ISSN: 2640-5571

Research Article

Advances in Nanoscience and Nanotechnology

Liquid Desiccant Air Conditioning System for Flat Plate Solar Collector with Nanofluids Regenerator

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Submitted: 27 Dec 2021; **Accepted:** 25 Feb 2022; **Published:** 29 Apr 2022

Citation: *Geleta Fekadu Daba .(2022). Liquid Desiccant Air Conditioning System for Flat Plate Solar Collector with Nanofluids Regenerator. Adv Nanoscie Nanotec 6(1), 01-09.*

Abstract

This paper deals with liquid desiccant air conditioning using solar flat plate collector. The problem in the use of liquid desiccant air conditioning is energy utilization for regeneration, corrosiveness and carryover. To overcome these developments of a dehumidifier for corrosion- resistant and solar regenerated are advised. A dehumidifier is made of stainless steel tubes of 316L type and stacked in aluminium fins to maintain the desiccant solution temperature. In this experiment, calcium chloride solution ($CaCl_2$-H_2O) is used. The solar flat plate collector is used for heating water using closed-loop of thermosiphon as regeneration. The flow rate for air is fixed at 10CFM and concentration of calcium chloride is 35% by mass is used. The inlet parameters considered are in the experiments solution volume flow rate, inlet temperature, inlet relative humidity, regeneration temperature, and desiccant solution temperature. The performance parameters are the absolute humidity reduction, outlet temperature and dehumidifier and enthalpy effectiveness. The experiments show that for a fixed Ta, inlet and RH% as solution volume flow rate increases, there is increase in absolute humidity reduction. The temperature of the dehumidified air is reduced compared to that of inlet air, if this air is passed over the pad used for the evaporating cooler. It is seen that the increase in relative humidity from 68.88% to 92.8% for the flow rate of 20 L/min and fixed inlet air temperature, increases absolute humidity reduction from 5.56 to 13.3 g/kg. The increase in solution temperature reduces the absolute humidity reduction due to solution vapor pressure increases and dehumidifier effectiveness. When the solution temperature changes from 31.5 to 34 ^{0}C, there are reductions in the absolute humidity reduction and dehumidifier effectiveness by 34.4% and 13.04% respectively.

Keywords: Solar Flat Plate Collector (SFPC), Al_2O_3-Water Nanofluid, Liquid Desiccant, Dehumidifier, Evaporative Cooler, Absolute Humidity, Effectiveness Nomenclature

Abbreviation/Symbol	***Description***
A/c	Air conditioning
Al_2O_3	Aluminium oxide
AHR	Absolute humidity reduction
$CaCl_2$	calcium chloride
$CaCl_2$-LiCl	a mixture of calcium-lithium chloride
CFM	cubic feet per minute
RH	Relative humidity (%)
T	Temperature (^{0}C)
X	Concentration (%)
$W\ H_20$	mass of water

Greek Letters

ρ	density (kg/m^3)
φ	Volume fraction of nanofluid

Subscripts

a,in/out	Air, inlet/outlet

Introduction

From the last few decades, there is a tremendous increase in energy demand and scientific developments observed in the solar energy field [1]. The energy sector plays an inevitable role in the development of economy [2]. The widening gap between demand in energy by consumer and supply is increasing [3]. Hence, it makes fossil fuel scarce. Nowadays, a global concern is on the exploitation of fossil fuel which leads to global warming and environmental pollution [4,5]. These factors have a motivational concern by researchers in the world for searching eco- friendly energy resources; mainly renewable energy [6,7]. There are various renewable energy resources such as solar energy, bioenergy, hydrogen energy [8]. and geothermal energy [9,10]. The solar technology nowadays emerges as a source for the conversion of the solar energy into thermal and electrical as of being an inexhaustible and eco-friendly technology using solar collector and panel [11]. Investigator estimates that the intensity of solar energy falling on the earth per hour can meet world energy demands per year [12]. However, the solar energy technology acceptance is not clear due to high operational cost and low efficiency. Among renewable energy, solar energy is the major exploitable resources in the present-day [13]. It is a very suitable, cheap source for heating activities and does not require energy-transportation cost. The numerical and experimental investigations for internally cooled dehumidifier with cross-flow type were carried out by [14]. They had built a thin plate membrane coated by epoxy to jeopardize or avoid corrosiveness for lithium chloride salt solution. The experimental results are very closely comparable with the results of the numerical model. The dehumidification by the lithium chloride and lithium bromide was compared; the dehumidification by lithium chloride attained better result than that of the lithium bromide. To cool the outlet temperature, a sensible cooling unit is required after dehumidified air; this could be in the form of direct or indirect evaporative cooler [15]. to maintain the desired comfort level. The moisture absorption occurs when the liquid desiccant has lower than that of the process air and the condition continues until the equilibrium is attained [16].

The "Nano" and "energy" are the timely important terms, not for the scientific area but in the life of day to day activity. During last decades, researchers are attempting to promote and apply the concept in the field of nanotechnology in the various power and energy systems mainly electric generators, batteries, fuel cell and most importantly in the solar cell [17,18].

Also, as the advancement of the field in the nanotechnology arises, the indigenous heat transfer fluid arises too. Nanofluids, a novel of fluid which consists of a base fluid and nano- sized particles, varying from 1 to 100nm and suspended within them [19]. These are generally metals and non-metal oxides. Now, Nano fluids are considered as a kind of heat transfer fluid due to their enhanced properties of thermal conductivity. Lately many scholars are searching in the use of the nanofluid as a working fluid in the solar collector areas [20, 21]. Besides, there have some limitations in the Nano fluid such as cost of preparation is high, and the stability issues. Numerous efforts have been done to enhance the applications of nanofluid in energy system such as devices based on solar energy, thermal, and cooling management of electronic equipment, absorption system, grinding and drilling, cooling and heating of buildings and so on. Many researches have been carried out in these areas and indicate that adding the nanoparticle to the base fluid (water or ethyl glycol) can enhance the solar collector efficiency up to 50% [22, 23]. [24] experimentally investigated the effect of different nanofluids on the efficiency of solar thermal collectors and found a 5% enhancement for the nanofluids as the absorption medium is obtained. [25]. have investigated the effect on thermal conductivity by changing the heat transfer coefficients. [26, 27]. evaluated the overall heat transfer coefficient and thermal conductivity of Al_2O_3-water-based nanofluids with various concentrations of nanoparticles in the base fluids. They found that 3% of nanofluids have optimum performance and with an overall heat transfer coefficient of 16% as compared base pure water.

Desiccants

Desiccant is a substance that exists as natural or synthetic, can adsorb water vapor from process air and also desorb easily with low-temperature heat sources. Desiccants are classified into liquid and solid desiccants [28]. The desiccants cooling system is taken as environmentally eco-friendly air conditioning technology without imposing shortcomings energy due to overcooling and reheating. The liquid desiccant system is considered as economical, lower air pressure drop, dust removal by filtration, flexible in utilization for the use of low-grade energy, higher dehumidification, and 1350 MJ/m^3 energy storage capacity as compared to solid desiccants [28, 29]. Air conditioning and ventilation based on desiccant materials remove the moisture by a natural process called sorption. The sorption process includes the adsorption and absorption in which an interaction exists between the sorbent and sorbate molecules through intermolecular interactions. The desiccant dehumidification is taken as the main component in the desiccant air conditioning system. So, the design of desiccant dehumidification for the replacement of the conventional A/C is paramount. One of the problems existing in the use of liquid desiccants as air conditioning is that saline salts are corrosiveness to metals and also leads to carryover of the solution, and reduce the level air quality and adds cost. Once the desiccant is used, there is a need to remove moisture from the desiccants materials to function the system cyclically. Figure 1 shows the basic concept of desiccant air conditioning technology.

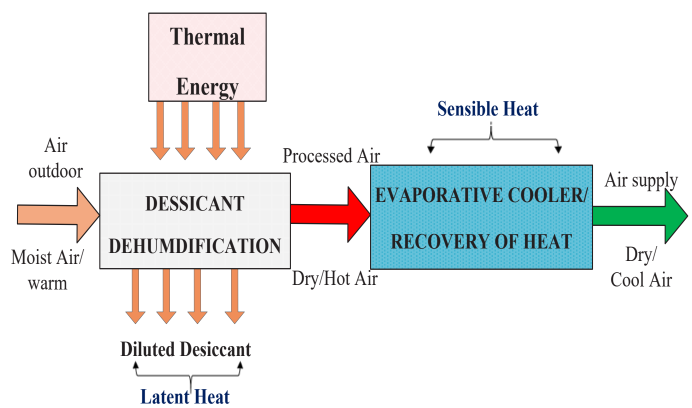

Figure 1: Physical principle for desiccant as air conditioning (A/C)

The present mainly focused on using of marquise-shaped channeled flat plate solar collector for heating water and nanofluids.

The thermosiphon solar energy is used for the regeneration of the diluted liquid desiccant. The liquid desiccant is used as air conditioning to make the room comfort by reducing the moisture contents from process air. This type of arrangement is important, where the intensity of solar energy radiation more and humidity is high.

Materials and Methods

Preparation of Nano Fluid

The first step is preparation of nanofluids, Al_2O_3–water nanofluid is prepared through the two- step method (Al_2O_3 nanoparticle, the average diameter is about 20 nm, the base fluid is distilled water). Two-step methodology is that the most generally used methodology for getting nanofluids ready as shown in figure 2. A nanoparticle employed here is made as dry powders by chemical or physical ways. Then, the nano-sized powder is distributed into a fluid within the second process step with the assistance of intensive attraction agitation, supersonic agitation, homogenizing, and ball edge. Two-step methodology is that the most economic methodology to supply nanofluids in large scale, as a result of Nano powder synthesis techniques have already been scaled up to industrial production levels.

As a result of the high expanse and surface activity, nanoparticles tend to combine. The necessary technique to reinforce the steadiness of nanoparticles in fluids is to use surfactants. However, the practicality of the surfactants beneath warm temperature is additionally an enormous concern, particularly for high-temperature applications. Due to the problem in obtaining ready stable nanofluids by one step methodology, many advanced techniques are developed to supply nanofluids, together with one step methodology. Measured masses of nanoparticles are dispersed into an appropriate base liquid of 100 ml to prepare nanofluid samples of required (0.1%). The resulting of synthesized nanofluid is calculated by using equation (1) [30]. The volume fraction for the experiment used is calculated by Eq.

(1) and mixed by 3.96g of Al_2O_3 nanoparticles used in for 1000g of base water.

$$\emptyset = \frac{\left(\frac{w}{\rho}\right) Al_2O_3}{\left(\frac{w}{\rho}\right) Al_2O_3 + \left(\frac{w}{\rho}\right) H_2O} \qquad (1)$$

Where is the volume fraction of the nanofluid, is the density of the aluminium nanoparticles, is the density of the base fluid (pure water), is mass of water, is mass of nanoparticles. The mixed property of the volume fraction for the experiment is indicated in table 1.

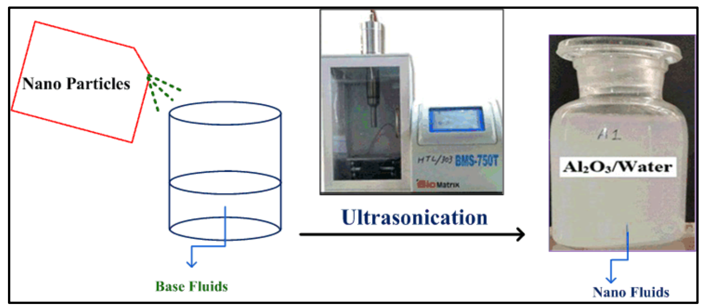

Figure 2: Set-up for Preparation of Nanofluids

Table 1: Thermo-physical properties of nanoparticle (Al_2O_3-H_2O) and base fluid (water)

Particle & base fluid	Average size particle (nm)	Density (kg/m³)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)
Al_2O_3	20	3960	773	40
Water	-	997.1	4179	0.606

Mass Concentration Calculation

The experimental procedure has been done by calculation of the maximum possible concentration of calcium chloride and it is found to be 74.5%, and possible solution concentration without crystallization is 35% - 45% used for experiments as the crystallization is one of the prominent problems. The selection of the calcium chloride powder is based on the low regeneration temperature, inexpensiveness and availability. A 35% by mass solution of calcium chloride solution is made and stored in a storage tank at different experiments used. The powder of calcium chloride is supplied and measured in kg and water in litre (l) as indicated in Table 2.

Table 2: The mass concentration used for the experiment

Concentration (X)	Mass of calcium chloride salt (kg)	Mass of water (l)
35(%)	10	18.57

Experimental Procedure

A novel internally cooled-liquid desiccant dehumidifier has been fabricated for handling latent heat as shown in Figure 3. The overall dimensions and materials used for dehumidifier, tanks and fins are given in Table 3.

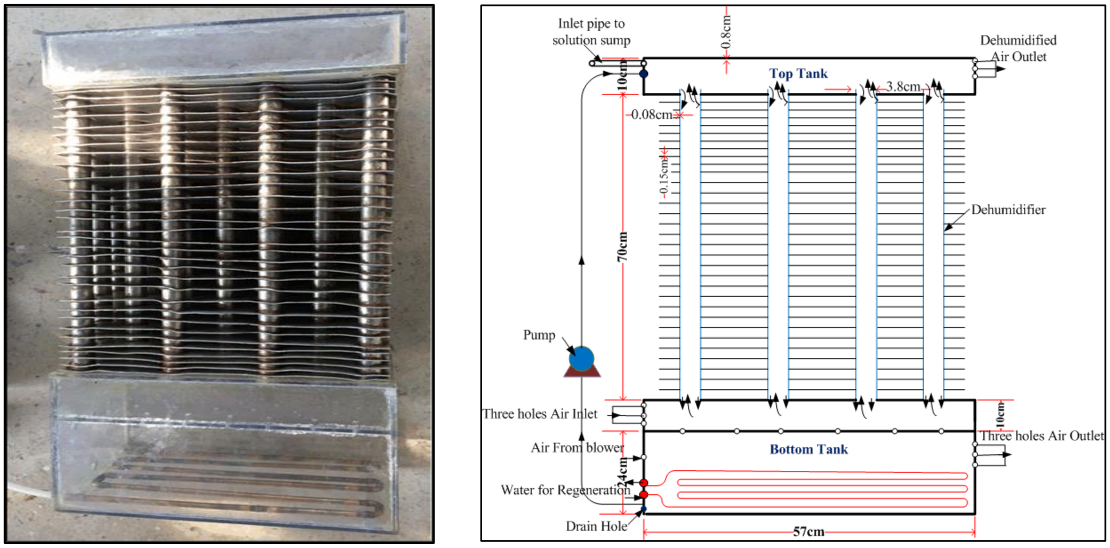

Figure 3: A dehumidifier with fins, storage tank, and regenerator coil regenerator coil and its schematic line diagram

Table 3: Dimension and Materials for Dehumidifier, Tanks and Fins

S.No.	DEHUMIDIFIER	
1	Material used	Stainless steel 316L
	Number of tubes	25
	Outer dia.	3.8cm
	Inner dia.	3.72cm
	Thickness	0.08cm
	Height	71cm
	Arrangement	Zig-zag
	Pitch distance from center	7.6cm
	FINS	
2	Material used	Aluminum sheet
	Dimensions	54X30X0.15cm (thickness)
	Number of fins	Thirty-two (32)
	Arrangement	Parallel
	Gaps b/n sheets	2cm
	Tanks	
3	Material made	Perspex sheet
	Thickness	0.8cm
	Top tank	57x32x10 cm
	Bottom Tank	57x32x34cm
	Compartment	Perforated Perspex sheet
	copper coil for regeneration dia.	0.95cm

Experimental Set-Up

The experimental set up is assembled and ready for the experiment after checking all the leakages of the system as shown in Figure 4 and Figure 5 for the actual photograph and the schematic line diagram.

Experimentation

The experiments for the liquid desiccant air conditioning system are conducted with solution of calcium chloride. The internal evaporative cooler is ready to circulate cooled air on the surface of the channel of the dehumidifier. The inlet air flows through the blower to the sprayer to humidify and heat the air by the constant temperature bath. The flow is checked for the steady-state by controlling the flow rate. The solar collector of the thermosiphon is used for heating the water for regeneration and waiting for temperature greater than 60 ^{0}C. After the steady-state circulation, the experiment is done for different mass flow rates of calcium chloride solution for consecutive days approximately at the same time and averaged it to analyze the results for comparisons.

The data logger is used to record the temperature at a different position and the thermo- hygrometer is used to take readings at inlet and outlet temperatures and relative humidities. Finally, the data is used for different calculations and analysis for the experiments performed.

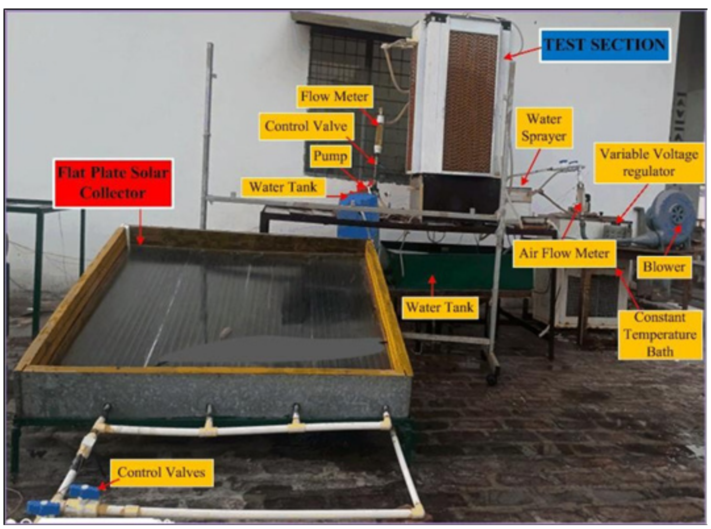

Figure 4: Actual Experimental set up.

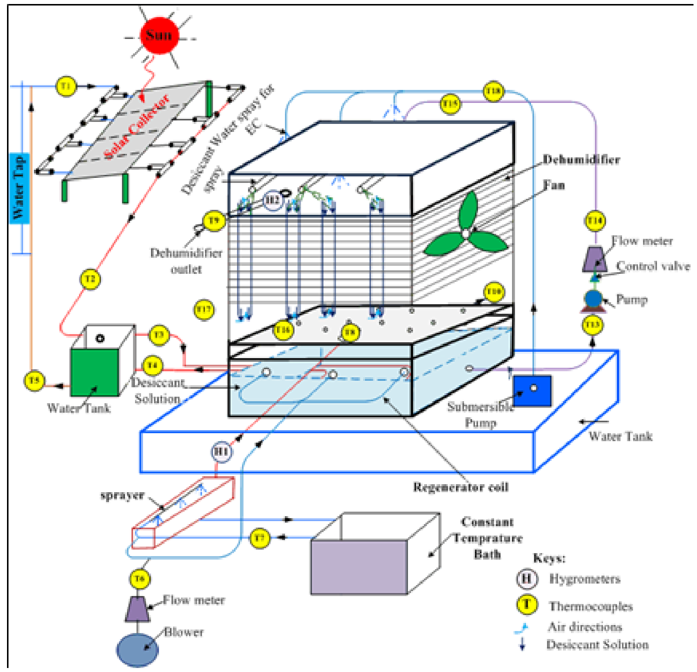

Figure 5: Schematic line diagram for the experimental setup.

Results and Discussion

The experiment has been performed for several times in consecutive days and each day the experiment has been conducted at a different solution volume flow rates of 14 L/min, 16 L/min, 18 L/min, and 20 L/min.

Effect of Volume Flow Rate of The Desiccant Solution on Absolute Humidity Reduction

The experiments are conducted several times and the fixed input parameters are solution concentration of 35% and the air mass flow rate of 0.00489kg/sec. The air temperature and the relative humidity of the date are maintained at steady-state and the experiments are performed for the solution volume flow rates of 14 L/min, 16 L/min, 18 L/min, and 20l L/min. Then, the absolute humidity reduction of the dehumidifier is evaluated for the experiment to see the effect of varying the volume flow rate on absolute humidity reduction. In Figure 6, T_a, in and RH (%) are fixed and taken as 35 ^{o}C and 68.4% respectively and the solution volume flow rate varies from 14 L/min to 20l L/min with the increased rate of 2 L/min. It is observed that the absolute humidity reductions are increased with the volume flow rates and these values are 5.99g/kg, 6.11g/kg, 6.22g/kg and 6.8g/kg respectively at above flow rates.

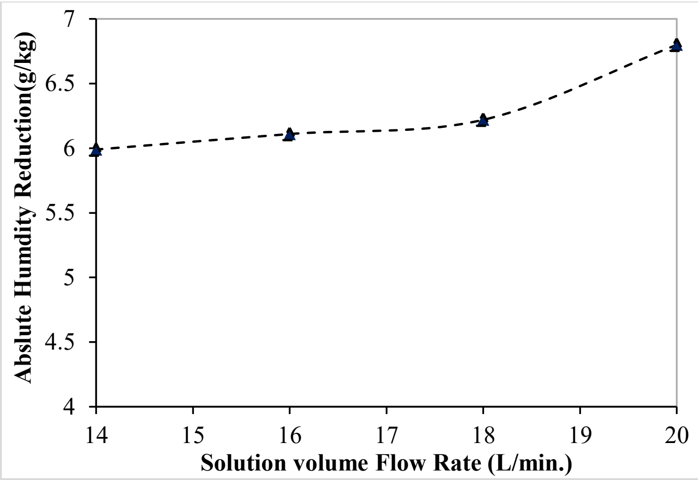

Figure 6: Effect of solution volume flow rate on absolute humidity reduction at inlet RH of 68% and inlet DBT of 35.0 0C

Effect of Solution Flow Rate on Outlet Temperature of Air from The Dehumidifier for the different solution flow rates, Ta, in and RH (%) are fixed and the variations of T_a, out are studied during the dehumidification. In Figure 8, T_a, out is lower than T_a, in for the solution volume flow rates of 14 L/min, 16 L/min, 18 L/min, and 20 L/min for the experiments.

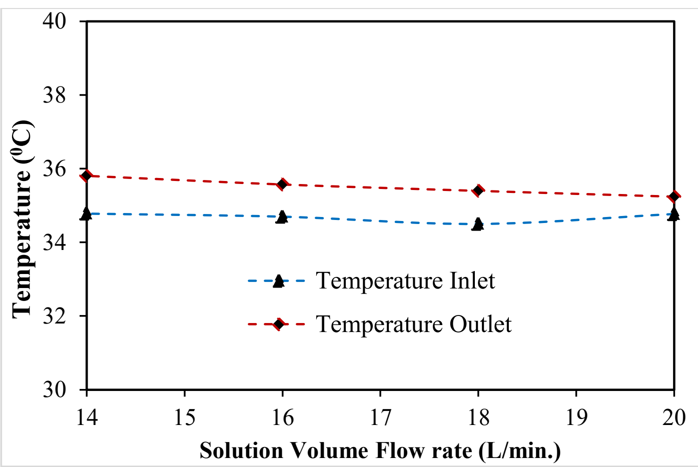

Figure 7: Effect of solution volume flow rate vs Ta, out during the dehumidification at inlet RH of 70% and inlet DBT of 35.0 °C

Figure 7 shows that T_a, in is lower than the T_a, out for the same flow rates used. This shows the outlet temperature increases after the dehumidification due to the exothermic reaction of the calcium chloride solution with the air. The outlet temperature needs to cool sensible to get a lower temperature than the inlet temperature after dehumidification. So, it is cooled sensibly by passing through the evaporative cooler as seen from Figure 9 the outlet temperature is lower than the inlet temperature due to this cooling arrangement.

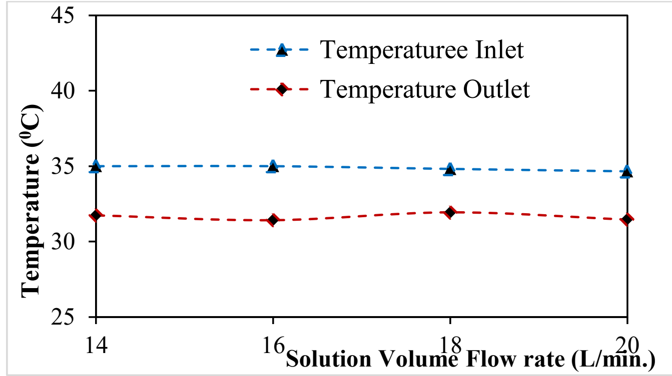

Figure 8: Effect of solution volume flow rate on Ta, out during the dehumidification at inlet RH of 68% and inlet DBT 35.0 °C

Effect of Inlet Air RH (%) on Absolute Humidity Reduction

The experiments are conducted to evaluate the effect of RH (%) on the absolute humidity reduction for a fixed Ta,in and solution volume flow rate. Figure 10 shows this phenomenon with the fixed Ta, in and solution volume flow rates of 35.0 0C and 20L/min respectively. When the RH (%) varies from 68% to 92%, the absolute humidity reduction increases from 5.56g/kg to 13.3g/kg for the solution volume flow rate

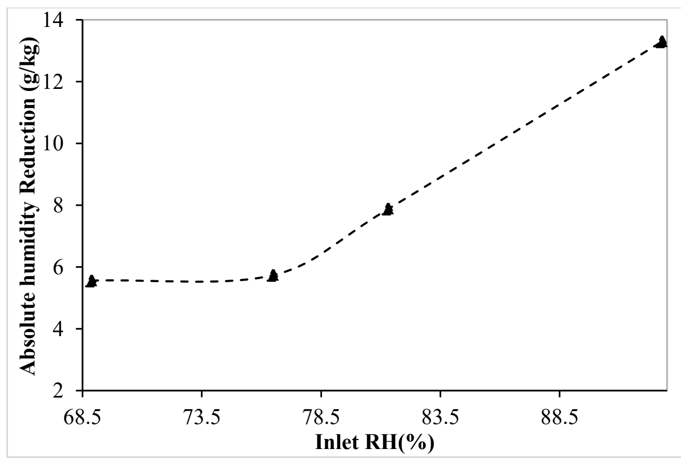

Figure 9: Effect Inlet RH% on absolute humidity reduction at Ta, in of 35.0 °C, and solution flow rate of 20 L/min.

Generally, for a fixed Ta, in, the increase in RH (%) indicates the increase in the absolute humidity reduction for a regeneration temperature of above 60.0 ⁰C. The increase in RH (%) increase the vapor pressure difference between air and solution surface, thus leading to the increase in moisture removal rate which tends to increase in absolute humidity reduction.

Effect of Inlet and Regeneration temperature on absolute humidity reduction

From the experimental findings, the T_a, in, and T_3 regeneration temperature are evaluated for the performance on the absolute humidity reduction. Figure10 indicates that as the T_a, in increases from 30.5 °C to 32.7 °C, the absolute humidity also increases from 3.84g/kg to 4.82g/kg.

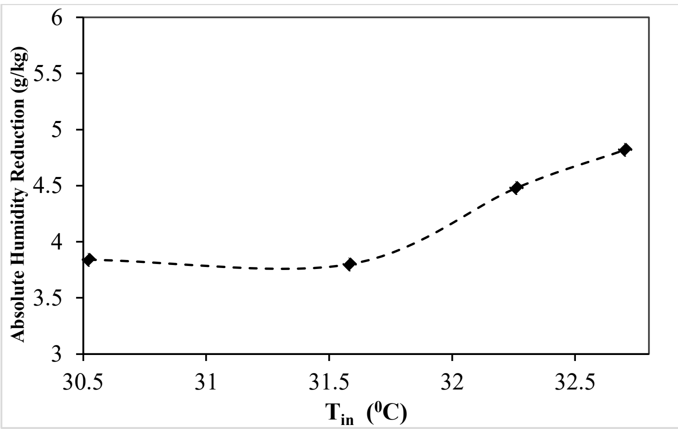

Figure 10: Effect of T_a, in an Absolute humidity reduction at 20 L/min. and 71% RH

Figure 11 shows the effect of regeneration temperature on the absolute humidity reduction. As the regeneration temperature increases from 45.0 0C to 60.0 0C, the absolute humidity increases from 9.76g/kg to 14.47g/kg. The increase in regeneration temperature removes more moisture from the solution surface; hence the absolute humidity reduction becomes more effective.

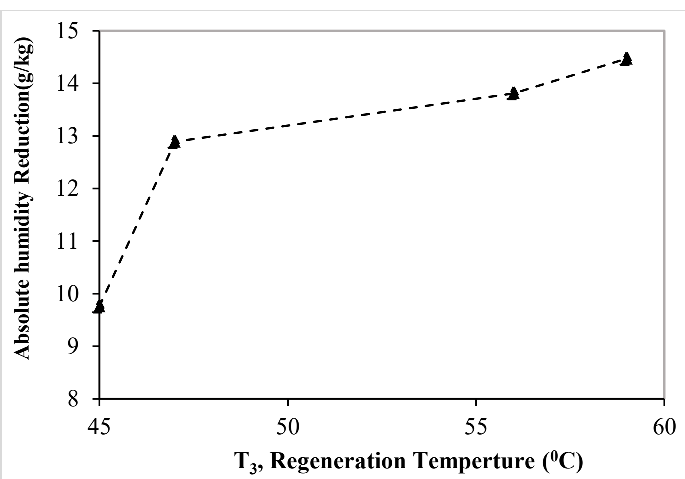

Figure 11: Effect of regeneration temperature on absolute humidity reduction at 20 L/min, 35.0 0C and 88% RH

Effect of Solution Temperature On Absolute Humidity Reduction And Dehumidifier Effectiveness

Figure 12 shows that as the solution temperature increases from 31.97 0C to 34.24 0C the absolute humidity reduction decreases from 11.23g/kg to 7.36g/kg (which is about 34.40% reduction and dehumidifier effectiveness decreases from 0.92 to 0.80 respectively. This increase in solution temperature rises the vapor pressure of the desiccant solution and reduces the maximum transfer potential between the desiccant solution and the moisture in the air.

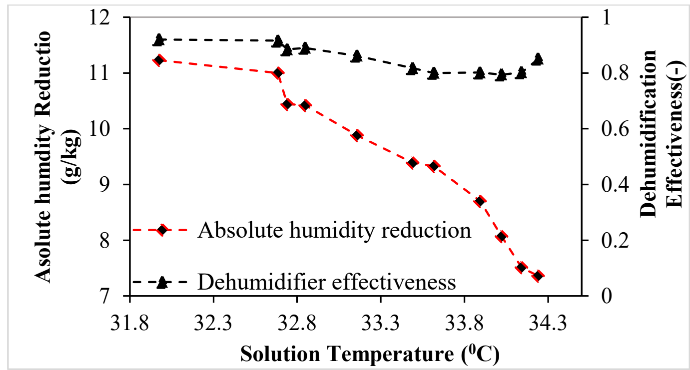

Figure 12: Effect of solution Temperature on absolute humidity reduction and dehumidifier effectiveness at 20 L/min, Ta, in = 35.0 ⁰C and RH (%) =88%

Figure 13 show that the dehumidifier and enthalpy effectiveness increase few cases. This phenomenon is due to the variation of both numerator and denominator in the definition of effectiveness. The vapor pressure of the solution is a function of solution temperature (Ts) and solution concentration (X) when the numerator is high the graph is increasing and when the denominator is more the graph is decreasing.

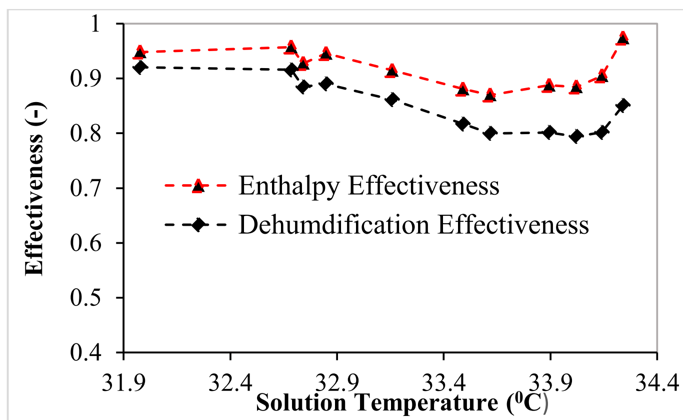

Figure 13: Effect of solution Temperature on Enthalpy effectiveness and Dehumidification effectiveness at 20 L/min, T_a, in=35.0 ⁰C, and 88% RH

Comparison with other Results

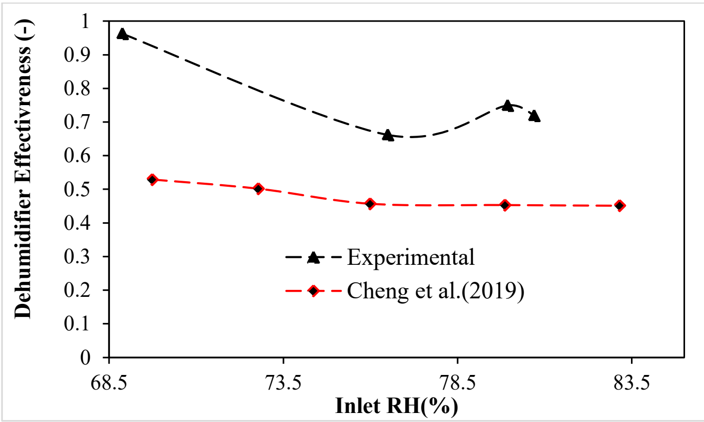

Figure 14: Dehumidification Effectiveness Vs Inlet RH (%) with other literature at 20L/min, and T_a, in=35.0 ⁰C

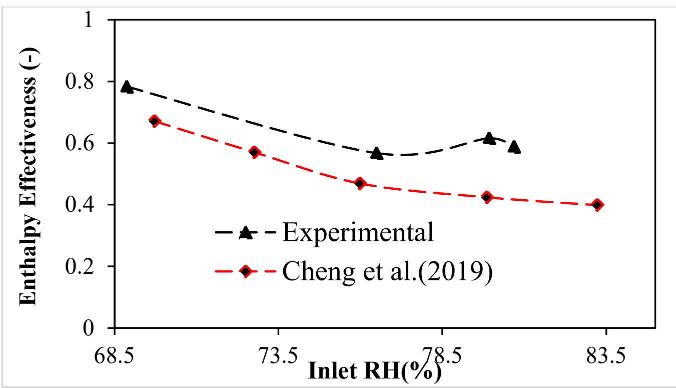

Figure 15: Enthalpy Effectiveness Vs Inlet RH (%) with other literature at 20 L/min, and $T_{a, in}$= 35.0 ⁰C

Figures 14 and Figure 15 show the comparison of our effective results with those of Cheng et. al. [31]. Both the dehumidifier and enthalpy effectiveness obtained in the present study are higher than those of the literature. This may be due to different type of desiccant used; our case is for liquid desiccant of calcium chloride ($CaCl_2$), the literature is for lithium chloride ($LiCl_2$) and also may be due to the different setups for regeneration.

Conclusions

The study of liquid desiccant air conditioning system using solar collector is done first by designing and fabricating special type of solar collectors. The internally dehumidifier of evaporative cooler type is designed and fabricated and then conclusion is given. So, the marquise shaped channeled flat plate collector is used for heating water using closed-loop of thermosiphon which is used for regeneration of the diluted liquid desiccant solution. The dehumidifier of a counter flow air to the solution is designed. The flow rate for air is fixed at 10CFM and the concentration of calcium chloride used for the entire experiment is 35% by mass. The inlet air is humidified and controlled by a constant temperature bath to maintain the inlet conditions. The inlet parameters are solution volume flow rate, inlet temperature, inlet relative humidity, regeneration temperature, and solution temperature.

The experimental results show that the absolute humidity reduction increases with the increase in solution volume flow rate for the fixed Ta.in and RH (%) due to increase in the surface contacts between the solution and air.

For a fixed inlet Ta, in and RH (%) for the particular solution volume flow rate, Ta, out is higher than Ta, inlet due to the exothermic reaction between the solution and air and hence sensible cooling is mandatory to cool the Ta, out. Here we have used cooling water of evaporating cooler for this purpose for some cases.

The increase in relative humidity from 68.4% to 92.8% for a fixed Ta, in increases the absolute humidity reduction from 5.56g/kg to 13.3g/kg for 20L/min solution flow rate. The increasing RH (%) caused the increasing vapor pressure difference between air and solution surface, thus leading to an increase in moisture removal rate.

From the experimental findings, as the temperature of the solution increases from 31.97 ⁰C to 34.24 ⁰C the absolute humidity reduction decreases from 11.23g/kg to 7.36g/kg (i.e., 34.4% reduction) and dehumidifier effectiveness decreases from 0.92 to 0.80 respectively. The increase in solution temperature increases the vapor pressure of the desiccant solution and reduces the maximum transfer potential between the desiccant solution and the moisture in the air. From the comparison of our effectiveness results with those of [32], both our dehumidifier and enthalpy effectiveness are higher than those of the literature. This may be due to different type of desiccant used; our case is for $CaCl_2$, the literature is for $LiCl_2$ and also may be due to the different setups for regeneration.

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