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Energy Efficient Liquid Desiccant Hybrid Air Conditioning System

Y.A. F. El-Samadony and B. M. Gibbs

***Abstract*—Desiccant systems are widely regarded as energy-saving alternatives to vapour-compression air-conditioning for handling the latent load. In the present work an energy efficient liquid desiccant hybrid air conditioning system is proposed with a novel liquid desiccant calcium chloride regeneration system. This regeneration is obtained by spraying fine liquid desiccant, calcium chloride, droplets into hot moist air. The effect of spray regeneration conditions, ambient conditions and space cooling load sensible heat factor on the performance of the proposed system was investigated. A comparison between the proposed liquid desiccant air conditioning system and the traditional one was studied. It was found that the values of the injected droplet diameter size, spray angle, hot air temperature, and spray injection speed, had an important role in the evaporation process. At RSHF= 0.6, the proposed system achieves 72% energy savings compared to a traditional air conditioning system.**

***Index Terms*—Hybrid air conditioning system, liquid desiccant, calcium chloride, spray.**

I. INTRODUCTION

Desiccants are substances known for their ability to absorb water vapour. Therefore, they can be used effectively not only to overcome the latent cooling load of air conditioning systems and improve the indoor quality but also to dehumidify air for any industrial applications. Recently, a number of hybrid air conditioning systems, in which desiccants (solid and liquid) were used to remove latent cooling load and conventional air conditioners were used to provide sensible cooling, have been suggested as alternative options to conventional vapour compression cooling systems. The aim of these systems was to conserve energy. These systems had different construction and methods of desiccant regeneration.

Regeneration energy is equal to the heat necessary to raise the temperature of the desiccant to make its surface vapour pressure higher than the surrounding air, plus the heat necessary to vaporise the moisture that it contains. The regeneration of liquid desiccant can be driven by different methods; for example, solar energy [1]-[6], a heat pump [7], [8] electrical heaters [9], waste heat or other low-grade heat source [10], packed bed column [11]–[14], and multiple stage boiler (gas-fired) [15]. Researchers studied also the effect of different working parameters on liquid desiccant regeneration process such as; liquid desiccant inlet temperature and concentration [3], [11], [14], [16], desiccant airflow rate [6], inlet air temperature and moisture content [3], [7], [8], and desiccant types [17]. Studak and Peterson [17] found that the best liquid for the anticipated application was found to be calcium chloride.

Spray drying or spray evaporation is widely used for the drying of heat-sensitive foods, pharmaceuticals, fuel, and other substances mainly due to rapid solvent evaporation [18] – [24]. Calcium Chloride solution as a liquid desiccant was listed among liquids that can be sprayed [25]. El-Samadony *et al.*, [26] simulated the spray evaporation of calcium chloride aqueous salt solution, into hot moist air using a three dimensional computational fluid dynamic software (CFX-10). Moreover, they validated the numerical results experimentally. They found a good agreement between the numerical and experimental results. Also, they found that the values of the injected droplet diameter size, spray angle, hot air temperature, and spray injection speed, had an important role in the evaporation process. As the injected droplet size decreases, the liquid desiccant outlet concentration increases. Therefore, the spray evaporation of a liquid desiccant can be used as a viable regenerator system

In the present work a theoretical study of an energy efficient liquid desiccant hybrid air conditioning system is proposed with a novel liquid desiccant calcium chloride regeneration system. This regeneration is obtained by spraying fine liquid desiccant, calcium chloride, droplets into hot moist air. To conserve energy, the outlet hot air of a conventional vapour compression condensing unit is used.

II. NUMERICAL WORK

In the present work, the validated numerical program of EL-Samadony *et al.*, [26] complete with its subroutine are used.

A. Geometry and Physical Definition

The geometry consists of a cylinder 86 cm in diameter and 200 cm in height, Fig. 1. The cylinder is fitted with a truncated cone, 50 cm in height, at its bottom. The truncated cone exit of 10 cm diameter, then attaches to the Calcium Chloride solution collection tank. Four 10 cm diameter tubes are connected to the cylinder wall, pointing upwards at a 45-degree angle in order to supply hot air. The geometry was assumed as one domain with four inlets (hot moist air) and two outlets. The first outlet is at the top of the cylinder for exhaust moist air and the second one is at the bottom of the truncated cone for the concentrated solution. The volume mesh spacing was defined as 4 cm for all the geometry.

A new material Solid Calcium Chloride, liquid Calcium

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Chloride aqueous solution and moist air were created, as the CFX10 materials library does not have these materials. The physical, thermodynamic and mass transfer properties of the created material were specified by using the correlations of [27], [28].

B. Droplet Phenomena

Particle tracking (Lagrangian) model was selected in this study because it is easier to represent the droplet size, velocity and properties from its injection point to final destination.

C. Heat and Mass Transfer

A FORTRAN computer subroutine called "MYMASSSOURCE" was designed to calculate the rate of mass transfer from or to the liquid desiccant particle instead of the default CFX method. This FORTRAN subroutine will deal with the rate of mass transfer between desiccant liquid and moist hot air taking into account moist air relative humidity condition. The subroutine uses the Manuel [28] Calcium Chloride aqueous solution vapour pressure correlation and the following rates of mass transfer correlation [29]:

$$\frac{dm_C}{d\xi} = -\pi d(\rho\lambda)\times(Sh)\times\left(mf_w - mf_{H2O}\right) \qquad (1)$$

where Sh= Sherwood number, which is given by Ranz and Marshall [30].

D. Numerical Output

Average property of all droplets at a certain position (or outlet) is not considered by the release of CFX-10. Therefore, A FORTRAN program called "MYAVERAGE" was designed to calculate the average properties for all droplets at the outlet. The FORTRAN program uses the CFX-post exported properties data (comma-separated data file) for each droplet (approx. 6000 droplets in total), to calculate their average property values. The program calculates the average of the following properties: droplet diameter, droplet total mass, droplet speed, Calcium Chloride mass fraction and droplet travelling time. The program takes into consideration the droplet volume to calculate the average value of the Calcium Chloride mass fraction.

To represent the droplet size distribution mass fraction and its corresponding Calcium Chloride mass fraction at the outlet, especially for the Rosin Rammler injected droplet size distribution, a FORTRAN program called "DSDMFAO" was designed for this job. The size of each band was 10 Micrometer. The number of droplets in each band to the total number of droplets will define each band mass fraction. Moreover, the average Calcium Chloride mass fraction in each band was calculated.

III. RESULTS AND DISCUSSION

A. Effect of Hot Air Temperature

Fig. 2 illustrates the variation of the air temperature with a uniform spray distribution on the mass fraction of the Calcium chloride droplets at the outlet. It can be seen that air temperature has a significant effect on small droplet size. This is because the mass transfer from the droplets to the hot air depends on three factors: first, mass transfer surface area, second, droplets residence time and finally, the liquid desiccant mass transfer driving force, the hot air and liquid desiccant vapour pressure. It can also be seen from Fig. 2. that at small droplet sizes (less than 100 micrometers), merely 45°C hot air temperature is enough for the regeneration process where mass fraction of the Calcium chloride at the outlet is equal to or over 0.45.

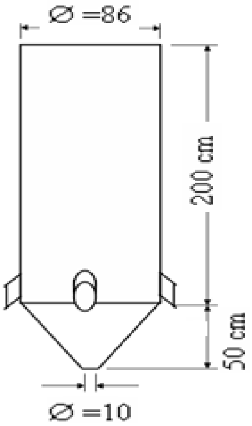

Fig. 1. modelled geometry.

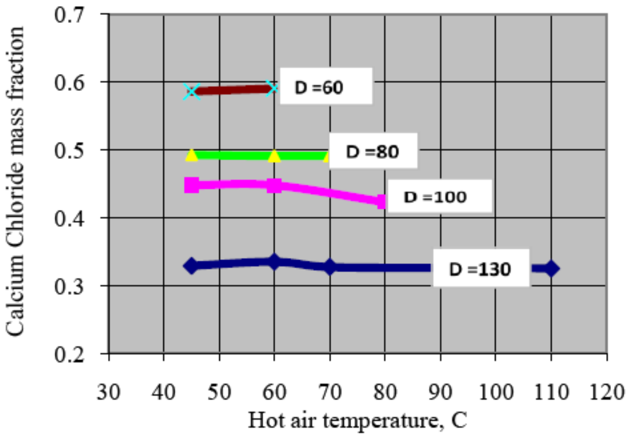

Fig. 2. Effect of inlet air temperature on $CaCl_2$ regeneration for uniform spray distribution on the mass fraction of the Calcium chloride droplets at the outlet [26].

B. The Mass Flow Capacity of the Model in a Real Plant

The amount of water vapour removed from the moist air in the air dehumidification process is only controlled by the liquid desiccant mass flow rate and the difference between the liquid desiccant concentration at the inlet and outlet. The outlet liquid desiccant concentration from the dehumidification process, which is the inlet to the regeneration process, was assumed to have a constant value of 20%.

Fig. 3 illustrates the effect of the inlet liquid desiccant spray mass flow rate (with a 5 m/s injection droplet velocity and 80 μm injection droplet diameter) on the mass fraction of the calcium chloride droplets at the outlet of the regenerator at different hot air mass flow rates. It can be seen from this Fig., that the mass fraction of the calcium chloride droplets at the outlet decreases as the liquid desiccant mass flow rate increases. This is because as the liquid desiccant mass flow rate increases, the total mass of hot air that can remove some water vapour from the droplets per liquid desiccant solution decreases, and consequently the rate of mass transfer decreases. In addition, as the hot air/injected liquid desiccant mass ratio decreases, the hot air kinetic energy decreases and consequently the droplet's drag force decreases. Therefore, the acceleration produced by air drag force increases and consequently the droplet residence time decreases. As a result the mass transfer rate from the droplet will decrease. Moreover, as the liquid mass flow rate increases, the interference between the boundary layer of adjacent droplets increases, which reduces the heat and mass transfer process. It can also be seen, from Fig. 3., that the proposed regeneration system can regenerate up to 0.025 kg/s of weak calcium chloride solution from 20% calcium chloride mass fraction to 0.35 or more.

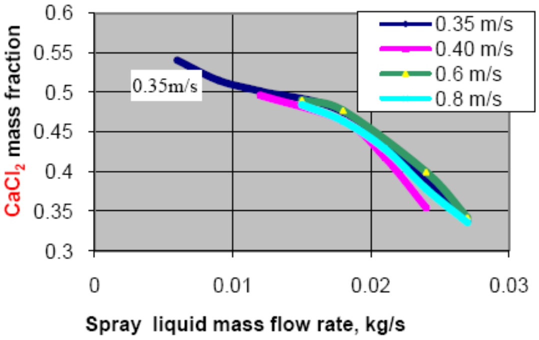

Fig. (3) effect of calcium chloride mass flow rate on CaCl2 mass fraction at outlet for different air mass flow rates.

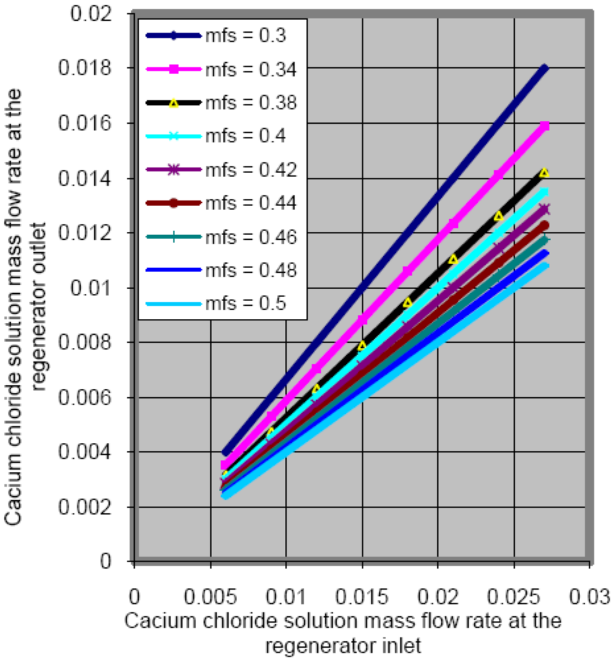

Fig. 4. The calcium chloride solution mass flow rate at the regeneration inlet to the outlet at different CaCl2 mass fraction at outlet.

C. Application of the Model to an Actual Real Plant Design

The amount of the air conditioning latent heat load of a conditioned space, which needs to be overcome by the proposed liquid desiccant system, is very important parameter for real plant design.

In a liquid desiccant regeneration process, a certain amount of water is evaporated. Therefore, the calcium chloride solution mass flow rate at the inlet is greater than that at the exit. Fig. 4 plots the relationship between the calcium chloride solution mass flow rate at the inlet and the outlet for different calcium chloride mass fractions at the exit.

Fig. 5 plots the corresponding latent heat load which can be overcome by a desiccant system as a function of calcium chloride mass flow rate and the mass fraction of the calcium chloride droplets at the air dehumidification process inlet, based on 20% calcium chloride mass fraction at the outlet. This Fig. can be used to obtain the required liquid desiccant design parameters for a given latent heat load. For example, after calculating the total latent load in the conditioned space, Fig. 4 and Fig. 5 can be used to select the best corresponding values of calcium chloride mass flow rate and calcium chloride mass fraction that fit the proposed system model in Fig. 3. Also, it can be seen from Fig. 3, 4 and 5 that, at the maximum proposed system calcium Chloride mass flow rate, 0.024 kg/s, the mass fraction of the calcium chloride droplets at the regeneration outlet was 0.42 and the corresponding latent heat load that can be taken by the system was 5.914 kW. Therefore, if the latent load is more than 5.914 kW, more than one spray regenerating system is required.

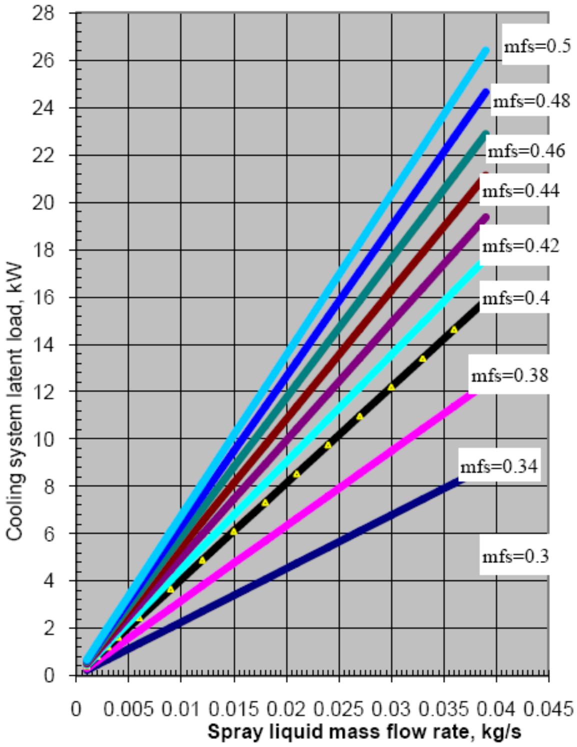

Fig. 5. the cooling system latent load as a function of the CaCl2 mass flow rate and CaCl2 mass fraction at inlet.

D. The Energy Saved by the Proposed System

To compare between the proposed liquid desiccant air conditioning system and a traditional one, two potential working systems were considered. These systems have the following characteristics unless stated otherwise:

- Grand total cooling load, Q_{ref} = 5 TOR
- Ambient air conditions:
    Dry bulb temperature, t_{adb} = 35 °C
    Wet bulb temperature, t_{awb} = 27 °C
- Room design conditions:
    Dry bulb temperature, t_{rdb} = 24 °C
    Relative humidity, ϕ_r = 50%
- Amount of fresh to re-circulated air, = 25 %
- Compressor isentropic efficiency = 92 %
- Injected droplet diameter, =80 μm
- Nozzle Injection droplet speed, = 5 m/s
- Nozzle spray angle, θ = 30°
- Number of nozzle's hole, = 6 holes

- Nozzle's hole spray direction from its axis = 30°
- Inlet hot air temperature, = 60 °C
- Inlet hot air velocity, = 0.35 m/s

Table I and II summaries the comparison between the power consumption of the proposed desiccant system and a traditional system at room sensible heat factors of 0.6 and 0.5 respectively:

TABLE I: COMPARISON BETWEEN THE PROPOSED SYSTEM AND A TRADITIONAL AT RSHF = 0.6

	Proposed system	Traditional system
Compressor power, W	1630	3001
Air reheating power, W	0.00	3558
Desiccant regeneration power, W	235	0.0
Total	1865	6559

TABLE II: COMPARISON BETWEEN THE PROPOSED SYSTEM AND A TRADITIONAL AT RSHF = 0.5

	Proposed system	Traditional system
Compressor power, W	1359	2872
Air reheating power, W	0.00	1647
Desiccant regeneration power, W	238	0.0
Total	1597	4519

It can be seen from these tables that about 72 % energy was saved at RSHF= 0.6 and about 65 % for RSHF= 0.50. Therefore, the proposed desiccant air conditioning system may be assumed to be an energy-saving system. The proposed system will use two spray-regenerating systems, which may increase the system's initial cost. However, as the vapour compression cycle deals with the sensible heat load only, the size of the compressor, evaporator and condenser (including its fan) will be decreased, and this in turn will reduce the system's initial cost.

IV. CONCLUSION

1) The exhaust air temperature from the air conditioning condensing unit is sufficient for the regeneration process when the injected droplet size is less than or to equal 100 microns. However, its magnitude may be not sufficient at high latent heat load.
2) The amount of hot air has an obvious influence on the liquid desiccant regeneration process for small-injected droplet sizes.
3) The proposed system is an energy efficient system especially at high sensible heat factor. At RSHF= 0.6, the proposed system achieves 72% energy savings compared to a traditional air conditioning system.

APPENDIX

d	Droplet diameter, micrometers
d_e	Diameter at which R_{Rosin} equal 36.8 %
Q_{ref}	Grand total cooling load, kW
m_C	The mass of the constituent in the droplet, kg
$mf\,H_2O$	Water vapour mass fraction in the air, dimensionless
mf_s	Solid Calcium chloride mass fraction, dimensionless
mf_w	Water mass fraction in the droplet, dimensionless
Sh	Sherwood number, dimensionless
t	Temperature, °C
v	Velocity, m/s
λ	Diffusivity of the mass fraction of H_2O in air, m^2/s
ξ	Time, sec
θ	Nozzle spray angle
ϕ_r	Relative humidity

Subscript

INJ	injected
a	air
adb	Air dry bulb
awb	Air wet bulb

Abbreviation:

AC	Air conditioning
RLH	Room latent heat
RSH	Room sensible heat
RSHF	Room sensible heat factor
TOR	Tons of refrigeration (3.5 kW)

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