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Review Article

A Technical Review of Desiccant Air Conditioning Systems

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Abstract: The present review provided an overview of past studies on solid and liquid desiccants. Moreover, the main flow configurations for desiccant dehumidifiers have also been discussed briefly. Another objective is to investigate the mathematical models of the liquid desiccant dehumidifier. Finally, for the first time, a summary of recent studies regarding the effect of nanoparticles on liquid desiccants have been especially reviewed in detail as well as the applications of computational fluid dynamics (CFD) for modeling the desiccant cooling system. This study has beneficial for the research and technical development process of desiccant air conditioning systems.

Keywords: *Dehumidifier, Liquid Desiccant, Solid Desiccant, Nanoparticle, Computational Fluid Dynamics (CFD).*

Kurutucu Klima Sistemlerinin Teknik İncelemesi

Özet: Bu derleme, katı ve sıvı kurutucular üzerine yapılan geçmiş çalışmalara genel bir bakış sağlamıştır. Ayrıca, kurutucu nem alma cihazları için ana akış konfigürasyonları da kısaca tartışılmıştır. Diğer bir amaç, sıvı kurutuculu nem alma cihazının matematiksel modellerini incelemektir. Son olarak, ilk kez, nanopartiküllerin sıvı kurutucular üzerindeki etkisine ilişkin son çalışmaların bir özeti, kurutucu soğutma sistemini modellemek için hesaplamalı akışkanlar dinamiği (CFD) uygulamalarının yanı sıra özellikle ayrıntılı olarak incelenmiştir. Bu çalışma, kurutucu iklimlendirme sistemlerinin araştırma ve teknik geliştirme süreçlerinde faydalı olmuştur.

Anahtar kelimeler: *Nem Alma Cihazı, Sıvı Kurutucu, Katı Kurutucu, Nanopartikül, Hesaplamalı Akışkanlar Dinamiği (CFD).*

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1. Introduction

In the past decades, desiccant cooling systems have received much attention. These systems are considered as an alternative way to decrease energy consumption and greenhouse gas emissions in humid and hot locations [1-3]. Researchers demonstrate that these systems can decrease total energy consumption by shifting the energy used away from electricity and towards renewable, cheaper fuels and waste energy which are good for solar energy [4,5]. Desiccants have the ability to absorb water moisture, so they can be applied effectively for overcoming the latent part of the cooling load. As desiccants can be either solid or liquid [6], they can be categorized into solid desiccant air conditioning systems, which include fixed bed type and rotary wheel type, and liquid desiccant air conditioning systems. Liquid desiccants have some advantages over solid desiccants [7,8]. The basic components of liquid desiccant air conditioning (LDAC) systems are the dehumidifier, regenerator, cooling coil, heating coil, and solution heat exchanger which is illustrated in Figure 1 (a). The main operating fluid in LDAC systems is the liquid desiccant solution, which is used for absorbing/desorbing water vapor from/to an air stream which can be seen from Figure 1 (b) [9]. Due to being advantageous in handling latent heat load, LDAC systems have been used widely [10,11].

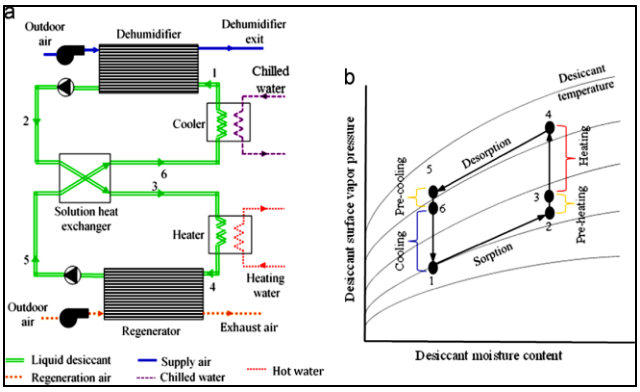

Figure 1. (a) LDAC system (b) liquid desiccant cycle [9,12].

In the present study, a review of desiccant air conditioning systems is presented by focusing on the past works on solid and liquid desiccants, the main flow configurations for desiccant dehumidifiers, especially the effect of nanoparticles on liquid desiccants, the mathematical models of the liquid desiccant dehumidifier and finally summarizing the recent works on modeling desiccant cooling system using CFD.

2. Solid and liquid desiccants

Desiccant cooling systems can be categorized into liquid desiccant and solid desiccant [13]. Commonly, many types of solid desiccants are applied such as calcium chloride, silica gel, zeolite, lithium chloride, lithium bromide, and alumina, which are presented by Sultan et al. [14]. Srivastava and Eames [15] concluded that silica gel is a solid desiccant used in drying out outdoor air before it is circulated inside a building [16]. Liquid desiccant is the most substantial component of desiccant systems. Among all of its properties, the surface vapor pressure is one of the most significant parameters which cause heat and mass transfer in the dehumidifier [17]. Generally, liquid desiccants are non-flammable, odorless, non-toxic, and inexpensive [18]. Figure 2 indicates the shortlisted properties of good desiccants.

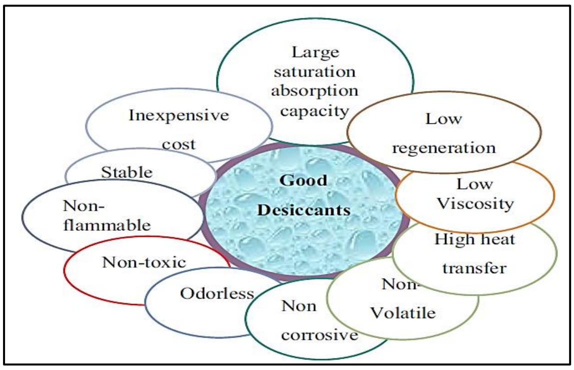

Figure 2. Shortlisted properties of good desiccants [19-21].

Commonly used liquid desiccants include lithium bromide (LiBr), lithium chloride (LiCl), and calcium chloride ($CaCl_2$). Among all of them, the absorption ability of calcium chloride ($CaCl_2$) is least. Choosing a desiccant material significantly affects the desiccant dehumidifier design [22]. Zuber et al. [23] and Ahmed et al. [24] introduced thermodynamic properties of single desiccants. Among them, LiCl has the lowest vapor pressure but it is very expensive as compared to the other ones. Park et al. [25] examined and added four 8-C alcohol additives to liquid desiccant for lowering its surface vapor pressure. Ertas et al. [26] provided the properties of LiCl and $CaCl_2$ mixture. They concluded that viscosity of the mixture is low and it is highly soluble. As compared to pure $CaCl_2$ solution the mixture has a lower vapor pressure. Liu et al. [27] compared the performance of two commonly used liquid desiccants namely LiBr and LiCl. Also, they considered the reasons for replacing tri-ethylene glycol (TEG) with other aqueous salts.

3. The main flow configurations for dehumidifiers

Generally, there are three different flow patterns for the dehumidifier such as parallel flow, counterflow, and cross-flow which are illustrated in Figure 3 [17].

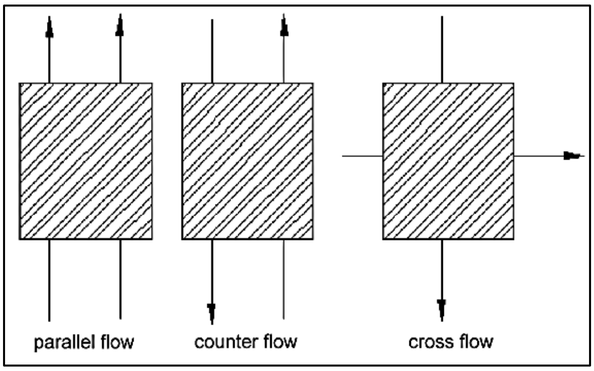

Figure 3. The main flow configurations [17].

Rahamah et al. [28] analyzed parallel flow in liquid desiccant using the control volume method. Their results indicated that low air flow rate and the increment of channel height cause to have better dehumidification and cooling processes. Counter-flow is the most widely used flow pattern in design of dehumidifiers as it can be seen in many related studies [29]. Ali et al. [30] studied the effects of addition of Cu-ultrafine particles in increasing heat and mass transfer in a cross-flow configuration of air and falling solution film. Also, the addition of Cu-ultrafine particles causes to improve heat and mass transfer between liquid desiccant and air. Yoon et al. [31] numerically investigated the heat and mass transfer between process air and desiccant solution in inner water-cooled plates with a cross-flow arrangement to demonstrate the changes of process air humidity and temperature along the plate. Nada [32] numerically considered the air dehumidification by a liquid desiccant falling on rectangular finned-tubes configuration for parallel, counter and cross-flow based on desiccant liquid film (Figure 4). Also, heat transfer between desiccant film, air, and the finned-tube arrangements was studied.

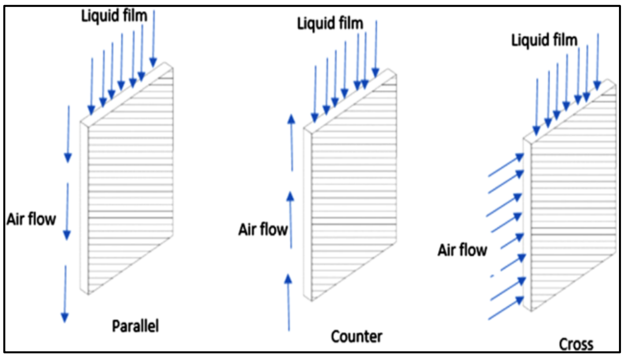

Figure 4. Different flow configurations [32].

Salah Hassan and Hassan [33] analyzed the performance of a counterflow channel type liquid desiccant dehumidifier. They found that with high temperature of inlet air and relative humidity, a better dehumidification process was obtained. Shahzad et al. [34] experimentally studied the performance of a solid desiccant dehumidifier integrated with Maisotsenko Cycle based cross-flow heat and mass exchanger. They found that the MC-DAC system gives higher temperature effectiveness than that of DAC even under low temperatures.

4. Effect of nanoparticles on liquid desiccants

A nanofluid is a fluid in which nanoparticles of less than 100 nm in diameter are stably suspended in a base fluid [35-37]. Many researchers considered heat transfer in nanofluids. Most studies investigated enhanced heat characteristics of nanofluids, such as convective heat transfer coefficient and thermal conductivity relative to their base fluids [38-40]. Few investigations have been done to analyze the enhancement of mass properties of nanofluids, such as diffusion coefficient and mass transfer coefficient [41-43]. Kim et al. [44] examined the vapor absorber performance by SiO_2 nanoparticles in $LiBr/H_2O$ nanofluid. They concluded that the maximum increase in the heat and mass transfer rates was 46.8 % and 18 %, respectively. Kang et al. [45] investigated the vapor absorption and heat transfer rates in the falling film flow of nanofluids containing $LiBr/H_2O$ solution with nanoparticles. They found that vapor absorption was higher than for fluids without nanoparticles and that mass transfer rate increase was much more important than heat transfer rate increase in nanofluids. Ali and Vafai [46] considered heat and mass transfer between air and falling desiccant film in inclined parallel and counter flow arrangements. Also, Cu-ultrafine nanoparticles were added to desiccant film to consider the improvement in heat and mass transfer between the air and desiccant film. The inclined parallel and counter flow channels between air and desiccant film are illustrated in Figure 5 (a) and (b), respectively.

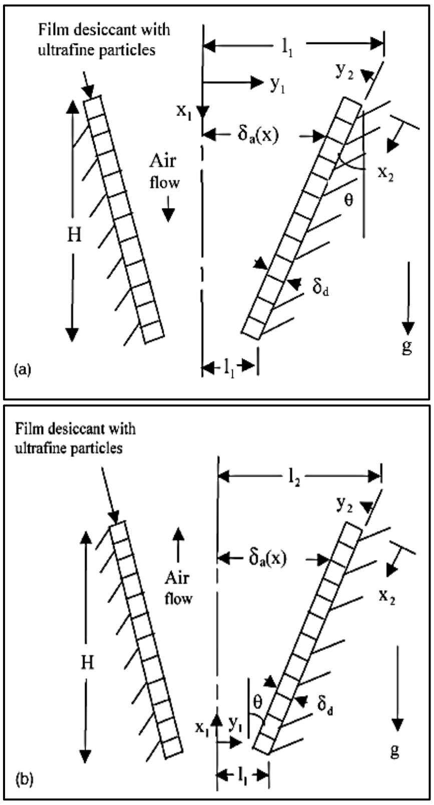

Figure 5. Schematic of inclined (a) parallel and (b) counterflow arrangements [46].

They found that the inclination angle plays a major role to augment dehumidification and regeneration process of liquid desiccant for both inclined parallel and counter flow channels [46]. Ali et al. [47] numerically analyzed the heat and mass transfer using nanoparticles between air and falling film desiccant in parallel and counter flow arrangements. They found that the parallel flow channel gives better dehumidification and cooling processes of the air than the counter flow arrangement. Also, the dehumidification and cooling rates of air were increased with an enhancement in the volume fraction of nanoparticles and dispersion factor. Omidvar et al. [48] experimentally investigated air dehumidification using $LiBr/H_2O$ solution with and without nanoparticles as a desiccant. They concluded that the average increment of mass transfer rate was 12.23 % and heat transfer rate was 13.22 % when nanoparticles were added to the solution.

5. Mathematical models of liquid desiccant dehumidifier

In A mathematical model is a set of equations to specify the unknown parameters based on known variables [49]. Luo et al. [50] reviewed some common mathematical models to predict heat and mass transfer processes in the liquid desiccant dehumidifier. For an adiabatic dehumidifier finite-difference model, effectiveness-NTU model, and simple analytical model are the three commonly used mathematical models [51]. Table 1 indicates a list of various types of models.

Table 1. Summary of mathematical models.

Type of model	Flow	Reference
Effectiveness NTU model	Counter-flow	[52,53]
Simple/quick prediction	Counter-flow	[54]
Empirical correlations	Cross-flow	[55]
Artificial neural network	Counter-flow	[56]
The kinetic mass transfer model	Cross-flow	[57]
Simple hybrid model	Counter-flow	[58]
Model based on Runge-Kutta fixed step method	Counter-flow	[59]
Simple analytical	Cross-flow	[60]
Simple analytical	Counter-flow	[61,62]

Salarian et al. [52] experimentally investigated the performance of a packed-tower dehumidifier. They presented the influence of dimensionless parameter air to liquid desiccant flow rate ratio (ASMR) on its performance. There is an optimum air-to-desiccant ratio, which is very beneficial in the design of dehumidifiers and regenerators. In Figure 6, enthalpy efficiency is shown against m^* for different NTU values.

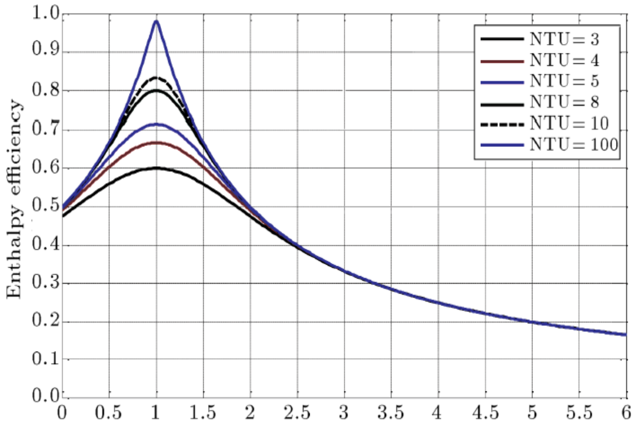

Figure 6. Effect of m^* and NTU on the enthalpy [6].

As it can be seen, there is an optimum number for the efficiency of enthalpy. Furthermore, their results demonstrated that there is maximal humidity effectiveness at a suitable humidity of the ASMR. Qi et al. [61] analytically analyzed a 2D theoretical model to predict the falling film desiccant dehumidification process. Based on their results, it is theoretically possible for evaluating the properties of a wave-wise liquid/air interface with heat and mass transfer, which could enhance the evaluation accuracy of falling film liquid desiccant. Bassuoni [60] applied an analytical method using Engineering Equations Solver (EES) for estimating all exit parameters of a cross-flow air dehumidifier using $CaCl_2$ as the liquid desiccant. Liu et al. [62] validated a simplified analytical solution for the heat and mass transfer model of a liquid desiccant dehumidifier. They concluded that the enthalpy efficiency of the dehumidifier equaled moisture efficiency. Gandhidasan and Mohandes [56] used an artificial neural network model and investigated the dehumidification unit for random packing using lithium chloride. Another such model was developed by Parmar and Hindoliya. They based their model on the desiccant wheel. Both the models were in excellent agreement with experimental results [57].

6. CFD Modeling of the desiccant cooling system

The prediction of fluid flow fields can be obtained by CFD based on numerical analysis relating to continuity, momentum and energy equations [64,65]. The numerical analysis can be done using Ansys Fluent [66] based on the CFD codes which are used to describe the complex behaviors of the heat and mass transfer in the absorption and separation process [63] and describing the fluid flow in diverse problems [67-73]. Although the absorption processes of the liquid desiccant dehumidifier modeled with CFD technique are seldom reported. In the dehumidifier, the fluid dynamics and vapor absorption of the desiccant solution are mutually coupled, so this case can be modeled with the CFD method [63]. Luo et al. [67] numerically analyzed the flow in the liquid desiccant dehumidifier using CFD solver. They concluded that the model predicted accurately the optimum flow rates of the solution and air. Also, Luo et al. [69] used a 2D CFD model to consider dehumidifier performance under different conditions. In their study, by increasing the desiccant temperature, the moisture concentration of outlet air enhanced dramatically. In the study of Luo et al. [63], a new simulation model based on CFD for simultaneous heat and mass transfer combined with the volume of fluid (VOF) method has been carried out for a liquid desiccant dehumidifier. The contour of the mass fraction of water vapor in the interior of the dehumidifier is illustrated in Figure 7 under different inlet air velocities.

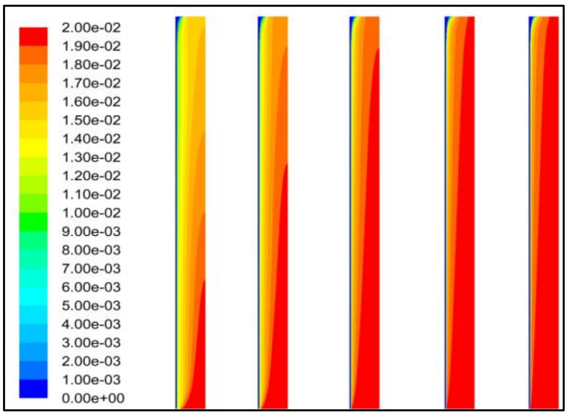

Figure 7. Contour of the mass fraction of water vapor [63].

It is found that for optimizing the operating condition, the air velocity should be set based on the channel size, including the channel length and width. Furthermore, they found that the CFD model has been proved to be reliable due to the good agreement results with other models. Recently, Lin et al. [74] numerically analyzed the cross-flow flat-plate membrane liquid desiccant dehumidifier using the 3D CFD model. A correlation is specifically developed for the dehumidified air temperature and humidity, respectively. Tao et al. [75] applied a 3D CFD simulation model for a falling film dehumidifier and compared the CFD results with experimental data. The simulation was able to analyze the impact of contact angle on dehumidification performance. Wen et al. [76] presented a novel quasi-3D model for simulation of heat and mass transfer process in a falling film dehumidifier. They concluded that the non-wetting of falling film and mass transfer resistance in the airside hindered the dehumidification performance. Consequently, the CFD simulation was proved to be reliable for simulating the dehumidification process.

7. Conclusion

This review provided an overview of past studies on the main flow configurations for desiccant dehumidifiers, solid and liquid desiccants and the mathematical models of a liquid desiccant dehumidifier. Moreover, for the first time, a summary of recent studies regarding the effect of nanoparticles on liquid desiccants have been especially reviewed in detail as well as the application of Computational Fluid Dynamics (CFD) within the desiccant cooling system. As referred previously in the body of the paper, the liquid desiccant is the most substantial component of desiccant systems. Among all of its properties, the surface vapor pressure is one of the most significant parameters which cause heat and mass transfer in the dehumidifier. It is noteworthy that the convective motion of nanoparticles had a considerable effect on the increase in heat and mass transfer of desiccant. Also, for an adiabatic dehumidifier, finite difference model, effectiveness-NTU model, and simple analytical model are the three commonly used mathematical models. Finally, according to the past studies on CFD modeling of the desiccant cooling system, it can be said that the CFD model was proved to be reliable for simulating the dehumidification process and desiccant cooling systems.

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