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Experimental Investigation on Vapour Pressure of Desiccant for Air Conditioning Application

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Abstract

Liquid desiccant cooling system by solar energy is an energy-conservative and environment-friendly air-conditioning system. Recently, the rapid development of desiccant air conditioning technology has expanded natural fluid to broader applications. To avoid the excessive waste of energy an alternative way to achieve desired electrical energy reduction is the use of liquid desiccant air conditioning system (LDAC) in which a desiccant material absorbs moisture from the humid air. Solar energy is used to regenerate the desiccant material and cycle continues. This system has been considered as a promising application as traditional air-conditioning systems. Its performance is strongly influenced by the thermal properties of liquid desiccant, especially the surface vapor pressure. The vapor pressure of desiccant solutions is the key parameter to select the best desiccant for liquid desiccant air conditioning system. In this paper 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 equipments are used. Several measurements are made in a relatively large range of operating conditions. It is 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 vapor 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. Vapor pressure of a liquid desiccant is directly proportional to its temperature and inversely proportional to its concentration. As the concentration of the desiccant in the solution increases its vapor pressure decreases. This difference in vapor pressure allows the desiccant solution to absorb moisture from air whenever the vapor pressure of air is greater than that of the desiccant solution. 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.

Keywords: *Evaporative air conditioning system, Desiccant, Vapor pressure, Mass transfer coefficient.*

1. Introduction

Air conditioning market is currently dominated by the vapor compression system which formed as a loop, comprising an evaporator, a condenser, a compressor and an expansion valve, with a refrigerant (e.g., R-134a). Owing to its relatively long history and massive scale production, the technology presents many advantages e.g., good stability in performance and long life cycle time. However, this type of system has a major disadvantage that lies in high demand to electricity for operation of the compressor. Owing to the high dependency of fossil fuel burning in current electrical industry, this

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technology is regarded as neither sustainable nor environmentally friendly [1]. In recent years, more and more attention of researchers has been attracted to desiccants and alternative 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 [2]. A promising alternative for replacing vapor compression machines, in thermal comfort applications, is (EC) evaporative cooling [3]. Desiccant-augmented evaporative cooling systems have gained attracted worldwide attention as an environmentally friendly technology for comfort air conditioning with the added advantages of simple design, robustness and low electric power consumption [4]. The desiccant cooling can be either a perfective supplement to the traditional vapor compression air conditioning technology to attenuate the effects of its drawbacks, or an alternative to it for assuring more accessible, economical, and cleaner air conditioning. Still more importantly, when powered by free energy sources such as solar energy, and waste heat, it can significantly reduce the operating costs and increase considerably the accessibility to the air conditioning for the populations in remote areas, especially in developing countries.

The desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapor due to the difference of water vapor pressure between the surrounding air and the desiccant surface. They are encountered in both liquid and solid states. Each of liquid and solid desiccant systems has its own advantages and shortcomings [5]. Both solid and liquid desiccants have been proposed, the mainly advantage of the former is its compact design. Many solid desiccant-augmented evaporative cooling cycles have been reported in the literature; while few studies discussed the liquid desiccant based evaporative cooling system [6].

Under the increasingly austere situation of energy sources and environment problems, solar energy-driven liquid desiccant air-conditioning systems (LDAC) Fig.1 [7], that can reduce electrical energy consumption by using solar energy and avoid ozone depletion by employing natural working fluids have been developed as an alternative to vapour compression cooling devices for air-conditioning applications [2].

A liquid desiccant system is preferable because of its operational flexibility, ability to absorb inorganic and organic contaminants from air and its ability also to operate under a relatively low regeneration temperature. Besides, using of brine as absorbents is frequently environmentally friend as it doesn't cause ozone depletion [1]. The use of liquid desiccant enhances the indoor air quality, reduces energy consumption, and produces an environmentally safe product [8]. 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 Fig.1.a.b.
Dehumidification is one of the most important processes in the liquid desiccant cooling system. 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; however, there is a mass transfer between the air and the liquid desiccant. Desiccants are widely used in many solar applications such as (LDAC) system.

Desiccant is a material which has strong affinity for moisture. This desiccant is a hygroscopic material used to remove water. In the dehumidification process, Fig.1.b, [9] 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, the desiccant has to be regenerated to an acceptable level of concentration. Regeneration means that the water absorbed by these substances can be separated from them and again they are used for dehumidification of air.

The driving potential for the absorption of moisture is the difference in the partial pressure. And regeneration process is carried out by solar energy. 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, etc., in solar applications [10] [11].

2. Liquid desiccant system

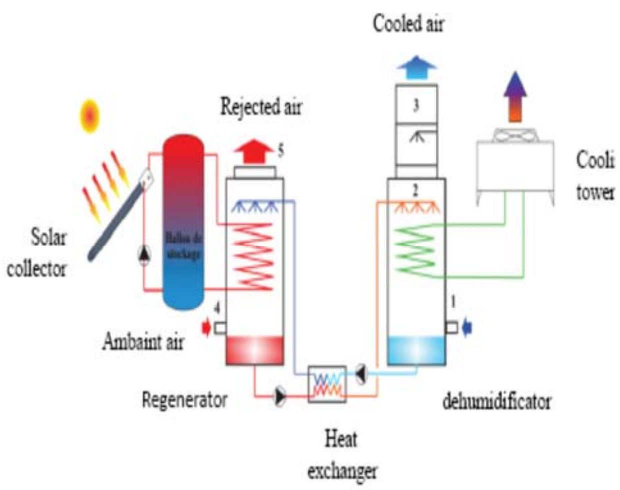

Fig.1a. Schematic representation of (LDAC) system [7]

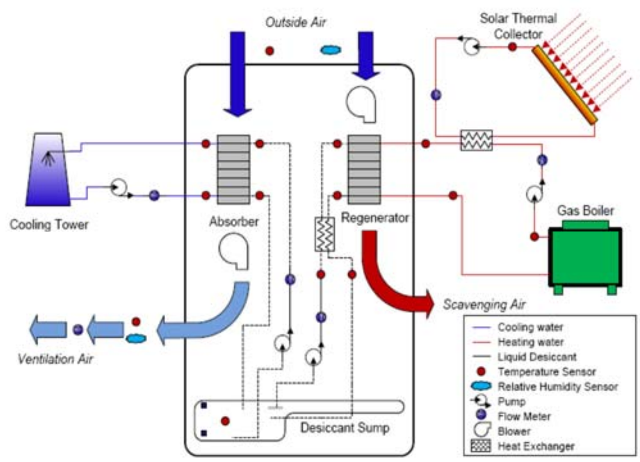

Fig.1b. Regenerator and absorber operation

The selection of desiccant depends on their ability to hold large quantities of water, their ability to be reactivated and cost. Liquid desiccant has several advantages over solid desiccant. The pressure drop through the liquid desiccant is lower than that through a solid desiccant system and can be stored for regeneration by some inexpensive energy. As the desiccant vapor pressure increases due to the presence of moisture that it has attracted, the desiccant material is transferred to a reactivation/regeneration process [12].
In addition of having lower regeneration temperature and flexibility in utilization, liquid desiccant have lower pressure drop on air side. Solid desiccant are compact, less subject to corrosion and carryover [4]. The desiccants are placed as beds through which wet gas is passed. The main limitation of the use of solid desiccants is that they absorb only limited quantities of water vapor [12].

The liquid desiccant system consists of three major components: an absorber, a desorber (or regenerator) and a solar collector Fig.1b. The working operation of liquid desiccant system is simple. In the dehumidification process, the strong desiccant solution that has been brought into contact with the air absorbs the moisture from the air and gets diluted. After that, the desiccants must be regenerated to a useful level of concentration. Desiccant solutions can be regenerated below temperatures of 80 °C for which hot air blower is used. Both air and concentrated desiccant enter the dehumidifier at low temperature, and the water vapor content is transferred from the air to the desiccant. In the regenerator, the diluted desiccant is heated to a high temperature by hot air blower. The air and the desiccant enter into the regenerator and water vapor is transferred from the desiccant solution to the air. Before the diluted solution enters the regenerator, it is initially passed through a liquid-liquid sensible heat exchanger. Mass transfer takes place due to the difference in vapor pressure [12] [13].

The dehumidifier/regenerator is one of the key components in liquid desiccant air-conditioning systems, which can be classified as either the adiabatic type or the internally cooled/heated type according to whether there is internal cooling/heating in the dehumidification/regeneration process [14]. Desiccant dehumidification is an alternate method to dehumidify the air. Desiccant is a substance that can attract and hold the water vapor. Desiccant systems work on the principle of removing the moisture from the air due to difference in vapor pressure of desiccant and water vapor present in air [15]. This system works by a natural material.

Commonly used liquid desiccants are generally aqueous solutions of salts like calcium chloride and lithium chloride. These solutions have high affinity for water vapor at lower temperature and higher concentration. Thus, they can provide dehumidification of air or latent cooling of the space when brought in contact with it in an air-liquid desiccant contacting device [16]. The liquid desiccant is expected to possess some important properties including low vapor pressure, low viscosity, low regeneration temperature, low crystallization point, high density and being cost effective. For the regeneration, thermal energy required at a temperature as low as 40–50°C that can be easily obtained by employing a flat plate collector. In fact, being regenerated at lower temperatures below 80°C is the one of the most favorable features of the liquid desiccant systems than the solid desiccant cooling systems due to the higher moisture mass transfer area. However, carry-over to the supply air is one of the main concerns of the liquid desiccant cooling systems. Thanks to fast advancement in the field, the potential of the liquid desiccant is remarkable [17].
Vapor pressure of a liquid desiccant is directly proportional to its temperature and inversely proportional to its concentration. As the concentration of the desiccant in the solution increases its vapor pressure decreases. This difference in vapor pressure allows the desiccant solution to absorb moisture from air whenever the vapor pressure of air is greater than that of the desiccant solution. The equilibrium vapor pressure of the desiccant solution depends on its temperature and concentration. The higher is the concentration and lower is the temperature, the higher will be the moisture absorbed and lower will be the humidity [15].

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 [18] 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 are 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 [19] 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 and mass transfer coefficient. Empirical equations are used to predict vapor pressure. Kabeel [20] 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 [21] evaluated the mass transfer coefficient 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.

The dehumidification process dominates the performance of liquid desiccant cooling system, while the thermal properties of the liquid desiccant play a key role in improving dehumidification effect. However, there is little work about how to choose a proper liquid desiccant that has a better performance. To settle this problem, a novel method is proposed by Xiu-Wei Li [22] to search an ideal liquid desiccant by applying the nonrandom two-liquid equation (NRTL equation). This idea is further applied to mixed LiCl and $CaCl_2$ solution to work out the right mixture ratio with a better dehumidification effect under certain working conditions. Moreover, the related experiments are carried out. The results show that: compared to single LiCl solution, the dehumidification effect could be raised by more than 20% with mixed LiCl and $CaCl_2$ solution. Also, the surface vapor pressure of desiccant solutions is the key parameter for modeling the liquid desiccant system.

There is little literature caring about the calculation accuracy of the two models for surface vapor pressure of mixture desiccant solution under different circumstances. An experimental system is built by Yao [23] to measure the surface vapor pressure of LiCl–$CaCl_2$ desiccant solutions under various conditions including temperatures ranging from 25°C to 75°C, total mass concentrations ranging from 5% to 40% and three mass mixing ratios of LiCl to $CaCl_2$ (e.g., 1:1, 1:2, 2:1). The two models for surface vapor pressure of mixture desiccant solution (i.e., the SMR and the NRTL) are compared with the test data. It is found that the SMR model has much better accuracy than the NRTL model in forecasting the surface vapor pressure of LiCl–$CaCl_2$ mixture desiccant solution when the solution mass concentration is lower than 10%, and it is the opposite for the case when the solution mass concentration is higher than 30%. Zhao [24] proposed a method based on the NRTL equation to predict the vapor pressure of mixed liquid desiccants. Six absorbents (LiBr/LiCl + $CaCl_2$/$MgCl_2$ + water/methanol) have been analyzed, and systems employing them have also been investigated. The results show that the dehumidification efficiency of mixed liquid desiccant is higher than that of a single solution. The LiBr–$CaCl_2$–water system can obtain higher COP compared with other systems under the condition of the same dehumidification performance in summer. Moreover, the LiCl–methanol–water may be a potential absorbent for energy saving.

Air dehumidification by a liquid desiccant falling on rectangular finned-tubes arrangements is numerically studied by Nada [25], for different air flow arrangements: parallel, counter and cross flow with respect to the desiccant liquid film. Heat and vapor transfer between desiccant film, air and the finned-tube arrangements are investigated. The effects of air/desiccant inlet conditions and the temperature of the fin-tube arrangement on air dehumidification, heat and vapor transfer are predicted for the different flow arrangements. The results show that the parallel flow arrangement gives more cooling and dehumidification rates.
Also, for all flow arrangements, the outlet air temperature and air humidity, increases/decreases with increasing mass flow rate of air and liquid desiccant in cooling dehumidification/desiccant regeneration processes. Wang [26] has carried out a theoretical and experimental study on the coupled heat and mass transfer process in a counter-flow adiabatic structured packed tower with the inlet air humidity ratio ranging from 20 g/kg air to 160 g/kg air. The finite difference model shows that the driving forces of heat and mass transfer decline much more significantly in high humidity conditions than in low humidity conditions. The experimental results indicate the optimal ranges of the main parameters in high humidity conditions. However, the dehumidification effect is more significantly influenced by the liquid-air flow rate ratio and less influenced by the desiccant concentration and temperature compared with the low humidity conditions. Sabek [27] carried out a numerical investigation on desiccant liquid air membrane energy exchanger to provide the optimal operating fluids properties as well as to enhance the exchanger performance. The physical problem involves a two dimensional model including the momentum, heat and mass transport equations in both air and desiccant liquid channels. The impact of air and desiccant liquid properties on the heat and mass transfer distributions is determined. Optimal values of inlet air and desiccant liquid properties are established.

The objective of this present study is to evaluate the vapor pressure of liquid desiccant $CaCl_2$. The regression constants depending on the solution concentration and temperature are used to calculate the vapor pressure of solution and to evaluate the mass transfer coefficient. Also, a study is performed to analyze 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.

3. 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 R. Manuel Conde-Petit [28]. 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, vapor pressure and solution concentration varies over a wide range. Therefore, a mathematical relationship between vapor pressure and concentration is required. On the other hand, during the regeneration process, temperature and concentration are also varied. 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, Ts is the solution temperature, 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:
a_0 = 10.0624, a_1 = 4. 4674, b_0 = 739.828, b_1 = 1450. 96.
The vapor pressure of $CaCl_2$ solution at the bed surface, P_S, 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 vapor 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:

$$\beta = \frac{\dot{m}_v}{A.\left(P_a - P_s\right)} \quad (6)$$

where β is the local mass transfer coefficient, ($\dot{m}_v$) is the mass flux of vapor from the surface, (P_a – P_s) the vapor pressure difference between the ambient air and desiccant surface, and A is the interfacial area of contact between liquid desiccant and air.

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 vapor can be evaluated from:

$$\dot{m}_v = \frac{\Delta m}{A.\Delta \tau} \quad (7)$$

where Δm is the difference in mass of the bed between two successive measurements and Δτ is the time interval.

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:

$$x = \frac{M_s}{M_{sol}} \text{ and } M_{sol} = M_s + M_w \quad (8)$$

4. Experimental set-up

Experiments are conducted to calculate the vapor pressure of used desiccant and to evaluate the mass transfer coefficient during absorption process. 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 vapor absorbent. The desiccant is in direct contact with the air and at different climatic conditions. 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.

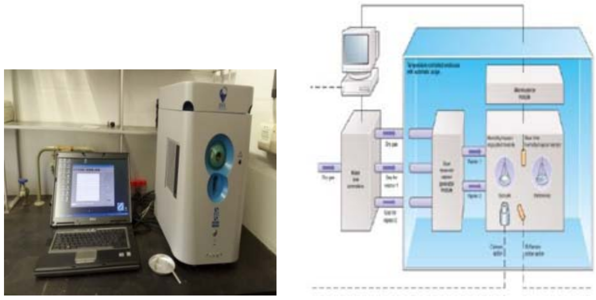

Fig. 2a. DVS

Fig. 2b. Convective Pilot Dryer

Fig. 2c. 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. Second equipment is a Discontinuous Convective Pilot Scale Dryer, as shown in Fig.2b, used to make regeneration tests of desiccant. 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 third equipment is a Climatic Chamber presented in Fig.2c and used for both 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 and regeneration processes.

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.

5. Results and discussion

The aim of the experimental work is to evaluate the vapor pressure of $CaCl_2$ and analysis of the variation of the mass transfer coefficient during absorption process at different air humidity. During this 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 vapor 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 mass transfer coefficient varied with varying climatic conditions.

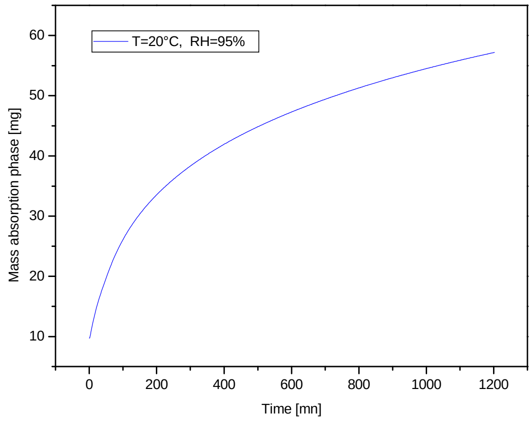

Fig. 3a. Mass evolution - test by DVS

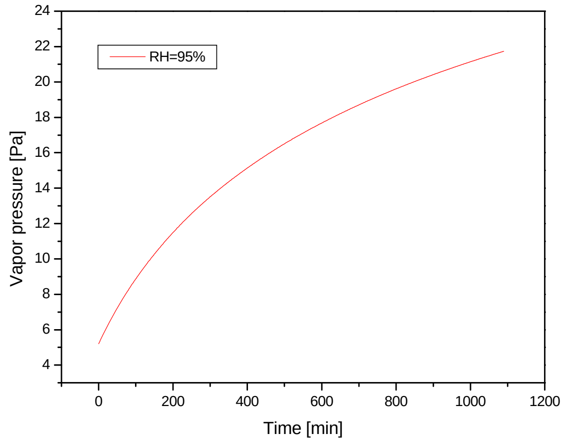

Fig. 3b. Vapor pressure of $CaCl_2$

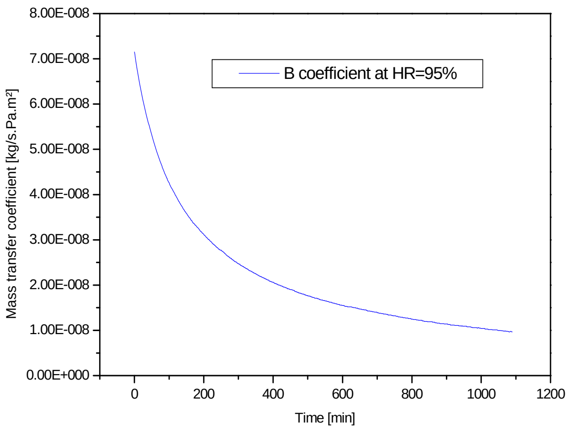

Fig. 3c. Mass transfer coefficient

The decrease in desiccant concentration directly affects the potential of mass transfer then, the vapor pressure of desiccant at the surface increases.

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.

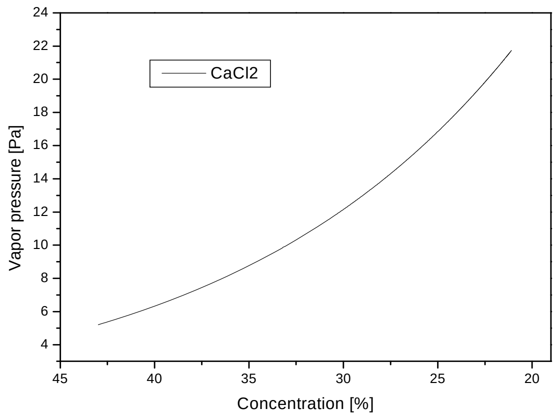

Fig.4. Relationship between vapor pressure and concentration

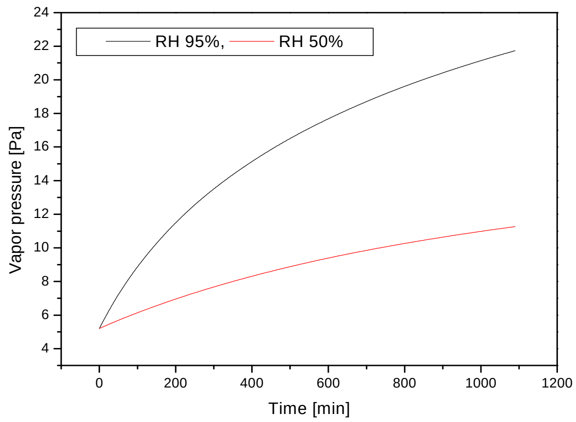

Fig.5a. Effect of humidity on vapor pressure – test by DVS

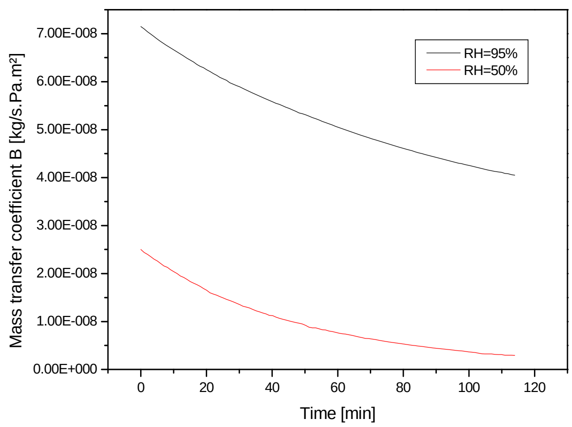

Fig.5b. Effect of humidity on mass transfer coefficient

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 the mass transfer potential 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.

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 of temperature and 50% of humidity during phase n°1 and 70% 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 relative humidity. 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 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 evolution as a function of the increase in air humidity. It can be pointed out that the value of mass transfer coefficient decreases in the start of the second phase at 70% of air humidity and decreases with time during absorption process.

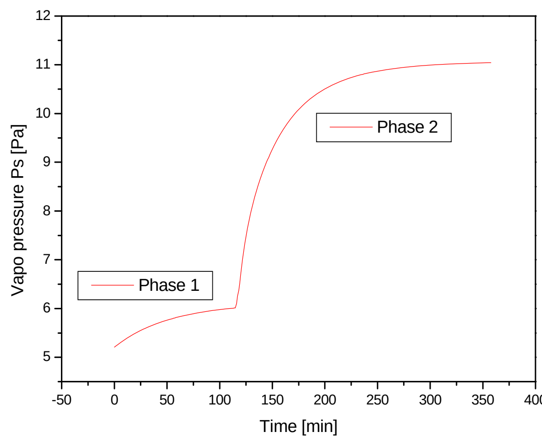

Fig.6a. Vapor pressure of $CaCl_2$ in successive phases

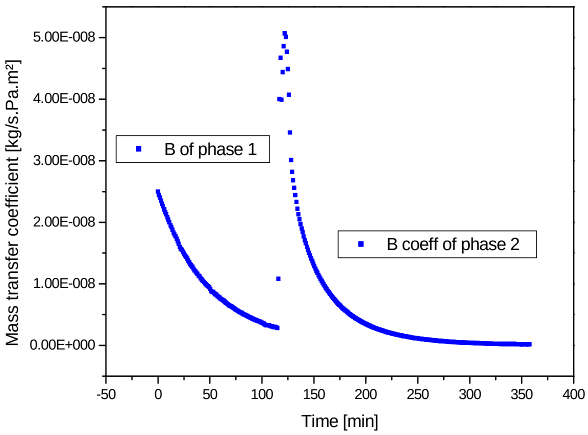

Fig.6b. Evolution of mass transfer coefficient in successive phases

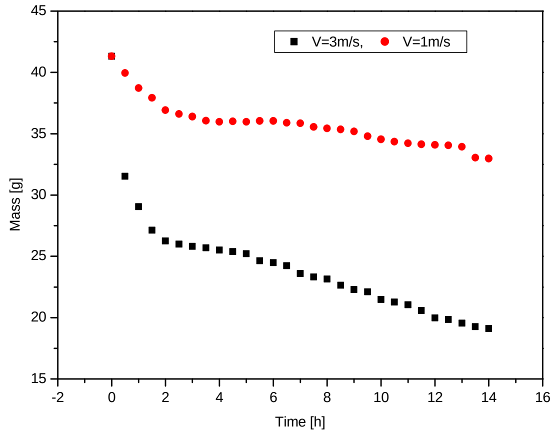

Fig. 7. Effect of forced flow convective on regeneration

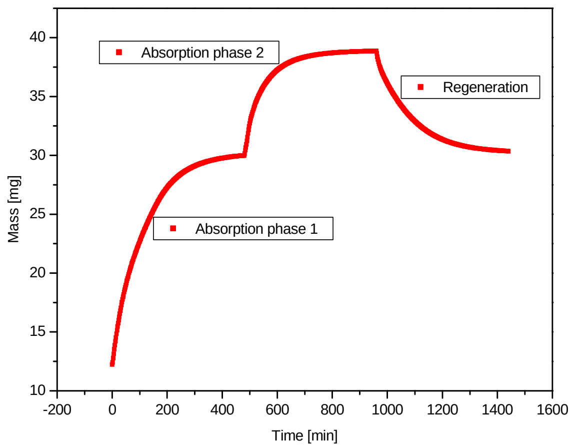

Fig.6c. Cycles: absorption and regeneration phases

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 relative humidity. 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 show the physical state of this desiccant the experiments for absorption/regeneration processes have been carried out, under different operating conditions in Climatic Chamber and Convective Pilot Dryer equipments.

It can be seen through the following figures that the small mass of $CaCl_2$, Fig. 8a, is more rapidly diluted than the large mass of $CaCl_2$, Fig.8b, at the same time, in the absorption phase.

On the other hand, it can be pointed out the appearance of a yellow color at the surface of $CaCl_2$ desiccant Fig.8c, during absorption phase. In addition, in the final phase of dehumidification the small quantity of $CaCl_2$ is more viscous and is in liquid form than the greater one.

Fig.8(a). Physical state small mass **(b). physical state large mass**

After the absorption process the solution undergoes the regeneration process. Then, the salt swells during regeneration phase and yellow color was observed at the surface Fig.9a. In addition, it can be pointed out that during the regeneration phase it was observed the appearance of grain of $CaCl_2$ salt.

Fig.8c. Yellow color **Fig.9a. Color at the surface**

Finally the desiccant became concentrated and it looks like a block of hard salt, if the regeneration temperature is not limited. However, the salt passes to the crystallization phase (solid block of desiccant), as shown in Figs. 9b,c.

Fig.9b

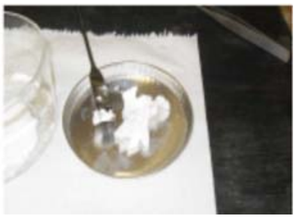

Fig.9c

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.10a, 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 air humidity as listed in Table.1. The graph on Fig.10b, 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.

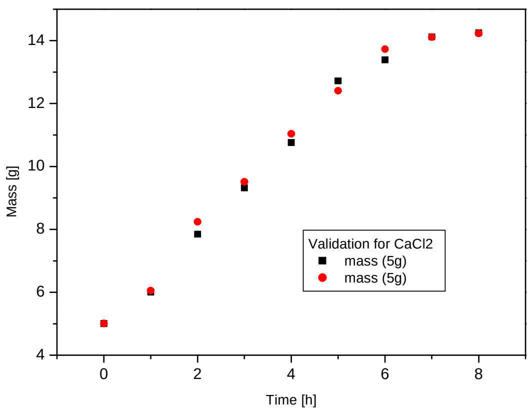

Fig.10a. Validation of absorption process

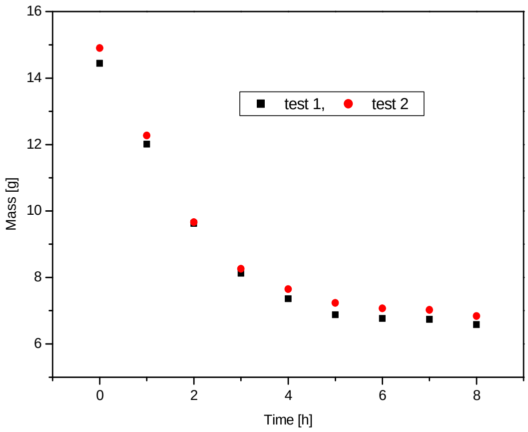

Fig.10b. Validation of regeneration process

To analyze whether the desiccant can be completely regenerated, an isotherm test was performed at different parameters. Fig.11 indicates that moisture removal rate absorbed by the desiccant increased in the dehumidification phase with increasing the mass of salt, but the solution mass decreased during drying phase and desiccant regains nearly its initial concentration.

Analyze of this result shows that the difference between the initial desiccant concentration and regenerated desiccant concentration is 0.07% of isotherm. Then the solution has regained nearly the initial value of concentration. This graph shows clearly that the initial mass value is 13.7709 and the final mass value is 13.7832, however, the difference is very small. Also, it can be clearly observed that the $CaCl_2$ has a better mass transfer in regeneration process.

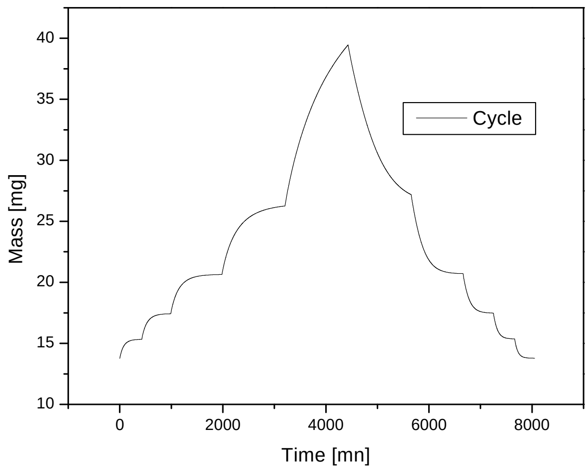

Fig. 11. isotherm

There is little literature caring about the mixed desiccants dehumidification. Experimental tests are performed to measure the water vapor rate absorbed during dehumidification process with using mixed desiccants LiCl and $CaCl_2$ under constant climatic conditions 27°C of temperature and 70% of relative humidity.

The comparison results of the experimental dehumidification process are shown in Fig.12. It is found that the mass transfer potential of mixed desiccants solution is better then the single desiccant solution made at the same climatic conditions. Then, the rate water vapor absorbed for mixed desiccants is important compared to those of single desiccant. However, the desiccant concentration is affected by the rate of water vapor absorbed, as we can see in Fig.13 that the concentration decreases during dehumidification process and the mixed desiccants solution provides the lower concentration.

These Figs.12 and 13 clearly show that the increase of mass solution decreases the desiccant concentration. It can be pointed out that the greater mass corresponds to the lowest concentration.

Also, by the comparison of water vapor rate absorbed the selection of the best desiccant for using in liquid desiccant air conditioning system can be done.

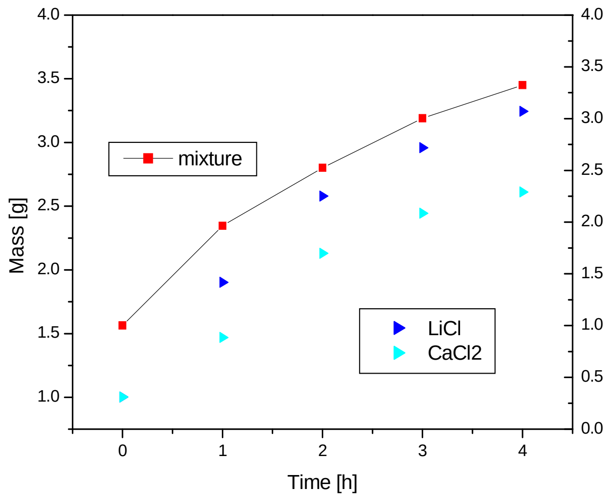

Fig.12. Mass of single and mixed desiccant

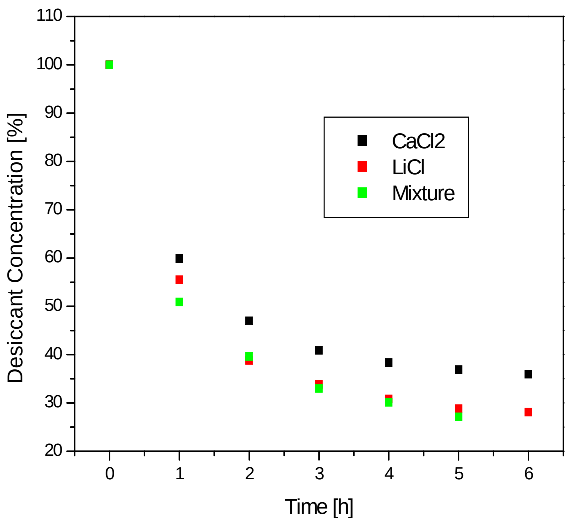

Fig.13. Single and mixed desiccant concentration

6. Conclusion

Better indoor environmental quality at lower energy consumption and less environmental impact are the goals of researchers working in the field of air conditioning. Liquid desiccant based air conditioning (LDAC) system seems to have good potential as an alternative air conditioning system for achieving above goal. The major problem associated with vapor compression system is that it causes the depletion of ozone layer and it also requires a lot of electricity for its operation.

The idea of a liquid desiccant evaporative cooling system is to combine liquid desiccant dehumidification with an evaporative cooling system in order to advance the overall system performance and use solar energy as a clean, renewable energy resource for regeneration process. Desiccant systems work on the principle of removing the moisture from the air due to difference in vapor pressure of desiccant and water vapor present in air. Desiccant is a substance that can attract and release the water vapor.

Liquid desiccant cooling system is an energy-conservative and environment-friendly air-conditioning system. Its performance is strongly influenced by the thermal properties of liquid desiccant, especially the surface vapor pressure.

In this paper experimental runs have been conducted to evaluate the vapor pressure of $CaCl_2$ desiccant at the surface in direct contact with the air.

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 vapor 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. Vapor pressure of a liquid desiccant is directly proportional to its temperature and inversely proportional to its concentration. As the concentration of the desiccant in the solution increases its vapor pressure decreases. This difference in vapor pressure allows the desiccant solution to absorb moisture from air whenever the vapor pressure of air is greater than that of the desiccant solution. In addition, the mass transfer process duration decreased with increasing the air velocity during the regeneration of desiccant. Also, the regeneration temperature must be analyzed and limited in order to avoid the crystallization of the desiccant.

A good desiccant should have better moisture absorption capability and lower regeneration temperature.

Mixed liquid desiccants may have better dehumidification efficiency that a single desiccant. However, a lowest vapor pressure solution can be obtained.

Nomenclature

A	Interfacial area, m^2
A(x)	Regression parameter
B(x)	Regression parameter
M_s	Mass of salt, g
M_w	Mass of water, g
M_{sol}	Mass of solution, g
P_s	Vapor pressure of desiccant, Pa
Pa	Vapor pressure of the air, Pa
T_s	Solution temperature, °C
x	Solution concentration, %

Greek symbols

β	Mass transfer coefficient, $Kg/Pa.m^2.s$
τ	Time, min

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