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Research Article

Experimental Investigation of the Hybrid Nanoparticles into the LiCl Liquid Desiccant as Nanofluid on the Efficiency of Absorption Dehumidification System

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ABSTRACT

In this study, to increase the heat and mass transfer coefficients in the system, a combination of liquid desiccant such as lithium chloride (LiCl) and hybrid nanoparticles of multi-walled carbon nanotubes (CNT-MW) Aluminum Oxide (Al_2O_3) and silicon oxide (SiO_2) has been used. Poly-Vinyl Pyrrolidone (PVP) surface activator or surfactant has been used for complete stability of hybrid nanoparticles in lithium chloride (LiCl) desiccant solution and liquid water. By the experimental data, heat and mass transfer coefficients in the system have been determined in a relational way for different combinations of nanoparticles and adsorbents. The effect of important parameters such as air flow intensity and desiccant liquid, air temperature and humidity, temperature and composition of incoming desiccant liquid nanofluid on the efficiency of the system has been studied. And from there the exergy analysis of the system has been done. In this way, the best operating conditions for the better performance of the system containing liquid desiccant nanofluid have been determined. The results of this research have clearly shown that, changes in the air humidity and temperature have been increased by adding the hybrid nanoparticles to $LiCl/H_2O$ liquid desiccant. In this regard, the mass transfer rate has been improved from 3.41% to 28.3% and the heat transfer rate has been improved from 4.18% to 29.11%. So, the average improvement has been 23.23% and 22.22%, respectively. Adding hybrid nanoparticles to $LiCl/H_2O$ liquid desiccant has increased the mass transfer coefficient from 17.42% to 29.26% and the heat transfer coefficient from 19.83% to 33.55%. Therefore, according to these results, the average value of improvement in mass and heat transfer coefficients has been about 22.73% and 26.51%, respectively.

1. Introduction

In the desiccant cooling process, which is a new kind of refrigeration method, the fresh air is dehumidified and then sensibly and evaporatively cooled before being sent to the conditioned space [1]. Desiccant-enhanced air conditioning equipment has exhibited both the capability to improve humidity control and the potential to save energy costs by lowering the latent energy requirement of the supply air stream. Controlling temperature and humidity within a conditioned space is important for a wide variety of applications. Desiccant dehumidifier, running in open cycle, can be driven by low-grade heat sources, e.g. solar energy, waste heat and natural gas. A procedure for the energy and exergy analyses of open-cycle

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desiccant cooling systems have been developed and it has been applied to an experimental unit operating in ventilation mode with natural zeolite as the desiccant [2]. Beccali et al. has presented a simple model to evaluate the performance of rotary desiccant wheels based on different kind of solid desiccants e.g. silica gel. The 'Model 54' has been derived from the interpolation of experimental data obtained from the industry and the correlations developed for predicting outlet temperature and absolute humidity. The 'Model 54' consists of 54 coefficients corresponding to each correlation for outlet absolute humidity and temperature and it is found that the model predicts very well the performance of silica gel desiccant rotor. Then a psychro-metric model has been presented to obtain relatively simple correlations for outlet temperature and absolute humidity. The developed psychro-metric model is based on the correlations between the relative humidity and enthalpy of supply and regeneration air streams [3]. Then the update on the desiccant wheel models developed. It is to be mentioned that the psychro-metric model is valid only for the desiccant wheel running with identical volume air flows in supply and regeneration side. When system runs with volume air flow ratio between supply and regeneration side, the model needs further modification. Some correction factors in order to update the model for correct prediction of the temperature and humidity of processed air at the outlet of desiccant wheel have been developed and also incorporated [4]. Many mathematical models on the rotary desiccant dehumidifier have been proposed. Maclaine-Cross IL presented that a finite difference computer program, MOSHMX, can be developed based on a detailed numerical analysis [5]. Barlow presented that DESSIM could be written where the dehumidifier was discretized and each node was treated as a counter flow heat and mass exchanger in which both the heat and mass transfer are assumed to be uncoupled [6]. Then Collier and Cohen developed ET/DESSIM that is more accurate than DESSIM [7]. The mathematical model by finite difference method to predict the performance and to optimize the operation parameters of rotary desiccant wheels have been proposed. The effect of the rotational speed on the performance of an adiabatic rotary dehumidifier was parametrically studied, and the optimal rotational speed was determined by examining the outlet adsorption side humidity profiles and humidity wave front inside the desiccant dehumidifier [8]. The mathematical model of a rotary desiccant wheel have been used to calculate the performance of stationary or rotary bed and transient or steady state operation is founded by considering some of the key components [9]. This is helpful for predicting the performance and evaluating the benefits of rotary desiccant wheels concerning the complicated heat and mass transfer in the rotary desiccant matrix that was suggested [10-11]. The continuity and energy conservation equations for the transient coupled heat and mass transfer using a finite differential model have been established and solved, that the present study was mostly derived from this research [12-13]. A simple mathematical model for explanation of the rotary desiccant wheel, in which the optimum rotational speed for achieving the maximum performance offered have been presented [14]. On the other hand, a mathematical model for a fixed desiccant bed to show the dehumidification trend of desiccant dehumidifier concerning Ackermann correction factor with no rotation have been derived [15]. As mentioned, in all activities like the above references, the attitude, model solution and outcome analysis are much different from this research. There are various numerical modeling presented of rotary wheels and also calculation of mass and heat transfer in those models by various researchers [8-9]. In these activities the effect of conduction within the desiccant wall has been considered. Also in this model an optimized velocity for exchangers has been determined. Experimental measurements on rotary silica gel exchangers has been presented in these researches and by using temperature distribution within wheel, an experimental statement for the optimized velocity of rotation has been suggested. They have some suggestions for analysis of exchangers or silica gel rotary wheels by using psychro-metric chart. Their focus is mainly on the understanding of the measure of mass transfer in silica gel rotary desiccant systems simply or by experimental parametric analysis, and also their experimental measurements has been done on silica gel desiccant wheel. As a general result, one can say that the type and atmosphere of these works are completely different [8-11].

Studies in recent years have been necessary to improve the system's performance and reliability and reduce their costs and also to enhance the commercial competitiveness of desiccant dehumidification systems and expand their market [16-20]. For example, the one-dimensional model by using MATLAB programing to simulate the desiccant wheel has been presented when it was combined with the direct evaporative cooling, or indirect evaporative cooling, or hybrid desiccant cooling systems then it has compared between their performances [16]. An experimental comparison between the fully and annular packed beds by Adding a new configuration that integrating each of them with oscillated helical coil heat pipes have been done [17]. Also the effect of channel geometry of the desiccant wheel on its performance has been studied and that in this case, Five types of channels have been examined (triangular, square, hexagonal, sinusoidal-1, and sinusoidal-2) [20].

In Table 1 some of the previously investigated liquid desiccant dehumidifier configurations including targets and some approaches have been summarized. In this regard, the detailed discussion of the current designs configurations and the main differences between them may help future researchers to come up with novel, innovative designs, to overcome the system's drawbacks and make them actual viable alternative competitors in the dehumidification market. So far, a lot of work to dehumidify or cooling the environment, has been done by desiccant dehumidifier materials. For examples, the theoretical investigation of heat and moisture transfer between air and falling desiccant material film has been done, by $CaCl_2$ solution for co and counter flow configurations with the presence of Cu-ultrafine particles in the solution film.

Table 1. Comparative study of some previous liquid desiccant investigations

Target	Desiccant Kind
Among the studies conducted can mentioned, on the dispersion of SiO_2 nanoparticles in binary nanofluids of Lithium Bromide liquid absorbent mixture and water H_2O/LiBr. Investigating key parameters such as nanoparticle concentration on stability of distribution in nanofluid and measuring vapor absorption rate. Distribution surfactants of Gum-Arabic or GA, and Poly-Vinyl Alcohol or PVA have been used to consider the stability of nanofluid based on liquid-desiccant absorbent. Finally, it has been determined that with the concentration of SiO_2 nanoparticles of about 0.005 vol.%, heat and mass transfer rate for the falling film flow of H_2O/LiBr liquid-desiccant binary nanofluids by about 46.8% and 18% respectively, has been improved [21].	Lithium Bromide/Water
In a similar study, the binary nanofluids of the mixture of liquid desiccant absorbent and water H_2O/LiBr has been made using metal-based iron nanoparticles and also carbon nanotubes (CNT) by three weight concentrations of 0.0, 0.01 and 0.1%. It has been observed that the improvement of the mass transfer rate using CNT nanoparticles is better than that of iron metal-base nanoparticles. In this way, the experimental data for heat and mass transfer rate in the absorption process of binary nanofluids falling film with iron nanoparticles and CNT has been earned. It has been considered as suitable options for good stability conditions and also without any sedimentation problems and significant improvement of effective thermal conductivity [22].	Lithium Bromide/Water
The characteristics of water vapor absorption using a uniform aqueous liquid desiccant solution of Lithium Bromide (LiBr) in the framework of a fin-shaped structure and on a flat and vertical plate with minimal thickness have been investigated in the form of a falling film. This proposed liquid-desiccant absorbent design is also verified and supported by the numerical model for experimental setup using dye visualization, geometric properties, fin spacing, size and surface wettability. Based on the final design, it has also been proposed as a potential model for the development of cooling and air conditioning systems including very compact liquid desiccant absorbent [23].	Lithium Bromide
Improvement of dehumidification operation and reduction of energy consumption by liquid-desiccant with coating, in a commercial building in Hong Kong has been simulated. This work is provided by Lithium Chloride (LiCl) as a liquid desiccant air conditioning system with dehumidifiers coated with titanium oxide (TiO_2) as a super-hydrophilic material to increase the surface wettability level of liquid desiccant absorbent plate dehumidifiers. Finally, about 80 MW.h have been saved in electricity consumption [24].	Lithium Chloride
The main goal of this study has been to try and identify the problems and inadequacies of air conditioning systems containing liquid desiccant absorbent materials through the examination of materials and equipment [25].	Liquid Desiccant
The air flow dehumidification by liquid desiccant absorbent materials in hollow fiber membrane converters has been studied. Extracting heat and mass transfer characteristics of liquid desiccant nanofluid in membrane contact surfaces has been one of the main goals. In this way, the effect of adding SiO_2 nanoparticles with the weight concentrations of 1 and 2%, the characteristics of heat and moisture transfer of the base fluid containing the liquid desiccant of calcium chloride $CaCl_2$ aqueous solution as a gas-liquid membrane system have been investigated experimentally [26].	Calcium Chloride/Water

Number of three samples of $LiCl/H_2O$ liquid desiccant absorbent solution as well as desiccant absorbent solution containing $LiCl/H_2O$-PVP surfactant as well as nanofluid based on $LiCl/H_2O$ liquid desiccant absorbent with multi-walled carbon nanotube (MWCNTs), in the experimental form of falling film flow has been investigated. In this way, experimental results have been shown that the regeneration effectiveness of $LiCl/H_2O$-PVP solution and $LiCl/H_2O$-MWNTs nanofluid has improved by 24.2% and 23.9%, respectively, compared to $LiCl/H_2O$ solution [27-29].	Lithium Chloride/Water
The effect of nanoparticles such as Al_2O_3, ZnO, and ZrO_2 in binary nanofluids mixed with water and ammonia NH3/H_2O on the absorption rate improvement of the falling film and in the state of pressure reduction has been investigated experimentally. The improvement mechanism of heat and mass transfer in these multi-component nanofluids including liquid desiccant absorbent has been investigated. The final results have been as follows: this category of nanofluids based on liquid desiccant absorbent had different enhancing effects on the absorption of ammonia falling film. All the above nanoparticles have significantly increased the adsorption performance. The highest effective absorption ratio (EAR) in these nanofluids based on Alumina, Zinc Oxide, and Zirconia nanoparticles have been: 1.122, 1.132, and 1.105, respectively. Thus, it has expected that this work has been provided a suitable insight into the mechanism of heat and moisture transfer enhancement in multicomponent liquid desiccant nanofluids [30].	Ammonia/Water
In order to investigate the absorption rate of the falling film between water-ammonia and water-ammonia with nanoparticles including: Al_2O_3, Fe_2O_3 and $ZnFe_2O_4$, comparative experiments have been conducted. The rate of ammonia absorption has been improved in the condition that the viscosity of the nanofluid based on the ammonia desiccant adsorbent did not increase significantly, and the optimal mass fraction has been observed for each type of nanoparticles and surfactant. In this way, the increase in absorption rate by nanofluid based on ammonia sorbent has been attributed to the increase in heat transfer and decrease in viscosity of nanofluid. And on the other hand, with the temperature difference in the cooling water and nanofluid, as well as the time of the falling film, it has been remained constant [31].	Ammonia/Water
Among other studies on liquid desiccant absorbents, there has been an experimental investigation of the effects of Al_2O_3 and SiO_2 nanoparticle suspensions in methanol absorbent base fluid. Methanol-based nanofluids have been experimentally analysed to absorb CO_2 gas flow from the opposite direction in an absorbent column with twelve acrylic tray plates. In this way, the results have shown that the maximum rate of absorption increased by 9.4% and 9.7% for alumina and silica nanoparticles, respectively, compared to pure methanol absorbent. In addition, using the above nanoparticles in the methanol absorber has been caused the bubbles to separate from the surface of the apertures. On the other hand, the results of the experiments have shown that silica nanoparticles have been a much more suitable option and with a volume concentration of 0.05%, an optimal condition equal to 9.7% increase for the rate of CO_2 absorption has obtained. Finally, nanofluids based on methanol desiccant absorbent are a promising option for CO_2 gas absorption applications [32].	Methanol
In liquid desiccant absorbent systems or combined air conditioners, nanoparticles have added to the desiccant liquid stream as a falling film. The effect of suspending nanoparticles in liquid desiccant absorbent in both absorption and regeneration streams has been investigated in these configurations. In the air flow with low Reynolds number, it has been observed that absorption processes, i.e., dehumidification and air cooling, have been increased for both flow configurations. At the same time, at high Reynolds number values of air flow, the regeneration process has been improved for liquid desiccant. Investigating the effects of very fine particles of metal Copper to the liquid desiccant falling film layer on the improvement of heat and air mass transfer has also been done [33-34].	Liquid Desiccant

On the other hand, the traditional consideration in the work of Hamilton, Crosser, Xuan and Roetzel have been rectified before [35]. At the same time, some extended relations have developed by Brinkman and also such like these equations have been used to determine fluid viscosity effectiveness [35-38]. Nanofluids have been used to improve and increase CO_2 gas absorption behavior. On the other hand, the amount of CO_2 absorption by nanofluids depends on various factors, including the type of nanoparticles, size and concentration, gas concentration, temperature, and gas and liquid flow rates. Conclusions and future research directions have also shown a reduction in energy consumption [39]. Studies related to the improvement of CO_2 gas absorption using nanofluids in a gas-liquid hollow fiber membrane contactor (HFMC) bed have been carried out through a two-dimensional mathematical model.

This model has been created considering the rate of molecular diffusion in radial and axial directions as well as non-moisture conditions. The absorption of CO_2 gas has done from a gas mixture, containing CO_2 and air, which flows in the shell. Also, the absorbents containing CNT and SiO2 nanoparticles have flowed counter-currently on the side of the tube. The effect of nanoparticles has been considered using two prominent mechanisms to enhance mass transfer in nanofluids [40]. So far, there have been a variety of studies in the field of dehumidification and air conditioning systems. Few studies have considered and shown the benefits of using cold roof systems as an auxiliary means to cover the obstacles of floor air distribution systems. However, research, especially in the analysis of indoor air quality, is still insufficient and ongoing [41]. Some studies have been done in the field of providing a mathematical model based on the two-dimensional Navier-Stokes equation to show the dehumidification process of the dehumidifier or desiccant wheel dryer. in which the effect of air flow velocity on the performance of the wheel as a relationship by the heat and mass transfer has also been investigated [42]. Research in the field of cooling parts in confined spaces is very important in the electronics industry. Therefore, in order to achieve the best performance in such systems, it has always been one of the challenges facing researchers [43]. The research in the field of various types of fluids or nanofluids that have the role of absorbent or effectiveness in chemical reaction and external vertical magnetic field on the initiation of convection flow has been studied so far [44]. Finally, as an ultimate goal of this study, to increase the heat and moisture transfer coefficients in a combination of liquid desiccant using surfactant material and also hybrid nanoparticles of multi-walled carbon nanotubes (CNTMW) Aluminum Oxide (Al_2O_3) and silicon oxide (SiO2) has been applied. The surfactant has been used for complete stability of hybrid nanoparticles in desiccant solution such as lithium chloride (LiCl) and liquid water. The effect of important parameters on the efficiency of the system has been studied. In this way, the best operating conditions for the better performance of the system containing liquid desiccant nanofluid have been determined.

2. Nano-Liquid Desiccant Dehumidification System Using Hybrid Nanofluids

2.1. Experimental Setup

In order to compare simple liquid desiccant absorbent with hybrid nanofluid based on liquid desiccant absorbent, hybrid nanofluid has been made. For this purpose and with the aim of creating a fully stable hybrid nanofluid based on the desired liquid desiccant absorbent, surface activating materials or PVP surfactant have been used.

The general process of making hybrid nanofluid has been shown in the flowchart of Figure 1. During this process, and according to Figure 1, PVP surfactant, mechanical stirring and ultrasonic vibration have been applied to create a stable hybrid nanofluid.

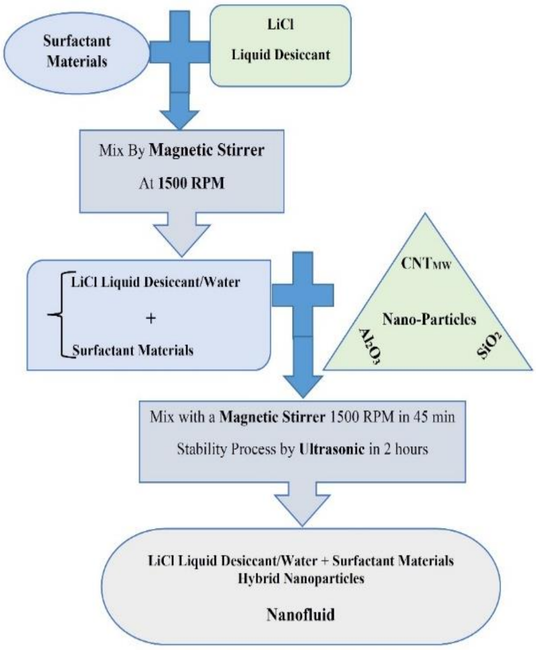

Fig. 1. Operational steps for preparation and production of hybrid nanofluid based on the liquid desiccant absorbent

Liquid desiccant cooling system is determined as the thermal driven cooling cycle that generally operates liquids as working fluid circulating and contacting directly with air. Liquid desiccant materials can be used as an absorption matter of cooling cycle such as lithium chloride. The vapor pressure of liquid desiccant materials at different mass concentration percent are shown in Figures 2-3.

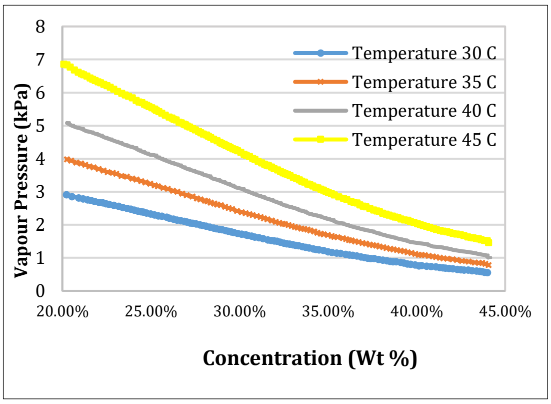

Fig. 2. LiCl Vapor pressure at different temperatures and mass concentration percentages

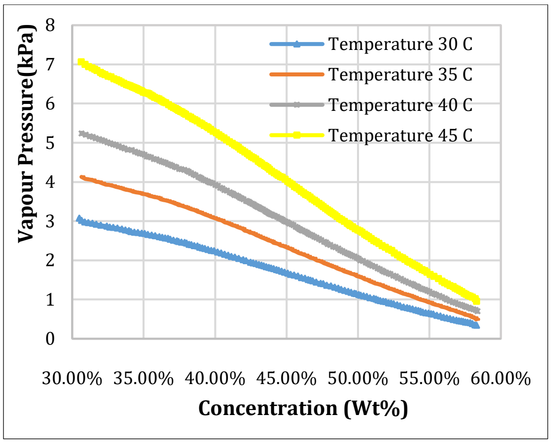

Fig. 3. LiBr Vapor pressure at different temperatures and mass concentration percentages

2.2. Steps of Dehumidification Process

Between the mentioned material types of cooling technique, using liquid desiccant as a working fluid is highly considered nowadays. Thermo-physical properties of liquid desiccant extremely prescribe to evaluate cooling capacity of liquid desiccant application. The vapor pressure of surface constitutes the key thermophysical property inducing heat and mass transfer. In addition to the thermophysical properties, the important requirements of liquid desiccant are non-toxic, odor free, non-flammable and unexpensive. Lithium chloride (LiCl), lithium bromide (LiBr) and calcium chloride ($CaCl_2$) owing to the low vapor pressure are generally used in liquid desiccant cooling system (LDCS). Lithium chloride (LiCl) constitutes the preferred choice due to the lowest vapor pressure and stable liquid. Nanofluids and using its heating specification could improve both the heat and mass transfer performance in desiccant dehumidifier materials.

In this regards, the mass transfer improvement efficiency of nanofluids dispersed into the desiccant materials also have been seldom examined. In the study, it proposed a novel research on LiCl/H_2O and hybrid nanoparticles of multi-walled carbon nanotubes (CNT_{MW}) Aluminum Oxide (Al_2O_3) and silicon oxide (SiO_2) for dehumidification by dispersing after mixture into Lithium chloride (LiCl) solution as base fluid.

The stable LiCl/ water-CNT_{MW} nanofluid was prepared by adding surfactant Poly-Vinyl Pyrrolidone (PVP) through mechanical methods. The concentration of MWNTs and PVP were 0.1 wt% and 0.4 wt% respectively. The influences of various parameters on dehumidification performance of LiCl/H_2O solution, LiCl/H_2O-PVP solution by two different weight concentrations of hybrid nanoparticles such as CNT_{MW}, Al_2O_3 and SiO_2 have been investigated and compared. The experimental results show that LiCl/H_2O-PVP nanofluid can enhance the dehumidification rate by up to 26.1% and 25.9% as a result of contact area. The dehumidification enhancement of nanofluid can be attributed to the adding and dispersing of 0.1 wt. % of surfactant and hybrid nanoparticles that has been desirable detected effect on the dehumidification performance. The results can provide some guidance for the mass transfer enhancement in liquid desiccant dehumidification in terms of adding surfactant and hybrid nanoparticles.

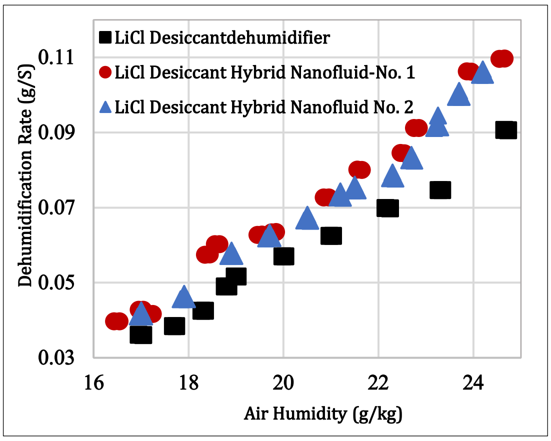

Fig. 4. Effect of air humidity on dehumidification performance of different samples

Figure 4 shows the effect of air humidity flow rate on dehumidification rate by desiccant dehumidifier and hybrid nanofluids desiccant. When the air flow rate humidity grows up from 17 g/kg to 24.7 g/kg, the dehumidification rate also improves from 0.036 g/s to 0.091 kg/s under the working conditions for desiccant solution of LiCl/H_2O. On the other hand, trends can also be considered by another two kinds of desiccant nanofluids. These conditions can be developed by increasing of mass transfer driving force with the improve of air flow rate humidity when the solution concentration keeps constant.

In this case, the driving force has been the partial water vapor pressure difference between the processed air and nanofluid desiccant solution, during the mass transfer process. Higher humidity rate corresponds to bigger partial water vapor pressure and leads to greater mass transfer force. For dispersion and using PVP surfactant, the dehumidification rate has been shown a distinct increase which is indicted in Figure 4. However, the dispersion of hybrid nanoparticles into LiCl/H_2O-PVP desiccant solution has influence on dehumidification performance as shown in Figure 4.

In the dehumidification system with a liquid desiccant absorbent, heat and mass transfer (i.e. moisture content) occurs simultaneously during the process of moisture absorption and regeneration. Therefore, the conservation of mass and energy laws, must be followed by the balance of humidity and heat. Which has shown by relations 1 and 2. Of course, regarding the conservation of mass law with moisture balance in equation 1, the changes in the concentration of the liquid desiccant absorbent hybrid nanofluid sample in the inlet and outlet flow have been measured and taken into account. As a result, only the equation of energy conservation with heat balance in equation 3 has been considered.

For the overall cases in which an experimental result r is a function of J measured variables X_i.

$$r = r(X_1, X_2, \dots, X_J) \tag{1}$$

Equation (1) is the data reduction equation used for determining r from the measured values of the variables X_i. Then the combined standard uncertainty in the result is given by the equation (2). Considering that the discussion of device and measurement errors in the experimental conditions may exist in any case, therefore the uncertainty analysis for experimental results can be calculated with equation (2). In relation (2), the analysis and estimation conditions of uncertainty have been done using the uncertainty propagation method [45].

$$\begin{aligned} u_r^2 = &\left(\frac{\partial r}{\partial X_1}\right)^2 u_{X_1}^2 + \left(\frac{\partial r}{\partial X_2}\right)^2 u_{X_2}^2 \\ &+ \left(\frac{\partial r}{\partial X_3}\right)^2 u_{X_3}^2 + \cdots + \left(\frac{\partial r}{\partial X_J}\right)^2 u_{X_J}^2 \end{aligned} \tag{2}$$

where the u_{X_i} are the combined standard uncertainties in the measured variables X_i or property values for any cases. The partial derivatives are called absolute sensitivity coefficients. The uncertainties in the measured variables cause uncertainty in the result, and this is modeled using propagation based on the Monte Carlo Method (MCM) or the Taylor Series Method (TSM) approach.

In this regards, Figure 5 is shown the energy conservation conditions of the dehumidifier. It can be considered that the maximum areas in the results evenly fell within ±25% error band, validating the accuracy of the experimental results. In addition, the heat released by the process air is a little higher than that absorbed by the liquid desiccant and the cooling water. It could be explained that part of the heat was released to the surroundings despite the thermal insulation of the system. And in this way, the validation results for the changes in enthalpy of liquid desiccant absorbent flow and hybrid nanofluid based on liquid desiccant absorbent have been shown in Figure 5. Due to this, almost all the differences between the absolute enthalpies have reported to be less than 25%. As a final result, the degree of acceptability and validity of the sample of the experimental system has been confirmed.

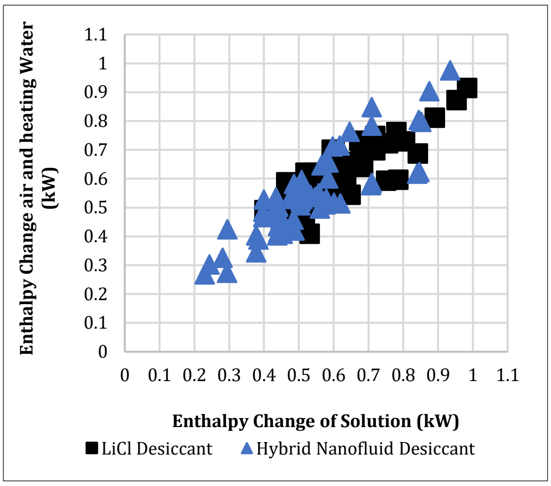

Fig. 5. Energy balance based on enthalpy changes of liquid desiccant absorbent flow and hybrid nanofluid based on liquid desiccant absorbent

3. Results and discussion

3.1. Effect of Factors and Experimental Investigation on Data Analysis

The rate of dehumidification from moist air flow has been actually an index that has considered to check the performance of the dehumidification absorber in different conditions. For this purpose, the total amount of moisture received or absorbed by the liquid desiccant absorbent, from the incoming moist air flow, has been considered. According to the definition has shown in relation 4 [24-26].

$$\begin{aligned} G_s(h_{s,o} - h_{s,i}) = G_w(h_{ww,i} - h_{w,o}) \\ + G_a(h_{a,i} - h_{a,o}) \end{aligned} \tag{3}$$

$$\Delta m = G_a \cdot (d_{a,o} - d_{a,i}) \tag{4}$$

$$G_a(h_{a,i} - h_{a,o}) = G_s X_{s,i} \left(\frac{1}{X_{s,o}} - \frac{1}{X_{s,i}}\right) \tag{5}$$

The mass flow rate of moist air for dehumidification section by liquid desiccant absorbent and also hybrid nanofluid sample based on desiccant absorbent has shown in Figure 6. The moist air from mass flow rate of 20 to about 80 g/s according to Figure 6, has been dehumidified. For this purpose, the solution of lithium chloride liquid desiccant absorbent and water LiCl/H_2O as a simple sample and triple hybrid nanofluid based on lithium chloride liquid absorbent and water, including surfactant surface activator, has been investigated separately as a triple hybrid nanofluid sample. In this way, the mass flow rate of moist air flow for both samples has observed to be less than 73 g/s. Of course, in the mass flow rate of more than 60 g/s, the dehumidification section rate has been decreased. Considering that according to equation 2, the dehumidification rate of the moist air flow has been the product of the air flow rate and the absolute moisture content of the flow. In this case, it has been observed that the amount of absolute humidity has decreased by increasing of the humid air flow velocity. By the way, in flow rate values less than 60 g/s, the dehumidification rate of the flow has an increasing improvement trend.

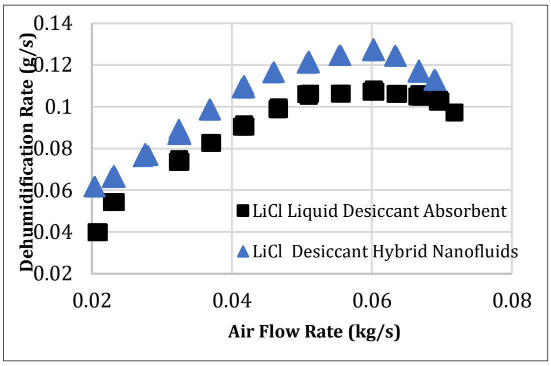

Fig. 6. The dehumidification rate in terms of mass flow rate of moist air

On the other hand, the values of changes in absolute humidity according to the rate of mass flow of moist air have been also shown in Figure 7. In this condition, the absolute humidity value for both simple desiccant fluid and triple hybrid nanofluid samples have a decreasing trend in values less than 70 g/s. Of course, to compare the LiCl/H_2O desiccant absorbent fluid and the hybrid nanofluid sample, the dehumidification rate has been clearly improved. For example, in the mass flow rate of moist air flow equal to 60 g/s, the dehumidification rate of the simple desiccant absorbent fluid is 105 g/s, while for the hybrid desiccant nanofluid, the amount has been equal to 130 g/s. Finally, the rate of improvement in dehumidification using hybrid nanofluids have been achieved up to 24%.

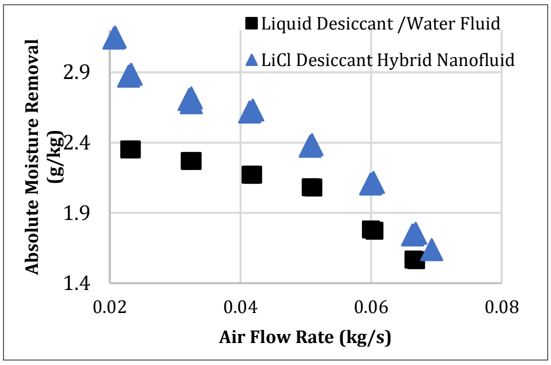

Fig. 7. The absolute moisture removal in terms of the mass flow rate of moist air

3.2. Absorbent System Exergy Analysis

To consider and check the efficiency of the dehumidification absorbent system using hybrid nanoparticles suspended into the liquid absorbent fluid, and by assuming that the dehumidification cycle is completely reversible, the coefficient of performance or COP has been determined. In this way, to analyze the exergy of the dehumidification system, if the heat source has transferred to the heat engine in the Carnot cycle, the cooling system will be reversible. And by this, the output work of the engine will be supplied to the Carnot refrigerator to remove the amount of thermal energy from the cooled space. The terms of the output work from Carnot heat engine, Carnot refrigerator cooling load and also Carnot cycle coefficient of performance (COP) in this reversible system have been presented in the following [24-26]:

$$Q_{in} = \frac{W_{out}}{\eta_{th,C}} \tag{6}$$

$$Q_L = COP_{R,C} W_{out} \tag{7}$$

$$COP_C = \frac{Q_L}{Q_{in}} = \eta_{th,C} COP_{R,C} = \left(1 - \frac{T_{ambient}}{T_{Source}}\right)\left(\frac{T_{space}}{T_{ambient} - T_{space}}\right) \tag{8}$$

where $G_{th,C}$ has actually the thermal efficiency of the Carnot cycle heat engine and the $COP_{R,C}$ factor of the Carnot refrigeration cycle, and the $T_{ambient}$, T_{space} and T_{source} have respectively indicated the temperatures of ambient, cool space and heat source, respectively. So, in an ideal cycle that has been considered, the ambient and cooled space temperatures have been reported, and the heat source temperature may be considered the regeneration temperature. For the experimental measurement of the LiCl nanofluid absorbent system and exergy analysis, a typical day of the summer season has been selected to create maximum cooling load conditions in the thermal performance of the liquid desiccant absorber nanofluid as well as the absorber air cooling system.

Figure 8 illustrates the hourly thermal efficiency of energy and exergy of the liquid desiccant absorber nanofluid. Earlier in the morning the thermal efficiency of the total nano-desiccant system dramatically increases and with the steady slop continues to decreasing that drops suddenly in the last hours of the day. The thermal efficiency decreasing is due to the reduction of solar radiation so that the output thermal energy of the nano-desiccant system does not change significantly. Besides, the efficiencies of thermal exergy are deprecated in

Figure 8, the maximum value of efficiency has been reported at the 13:00 approximately 5.5%.

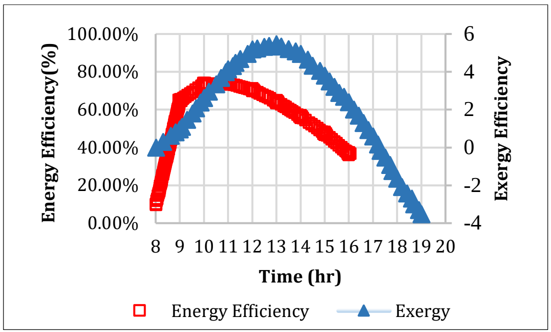

Fig. 8. Thermal energy and exergy Efficiencies of the liquid absorbent nanofluid

The temperature changes after about 7 hours for energy absorbent liquid desiccant nanofluid from June to October in the summer season are shown in Figure 9. The thermal energy production of liquid desiccant absorbent systems and also the output thermal exergy have shown in Figure 8.

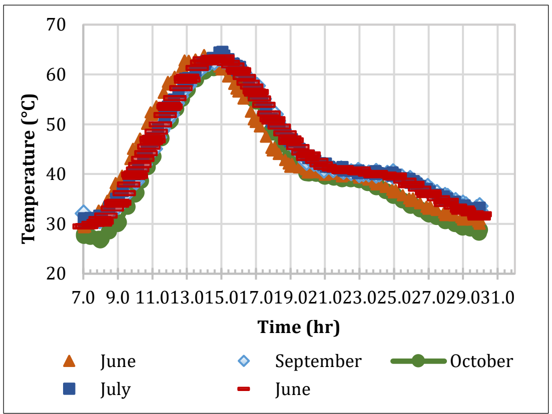

Fig. 9. The temperature variation of the liquid absorbent nanofluid from June to October.

So, the temperature of air flow to the liquid desiccant nanofluid and between June and October by moisture removal and heat transfer in free air flow caused by solar energy radiation has shown in Figure 9, noting that the maximum temperature of liquid desiccant nanofluid is about 61.4∘C throughout a typical day. Following these results, the low level of the supplied air is needed at noon for July due to the higher temperature of the desiccant dehumidifier. It is self-explanatory that the regeneration temperature for considered time is about 50.32◦C, consequently assuming the zero thermal losses and maximum thermal exchange in the liquid desiccant nanofluid, the more heating is not required to gain the necessary regeneration temperature. But from 6:00 to 11:00 the more heat transfer is required because the absorber temperature at the discussed instance is lower than the regeneration temperature.

3.3. Effect of Hybrid Nano-Particles

According to the mass and energy balance relationships, the experimental data related to the investigation of the hybrid nanoparticles dispersion have been selected and carried out. In this way, changes in air humidity and air temperature, mass and heat transfer rate and mass and heat transfer coefficients have been done with and without adding hybrid nanoparticles to $LiCl/H_2O$ solution. Also, in order to compare the conditions resulting from the increase in the rate of mass transfer as well as the rate of heat transfer, the improvement relations of the transfer rate have been defined as follows [24]:

$$\eta_{MT} = \frac{J_{HNF} - J_{LD}}{J_{LD}} \times 100 \tag{9}$$

$$\eta_{HT} = \frac{q_{HNF} - q_{LD}}{q_{LD}} \times 100 \tag{10}$$

Experimental data related to the comparison of the effect of adding hybrid nanoparticles to liquid desiccant absorbent has shown in Figure 10-13. According to this Figure, the improvement factor in heat and mass transfer and heat and mass transfer coefficients in terms of humidity ratio (gr/kg) of wet air flow have been considered for hybrid nanofluid based on liquid desiccant absorbent and simple desiccant absorbent fluid. As observed, changes in the air humidity and temperature have been increased by adding the hybrid nanoparticles to $LiCl/H_2O$ liquid desiccant. In this regard, the mass transfer rate has been improved from 3.41% to 28.3% and the heat transfer rate has been improved from 4.18% to 29.11%. So, the average improvement has been 23.23% and 22.22%, respectively. Adding hybrid nanoparticles to $LiCl/H_2O$ liquid desiccant has increased the mass transfer coefficient from 17.42% to 29.26% and the heat transfer coefficient from 19.83% to 33.55%. According to these results, the average value of improvement in mass and heat transfer coefficients has been about 22.73% and 26.51%, respectively.

Therefore, these values have been quite significant and impressive in improving the transfer results. From this, it can be seen that the hybrid nanoparticles with the characteristics resulting from displacement flow in the Brownian motion by different nanoparticles have been increased the performance of heat and mass transfer phenomena. On the other hand, both the humidity of the outlet air stream and the temperature have been reduced after the dispersion of nanoparticles, which produces favorable results for the cooling liquid desiccant absorbent systems.

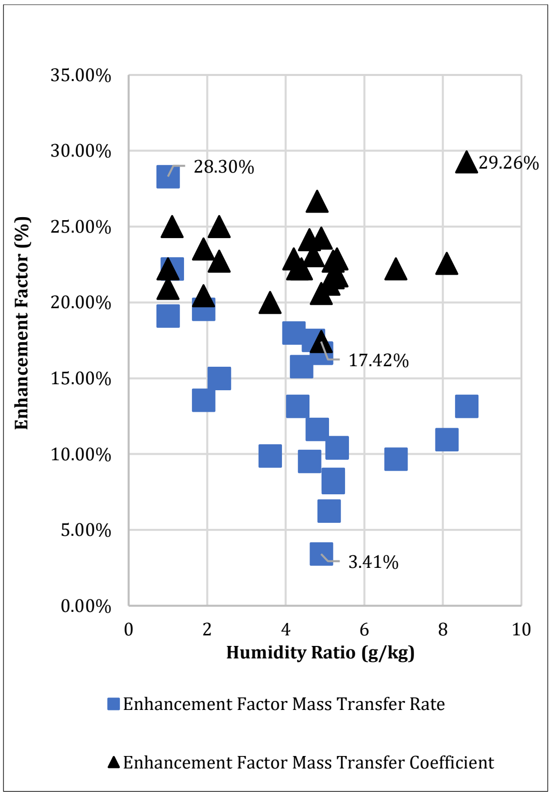

Fig. 10. Improvement Efficiency Factor in mass transfer and mass transfer coefficient versus humidity ratio

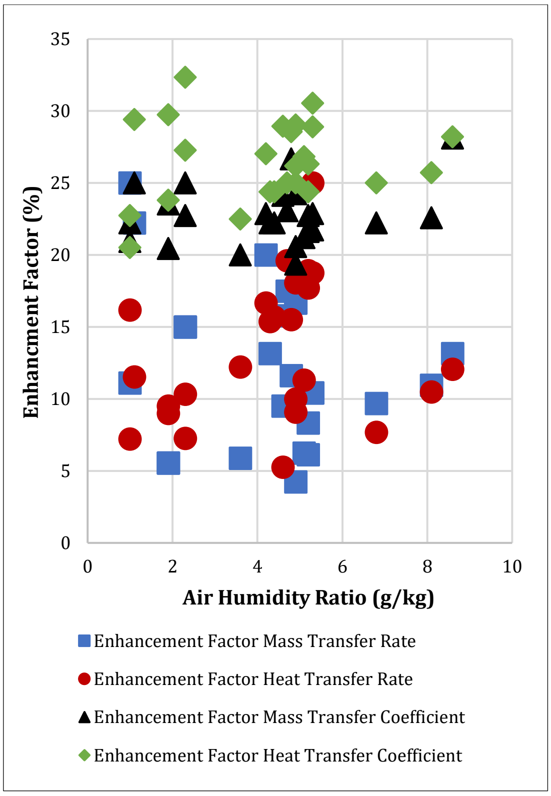

Fig. 12. Improvement Efficiency Factor in mass transfer and mass transfer coefficient versus air humidity ratio

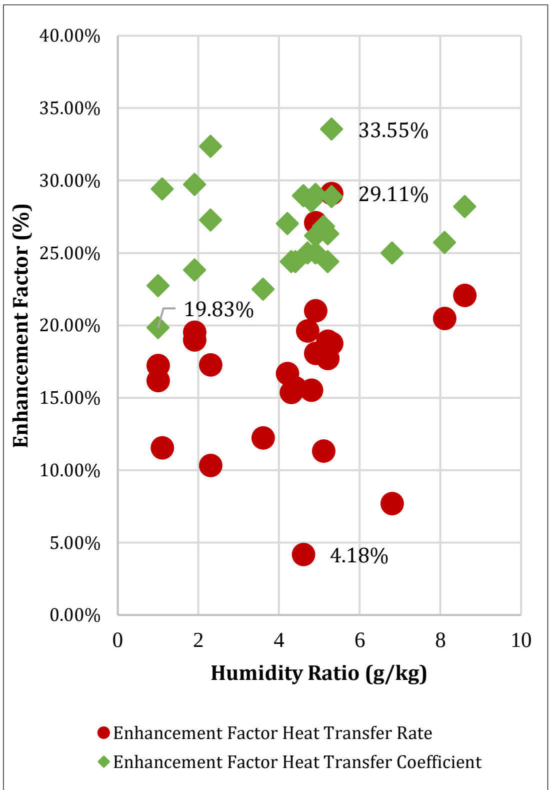

Fig. 11. Improvement Efficiency Factor in heat transfer and heat transfer coefficient versus humidity ratio

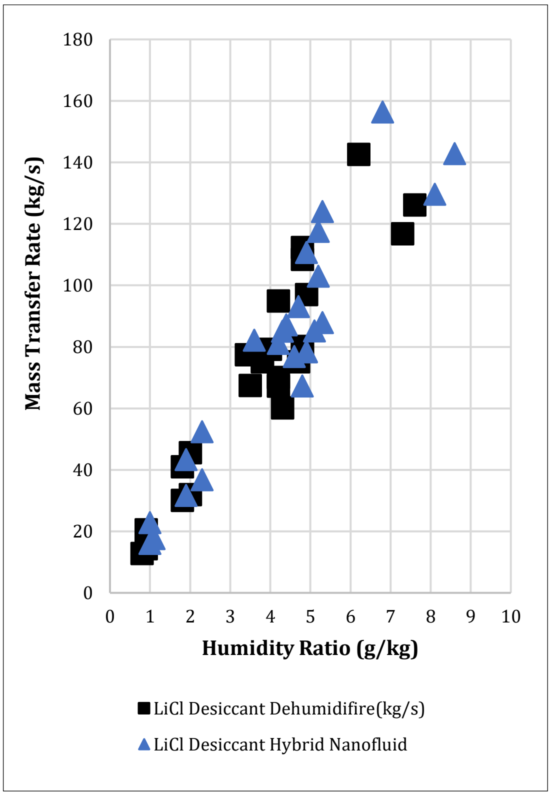

Figure 13. Changes mass transfer rate in pure LiCl desiccant and Hybrid nanofluid based LiCl versus humidity ratio

Results show that the hybrid nanoparticles of multi-walled carbon nanotubes (CNT-MW), Aluminum Oxide (Al_2O_3) and silicon oxide (SiO_2) doped by LiCl is an effective liquid desiccant by reducing the sensible heat load by about 49% thus enabling new avenues to test with wide range of nanomaterials for efficient heat transfer applications during water desorption. In this regard, it has been considered that the specific energy requirements can be obtained as low as 0.67 kWh/gal, while changing the inlet desiccant stream concentration of hybrid nanoparticles-doped LiCl at saturation conditions.

4. Conclusions

In this research, air moisture absorption by a combined liquid desiccant system has been investigated in a simple way and in comparison using by hybrid nanoparticles. In order to increase the heat and mass transfer coefficients in the system, a combination of liquid desiccant such as lithium chloride and by dispersion of the hybrid nanoparticles of Alumina, Silica and Multi-Walled Carbon Nanotubes has been used. From the experimental data, heat and mass transfer coefficients in the system have been determined in a relational way for different combinations of nanoparticles and absorbents. The effect of important parameters such as the rate of air flow and desiccant, air temperature and humidity, temperature and composition of input desiccant on the efficiency of the system has been studied. And the exergy analysis of the system has been done. The best operating conditions have been determined for the best system performance.

Nomenclature

d	Absolute humidity(g/kg)
G	Mass flow rate(kg/s)
h	Enthalpy(kJ/kg)
J	Mass Trasfer Rate (kg/s)
LDCS	Liquid desiccant cooling system
LiCl	Lithium Chloride
MWNTs	Multi-walled carbon nanotubes
Δm	Dehumidification rate (g/s)
PVP	Poly-Vinyl Pyrrolidone
q	Heat Transfer Rate (kW)
T	Temperature(°C)
u_{Xi}	Combined Standard Uncertainties
VCS	Vapor compression system
X	Concentration (%)

Greek Symbols

φ	Relative humidity (%)
ρ	Density(kg/m^3)
η	Improvement Efficiency (%)
Δ	Change value

Subscripts

a	Air
dry	Dry bulb
i	Inlet
HNF	Hybrid Nanofluids
HT	Heat Transfer
LD	Liquid Desiccant
MT	Mass Transfer
o	Outlet
s	Solution
w	Cooling water

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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