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Investigations on Passive Solar Liquid Desiccant Regenerator in Indoor Simulated Summer Ambient Conditions

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***Abstract* – Liquid desiccant-based air conditioning (LDAC) system is a promising alternative air conditioning system among various thermally driven cooling technologies, which can help to alleviate burden on natural resources and the earth. The regenerator of LDAC systems utilizes thermal energy to remove water from the dilute LD solution to concentrate it. The effect of weather parameters like solar insolation, wind velocity, ambient temperature and system parameters like concentration on the performance of the regenerator is investigated in terms of regeneration rate and regeneration efficiency in literature. But there is a need to establish significance of each parameter on the performance with the help of a systematic experimental study. A 'passive solar' regenerator indoor test set-up required for such study is developed in the current work. Experiments were designed and carried out as per DoE principles. Regression analysis of full factorial study was done to understand the effect of various parameters on performance of the passive solar regenerator. It is observed that as independent parameters, solar insolation, concentration of LD and ambient temperature have significant effect on the performance of the solar passive regenerator. The pareto chart shows that solar insolation has the most prominent and positive effect on performance. This is followed by the concentration of LD, but the effect is negative. The insights developed in current work would help decide viability of using the passive solar regenerator for a given climatic condition and deciding the concentration range to be used in LDAC systems.**

***Keywords* – Air conditioning; green technology; renewable energy technologies; solar thermal energy; sustainable development.**

Nomenclature		
I	Solar irradiance	W m^{-2}
V_w	Wind speed	m s^{-1}
T_a	Ambient temperature	°C
x	Concentration of liquid desiccant	wt. %
$\dot{m}_w$	Moisture removal rate of water	mL m^{-2} h^{-1}
η_{reg}	Regeneration efficiency	%

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1. INTRODUCTION

1.1. Background

Demand for air conditioning is rising exponentially due to improving economic conditions of large population of the world, growth of built-up space, changing lifestyles of people and higher comfort expectations. Most of the air conditioning systems use vapor compression refrigeration technology which needs electrical power to run. This has resulted in issues like higher peak demands for electrical power and higher direct and indirect emissions of greenhouse gases as well as other pollutants [1]–[4]. The above issues can be alleviated by developing thermally activated air conditioning technologies, which use heat as the main source of energy rather than electrical energy [5]–[7].

1.2. Liquid Desiccant-based Air Conditioning System

Out of various thermally activated air conditioning technologies, liquid desiccant-based air conditioning (LDAC) systems are very attractive due to their adaptability for solar thermal energy [8]. In LDAC systems, the dehumidifier provides cooling of air (latent cooling in particular) using concentrated LD solution. The LD solution gets diluted there by absorbing moisture. The regenerator of LDAC systems utilizes heat energy to remove water from the dilute LD solution to concentrate it and thus complete the cycle [9]. Heat is required to be supplied for the process of regeneration, either to air or to LD [10]. This heat is supplied many times before the regenerator if the regenerator is an adiabatic LD-air contacting device. It may be supplied in the regenerator if it is internally heated regenerator [11]. The air movement is created using a fan and LD spray is created using a pump. The LD spray in the air-LD contacting device distributes it uniformly over the contact media. As the fan and pump need electrical energy to run, such a regenerator may be called active regenerator or scavenging type regenerator.

Oyieke and Inambao (2011) presents a review of the coupled heat and mass transfer processes in the contacting devices used as regenerator or dehumidifier [12]. The packed bed design for regenerator is very effective and the studied the most in literature. The packed bed design of the contacting device is studied and the effect of various parameters on its performance is investigated in literature [13]–[15]. Factor and Grossman (1980) developed a computer model and performed experiments on such design of contacting devices [16]. They also raised concern related to high pressure drop of air across the packed bed. When solar thermal energy is utilized for LD regeneration, a separate solar air heater or solar water heater and heat exchanger are generally used. Parasitic power consumption can become high, which is not desirable for thermally driven air conditioning systems [17].

1.3. Solar Collector cum Regenerator (C/R)

The functions of solar energy collection and regeneration of LD may be combined in a single component in a solar LDAC system to reduce the number of components and complexity of system, which can also help to reduce parasitic power consumption. Open pan type, solar still type, natural convection type and forced draft type and evacuated tubes with heat pipe type solar collector cum regenerator (solar C/R) are used in literature [18]–[23]. In the solar still type C/R, the heating of LD is achieved by solar radiation passing through the glass cover and absorbed by the LD and blackened base. Water vapors produced due to heating of LD rise upward and get condensed on the inner surface of glass due to cooling provided to the outer surface of glass by wind. This condensate slides on the inclined surface of the glass and get collected in the channel provided at the end of glass cover. As the LD in the basin is stripped off water, it gets concentrated.

The condensate is distilled water which is also a useful product. No dedicated floor space may be needed for such solar C/R as it can be integrated with the terrace of a building.

1.4. Performance Evaluation of Solar C/R

The performance of the solar regenerators may be evaluated in terms of regeneration rate or moisture removal rate per unit area of collector, $\dot{m}_w$ (in mL m^{-2} h^{-1}) and regeneration efficiency η_{reg} (useful heat or heat utilized for water removal/solar energy input, unitless). The electrical coefficient of performance (COP_{el}) is also an important parameter which is defined as useful heat/electrical power consumption (kW/kW, unitless). It is observed that this parameter is often not considered or not reported in literature.

Effects of various weather parameters like solar radiation, inlet air humidity ratio and controllable parameters like air flow rate, concentration of LD, length of regenerator etc. on performance of solar regenerator is also studied in literature. Some of the above studies are experimental while others are simulation studies [24], [25]. Hawlader et al. (1997) carried out performance analysis of a glazed and unglazed tilted C/R [26]. They noted that glazed C/R is less sensitive to independent variables while the efficiency of unglazed collectors is on average 7.6 % higher than that of the glazed one. Tafesse et al. (2016) investigated performance of solar C/R using calcium and lithium chloride solutions. The area required for operating unit cooling load (1 TR i.e., 1 ton of refrigeration) of a desiccant cooling system (at lithium chloride concentration of 0.4 and in month of May) was found to be 10.2 m^2 [27], while Mehta et al. (2021) found it to be 3.7 m^2 per kW of cooling load for aqueous calcium chloride solution [28]. Very few researchers have carried out systematic parametric investigations to study the effects of various parameters experimentally, which would be possible only in indoor simulated experiments.

2. METHODS AND METHODOLOGY

2.1. Current Prototype Details and Objective

The current prototype of solar C/R (passive solar LD regenerator) aims at minimizing electrical energy for regeneration and avoiding dust contamination that would occur in unglazed as well as glazed natural convection or forced convection solar C/R which continuously use air from ambient. A regenerator covered with glass, which doesn't encounter ambient air and doesn't use any electrical energy is fabricated (see Fig. 1) in the current work. The gross area of this passive solar LD regenerator is 1 m^2. Aqueous solution of calcium chloride is used as LD as it is economical and easily available.

The basin of the passive solar regenerator is fabricated from aluminum plate and insulated with cera-wool and then covered in a wooden box. Its top is covered with sloping glass and has channel for collection of condensed water below the glass cover at the lowest edge. The LD can be filled up in the basin though inlet pipe provided on side of the basin.

Weather parameters like solar insolation, wind velocity, ambient temperature and system parameters like concentration, affect the performance of this solar regenerator. Parameters like air flow rate and inlet air humidity ratio are irrelevant in the current set up. Thus, the current work aims to find the effect of these four parameters: solar insolation, wind velocity, ambient temperature and concentration of LD on the performance of this passive solar regenerator.

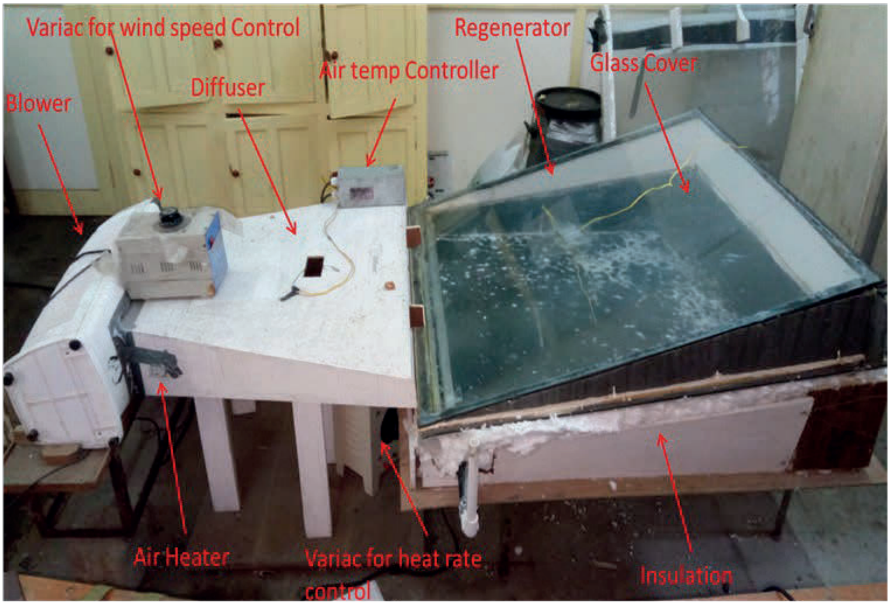

Fig. 1. Experimental set up for indoor regenerator testing with heat and wind generation facility.

2.2. *Provisions to Simulate Summer Ambient Conditions*

Simulation for heat generation by absorption of solar energy is obtained by heating LD (aqueous solution of calcium chloride). A serpentine shaped heater provided at the bottom back side of the basin, which heats LD through bottom of the basin. A variac is used to set the heating rate at desired value. Additional polyurethane foam (PUF) insulation is provided on the bottom side below the cera-wool insulation to ensure that almost all heat produced is used to heat LD and heat leakage to the ambient is minimal; perfectly providing measure of heat absorbed in the device. A horizontal fan with a rectangular shaped outlet along with a diffuser is used to simulate the wind. The fan speed can be adjusted to produce required wind velocity. An air heater is placed in the path of flow of air with a temperature controller to achieve desired air inlet temperature which simulates ambient temperature.

2.3. *Design of Experiments*

Seven different representative cities of India (Ahmedabad, Mumbai, New Delhi, Kolkata, Varanasi, Vishakhapatnam and Bhopal) were identified to decide the range of variation of the ambient parameters for the experimentation [29]. These cities represent diverse climatic conditions, not just for India but whole tropical and subtropical climatic zones worldwide. The values used are for the months of March, April and May; while the time considered is 09:00 am to 05:00 pm, when a significant amount of solar radiation is available for effective regeneration. Three levels of the four parameters; solar insolation, wind velocity, ambient temperature and LD concentration are used (see Table 1). These three levels provide realistic low, mid and high values of those parameters as per climatic conditions pan-Indian subcontinent.

TABLE 1. LEVELS OF PARAMETERS FOR FULL FACTORIAL STUDY

Parameter	Unit thickness	Level 1	Level 2	Level 3
Solar insolation (I)	W m^{-2}	550	730	910
Wind speed (V_w)	m s^{-1}	0.8	3.35	5.9
Air temperature (T_a)	ºC	24	32	40
Concentration (x)	%	36	37.5	39

The full-factorial design is used to investigate the entire response surface formed by these four factors and to measure both main effects and interactions. A full-factorial experiment implies that all factor level combinations are tried. Since each factor was explored across three levels, the number of distinct combinations (experimental runs) is: $3^4 = 81$ (three levels for four factors). A three-level selection was considered because two levels only allow for estimation of linear effects, whereas three levels allow for the detection of curvature (non-linear responses) in the main effects and improve the ability to identify and interpret two and higher-order interactions.

In each experiment, parameters such as solar insolation, wind velocity and air temperature are set to the desired levels. The heating continues for 3 to 4 hours till steady state conditions are achieved, which is indicated by steady LD temperature in the basin. After achieving steady state conditions, heating continues for two more hours and parameters such as LD temperature, air temperature and mass of condensate collected are measured every half an hour and used for further calculations. The water collected is added back to the LD in the basin every half an hour after measurement to have constant concentration of LD in the basin throughout the experiment.

2.4. Instrumentation

The list of instruments used for measurement of various parameters and their details are provided in Table 2.

TABLE 2. SPECIFICATIONS OF INSTRUMENTS USED FOR EXPERIMENTS

Parameter	Instrument Name	Make and model	Accuracy
LD temperature	K type Thermocouple and digital indicator	Testo 176 T4	± 0.3 °C
Wind speed	Vane type Anemometer	Testo - 480	±(0.1 m/s, +1.5 % of measured value)
Air temperature	Thermistor	Rotronic (HL – 1D)	± 0.3 °C
Electrical Power	Digital Power Monitor	Meco-PS09	Precision- Class 1

3. RESULTS AND DISCUSSION

3.1. Analysis of a Representative Reading

One sample result chart is shown in Fig. 2, where the regeneration efficiency is plotted against the solar insolation at a particular concentration of LD and air temperature. It is clearly seen that as solar insolation increases, regeneration efficiency increases significantly. Low insolation and low wind speed are the worst cases, while high isolation and high wind speed are the best cases. Highest regeneration efficiency is 23.95 % at solar insolation equal to

910 W m^{-2} and wind velocity equal to 5.9 m s^{-1}. This means that the useful energy used for moisture removal is 218 kW (0.2395 × 910 W) and the regenerated LD can provide latent cooling at the same rate, i.e., 218 W in air dehumidifier of an LDAC system. Thus, an area of 4.6 m^2 of such solar regenerator would be required per kW of latent cooling to be produced by an LDAC system.

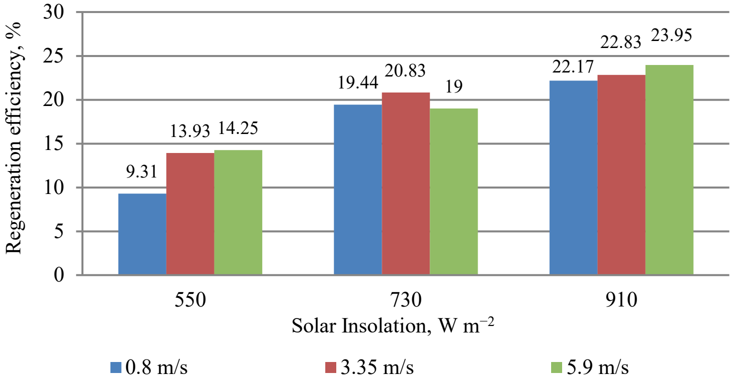

Fig. 2. Regeneration efficiency Vs. Solar Insolation at various wind speeds; 40 °C air temperature and 37.5 % concentration of LD.

3.2. Regression Analysis of Full Factorial Study

Results of the experiments were analyzed with Minitab software using general factorial regression model and confidence level equal to 95 %. It was observed that as independent parameters; solar insolation, ambient temperature and concentration of LD have significant effect on the performance of the regenerator as "p-value" for these parameters are below 0.05. The pareto chart is also used to determine the magnitude and importance of the effect of various factors on regeneration rate. In this chart, bars that represent the factors solar insolation, air temperature, concentration and interaction of wind velocity and concentration cross the reference line, that is 2.11 (Fig. 3). It is observed that the magnitude of solar insolation bar is the longest and thus has highest effect on regeneration rate, followed by concentration. The effect of wind velocity was found to be negligible. It was found that only two-way interaction of wind velocity and concentration has significant effect on the performance, while no three-way interactions are significant.

Main effect plot for parameters to be investigated is presented in Fig. 4. It can be observed that as solar insolation increases regeneration rate would increase, while on the other hand as concentration increases, regeneration rate decreases. As concentration of LD increases, it becomes more difficult to remove water from it due to higher vapour pressure depression. So, the regeneration occurs at higher temperatures, leading to higher heat losses and lower regeneration (water removal) rate. The air temperature can affect the performance in two different ways. Higher temperature of air can reduce overall loss from the solar regenerator due to lower temperature potential, while on the other hand it can also reduce the heat transfer from glass to air, obstructing the condensation of water vapour on the inner surface of glass. It is observed from the main effect plots that air temperature increases from 24 °C to 32 °C, regeneration rate increases while at higher air temperature regeneration rate decreases. The effect of wind velocity on regeneration rate is negligible.

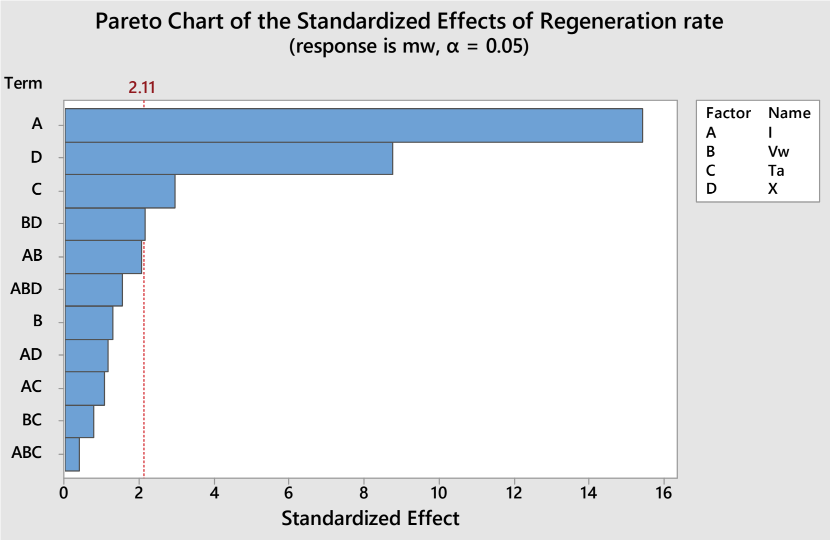

Fig. 3. Pareto chart of the standardized effects of regeneration rate (response is mW, α = 0.05).

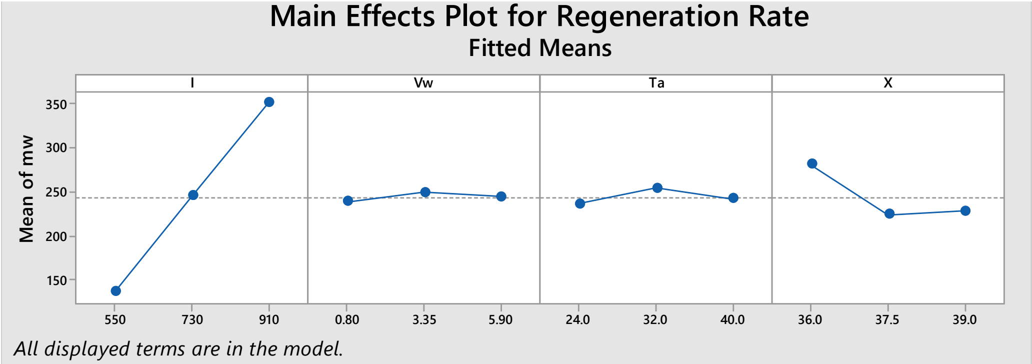

Fig. 4. Main effects plot for regeneration rate.

In case of regeneration efficiency also, solar insolation, concentration and air temperature are found to be significant parameters with weight reducing in that direction (see Fig. 5). Trends are also like regeneration rate. At higher value of solar insolation, rate of regeneration efficiency rise reduces, probably due to regeneration occurring at higher temperatures, leading to more heat loss (Fig. 6). Air temperature can have dual effect on regeneration efficiency as explained in case of regeneration rate. Similarly, as concentration of LD increases, it becomes more difficult to remove water from it due to higher vapour pressure depression. So, the regeneration occurs at higher temperatures, leading to higher heat losses and lower regeneration efficiency. Again, effect of wind velocity on performance is negligible.

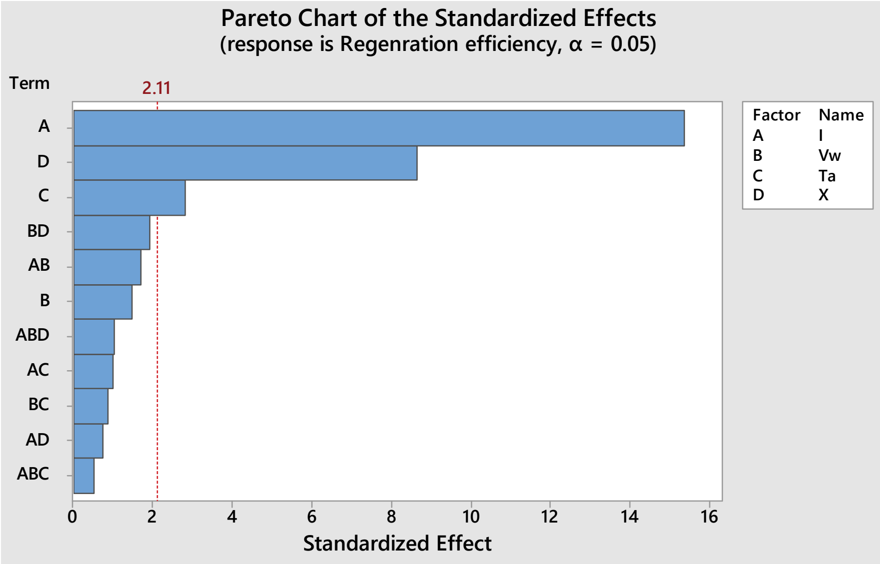

Fig. 5. Pareto chart of the standardized effects (response is regeneration efficiency, α = 0.05).

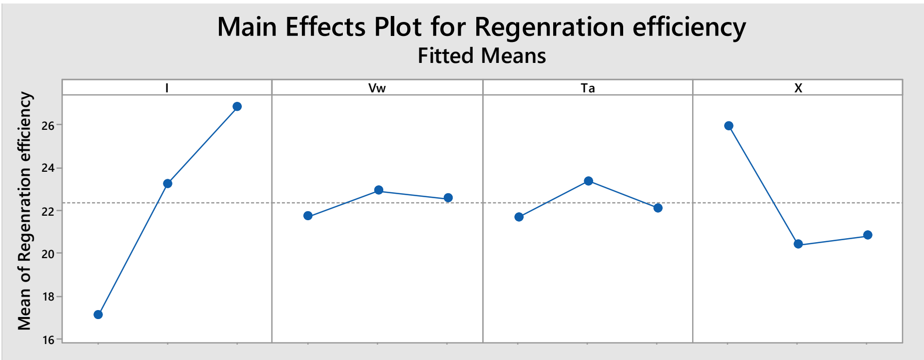

Fig. 6. Main effects plot for regeneration efficiency.

4. CONCLUSION

A 'passive solar' regenerator is developed and tested in the current study which can regenerate liquid desiccant solution without using any fan, or pump and using solar thermal energy as the only source of energy. Highest regeneration efficiency achieved is 23.95 % at solar insolation equal to 910 W m^{-2} and wind velocity equal to 5.9 m s^{-1}. When this regenerator (1 m^2 area) works under this condition, the regenerated liquid desiccant can provide 218 W latent cooling in dehumidifier. Thus, an area of 4.6 m^2 of such solar regenerator would be required per kW of latent cooling to be produced in dehumidifier. Regression analysis of full factorial study was carried out using Minitab^{TM} software which showed that as independent parameters, solar insolation, concentration of LD and ambient temperature have significant effect on the performance of the solar passive regenerator. Out of these, solar insolation has the most prominent and positive effect on performance, followed by the concentration of LD, but the effect is negative in case of the latter. The insights developed in current work would help decide viability of using the passive solar regenerator for a given climatic condition and deciding the concentration range to be used in LDAC systems using such a regenerator.

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