tag{6}$$

where β is the local mass transfer coefficient (kg/Pa.m².s), (mv) is the mass flux of vapour from the surface, (kg/s) and (Pa–Ps) the vapor pressure difference between the ambient air and desiccant surface, (Pa) and A is the interfacial area of contact between liquid desiccant and air (m²).

The average mass transfer coefficient is defined as the rate of moisture flux passing through a unit area. It can be obtained from the measured data. From the experimental measurements, mass flux of vapour can be evaluated from:

$$\dot{m}_v = \frac{\Delta m}{A \cdot \Delta \tau} \tag{7}$$

where Δm is the difference in mass of the bed between two successive measurements, Δτ is the time interval. The driving force for dehumidification is the partial pressure difference between the air and the interfacing desiccant solution.

Then, the vapour pressure on the interface can be evaluated by knowledge of bed surface temperature and solution concentration by applying the correlation presented by Eq.(3). Solution concentration *x* is defined as the ratio of mass of salt M_s to the mass of solution M_{sol}, which equals the summation of the mass of water M_w and mass of salt M_s:

$$x = \frac{M_s}{M_{sol}} \quad \text{with} \quad M_{sol} = M_s + M_w \tag{8}$$

3. **Experimental set up**

Experiments are conducted to calculate the vapor pressure of used desiccant and to evaluate the mass transfer coefficient during vapour absorption. This study allows selecting the best desiccant for use in LDAC system. Since calcium chloride is the cheapest and most easily available desiccant, it is used in this investigation as the water vapour absorbent. The desiccant is in direct contact with the air and in a stationary state. The air is above the bed containing the desiccant at temperature and humidity kept constant during the process and in natural convection for absorption process. The air is in forced convection in regeneration process. The experimental set-up is shown in Fig.2a, which consists of "DVS" (Dynamic Vapor Sorption System) equipment. The "DVS" includes a simple chamber, inside incorporated a balance.

Fig. 2. (a) DVS - (b) Convective Pilot dryer - (c) Climatic chamber

This equipment is a highly sensitive, accurate and rapid means for automated determination of mass solution and moisture sorption properties. In addition, the "DVS" has a Computer interface TCP/IP and USB. This equipment contains a horizontal plate suspended by a hook. The experimental data are collected with a time interval of 1 min at each condition. A second equipment is a "Discontinuous convective pilot scale dryer" used to make regeneration tests of desiccant, as in shown in Fig. 2b. Two pieces of glass of 30 cm height are the core device of this equipment. The plate containing the desiccant solution has a diameter of 16 cm. The the third is equipment the "climatic chamber" presented in Fig. 2c, used for dehumidification and regeneration process. All equipments have accuracy of ±0.1°C and ±0.1% of temperature and humidity respectively, and ±0.001of mass.

The solution concentration is determined by measuring the solution mass. The air vapor pressure is calculated in function of saturated vapor pressure and air temperature. Table 1 lists the experimental data for the dehumidification process.

Table 1. Experimental measurements

Tests	Temperature	Humidity	Desiccant mass	Concentration
Test n°1	20 °C	95 %	28.06 mg	42.98 %
Test n°2, phase 1	20 °C	50 %	28.44 mg	42.88 %
Test n°2, phase 2	40 °C	70 %	29.99 mg	40.77 %
Test n°2, phase 3	20 °C	50 %	38.86 mg	31.46 %
Test n° 3	20 °C	45 % - 92,5 %	28.43 mg	42.90 %
Test n°4	40 °C	45 %	5.16 mg	20.00 %
Test n°5	80 °C	0 %	41.303 g	12.10 %
Test n°6	28 °C	75 %	5.04 g	98.99 %
Test n°7	80 °C	25 %	14.4 g	35.40 %

The experimental tests start with absorption at constant air temperature, humidity and air flow rate. At the end of all tests, the total mass of the solution and air parameters are recorded for small time intervals 1min. The total mass which is measured by incorporated balance is used with the measured air parameters to evaluate the mass transfer potential. The Eq (3) is used to evaluate the vapor pressure of desiccant.

4. **Results and discussion**

The aim of the experimental work is to evaluate the vapor pressure of $CaCl_2$ in a stationary state and analysis of the variation of the mass transfer coefficient during absorption at different air humidity. During absorption process, the moisture passes from the air to the calcium chloride solution; this will increase the mass of solution such as shown in Fig.3a and increase the vapor pressure of desiccant at the surface this is due to the decrease of the solution concentration. Fig.3b illustrates the calculated vapour pressure on the desiccant surface. It can be seen that the vapor pressure gradually increases with the increase of solution mass. It can be pointed out that the $CaCl_2$ is able to absorb moisture. Fig.3c shows the variation of evaluated mass transfer coefficient. It can be seen that the mass transfer coefficient β has higher values at the beginning of dehumidification process and its value decreases then; the mass transfer potential decreases with time. The change in the mass transfer coefficient during the absorption process is due to the change in the solution concentration from the experimental beginning time until the end. Additionally, the calculated values of'β coefficient are small because the solution is in a saturated state.

The decrease in desiccant concentration directly affects the potential of mass transfer then, the vapor pressure of desiccant at the surface increases. However, the concentration and the pressure are inversely proportional. As shown in Fig.4, the relationship between the concentration of desiccant in solution and vapor pressure.

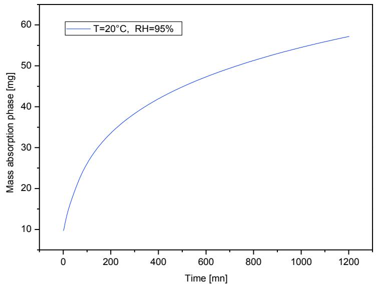

Fig. 3a. Mass evolution- test by DVS

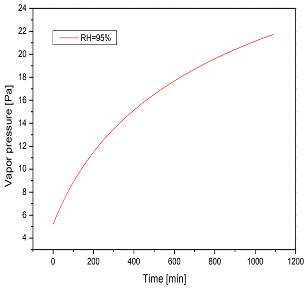

Fig. 3b. Vapor pressure of $CaCl_2$

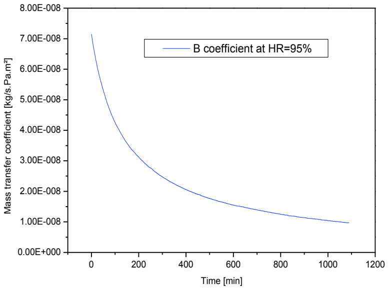

Fig. 3c. Mass transfer coefficient

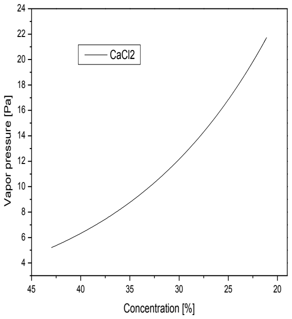

Fig. 4. Relationship between vapor pressure and concentration

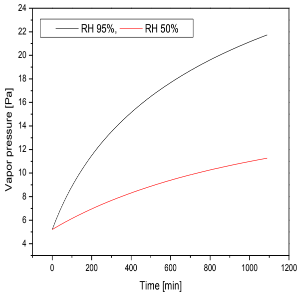

Fig. 5a. Effect of humidity on vapor pressure – test by DVS

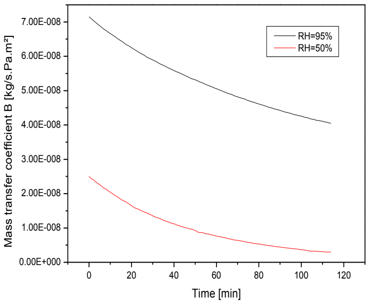

Fig. 5.b Effect of humidity on mass transfer coefficient

In the dehumidification process, the moisture rate absorbed is significantly affected by the humidity ratio of the air. However, the mass of solution increases linearly with the air humidity. It can be pointed out that variation of humidity affects the vapor pressure.

Fig. 5a shows the vapor pressure of CaC_2 at different humidity during absorption process at the same condition. It can be observed that the vapor pressure is higher at 95% of humidity then that at 50%; and consequently, this variation has an effect on mass transfer coefficient such as shown in Fig. 5b. The higher air humidity increases β coefficient between the desiccant solution and air stream. This can be explained that the average moisture rate of passing from air through the solution is higher at higher air humidity then, the concentration strongly decreases with high humidity.

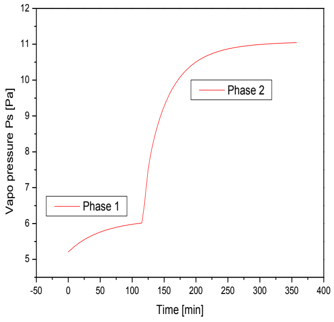

Fig. 6a. Vapor pressure of $CaCl_2$ in successive absorption phases

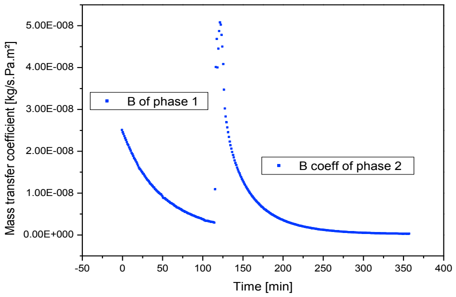

Fig. 6b. Evolution of mass transfer coefficient in successive phases

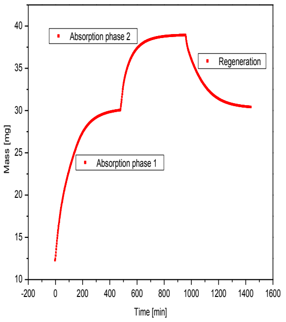

Fig. 6c. Cycle (absorption and regeneration phases)

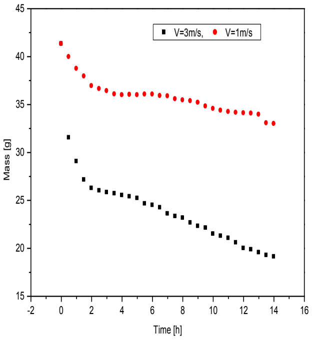

Fig. 7. Effect of forced flow convective on regeneration

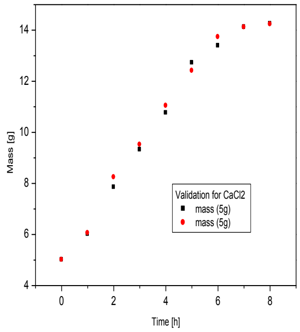

Fig. 8a. Validation of absorption process of $CaCl_2$.

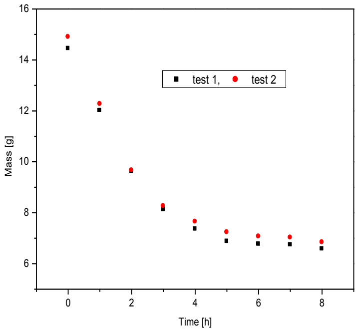

Fig. 8b. Validation of regeneration

In order to see the behaviour of $CaCl_2$ in a continuous process a test has been established during 7 days with successive phases of dehumidification and regeneration. This desiccant has been used under the conditions of dehumidification 20°C, 50% of humidity during phase n°1 and 70% of humidity in phase n°2. Fig. 6a illustrates the evolution of vapor pressure on two successive absorption phases. At the first time, a mass transfer has been established until the equilibrium state at 20°C and 50% of humidity. But the second phase of regeneration has not taken place directly after the first one. The second phase is also dehumidification with 70% of RH. The obtained solution has absorbed yet the moisture from the air. This state is due to the increase of relative humidity from 50% to 70% which provoked a new vapor pressure difference between the air and the solution at the surface. This vapor pressure difference established is the new force of mass transfer potential and the process continues until the second equilibrium state. It can be seen that the vapor pressure increases during the first absorption phase until the equilibrium state and increases again during the second absorption phase, this is mainly due to the humidity rise on the air; thereby increasing the moisture rate absorbed and reducing the concentration. In the same case, the mass transfer coefficient was analyzed, which is presented in Fig.6b. It has been observed that the coefficient has undergone the same evolution as a function of the increase in air humidity. It can be pointed out that the value of mass transfer coefficient increases in the start of the second phase at 70% of RH and increases with time during absorption process.

The last phase of cycle represents the desiccant regeneration. It can be pointed out that $CaCl_2$ can be regenerated at low temperature, is able to return to almost its original concentration and it can undergo successive phases such as presented in Fig.6c of mass evolution.

In order to analyze the forced flow convection in the regeneration process an experimental study has been carried out using 41.303 g of $CaCl_2$ desiccant solution in convective dryer under 80°C and varying the air velocity from 1 to 3 m/s such as listed in Table 1, (test n°5).

The diluted solution has been prepared in climatic chamber equipment at 25°C and 70% of RH. Fig. 7 shows the effect of air velocity on mass transfer during regeneration. It can be clearly seen that the moisture removal rate increases with increasing air velocity. Therefore, a higher Reynolds number gives a higher potential of mass transfer and shorter regeneration duration.

In order to validate the experimental results of mass transfer in absorption process, an identical experiment has been carried out with the same salt and under the similar operation conditions. Fig. 8a shows the reproducibility of the absorption process of $CaCl_2$. It can be observed that the curves are superimposed. On the other hand, to validate the results of regeneration process, two tests have been performed in ″climatic chamber″ using 14.4g at 80°C and 25% of humidity as listed in Table 1. Fig. 8b shows the reproducibility of this regeneration process. It can be clearly seen that the two curves are superimposed. Also, it can be pointed that the $CaCl_2$ is able to release moisture and return to almost its initial concentration. Finally, the obtained results by ″DVS″ are reproducible.

5. **Conclusion**.

Experimental runs have been conducted to evaluate the vapor pressure of $CaCl_2$ at the surface in direct contact with the air. The desiccant is in a stationary state. The vapor pressure is calculated by using the correlated equation with regression constants depending on the solution concentration and temperature. The effect of relative humidity on vapor pressure is studied while other parameters are maintained constant. The analysis of mass transfer coefficient is made relatively on air humidity and desiccant concentration. The results show that the mass of solution increases linearly with the relative humidity. The decrease in mass transfer potential with time is mainly due to vapour pressure rise on the desiccant surface during absorption. The vapor pressure of desiccant is significantly affected by the air humidity variation. At higher humidity, the concentration decreases while the vapor pressure increases. The average solution concentration during the absorption process period depends on the mass of the solution, and the higher the concentration, the higher the moisture absorbed. The analysis has also shown that a strong relationship exists between the vapor pressure and the salt concentration. In addition, the mass transfer process duration decreased with increasing the air velocity during the regeneration of desiccant.

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