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Experimental Investigation of the Dehumidification Performance of a Novel Flat Plate Liquid Desiccant Dehumidification System

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ABSTRACT: Continuously rising energy demand for air dehumidification in space cooling and expeditiously reduction in conventional resources have stimulated the necessity for creating a novel and comprehensive range of sustainable energy technologies. Liquid Desiccant (L.D.) dehumidification systems are the most positive approach due to their lower energy consumptions, regeneration temperature, high COP, lower reactivation temperature. However, certain complications like desiccant residue with Process air (P_{air}), air side pressure drop, and low wetted walls need to be additional examinations. The L.D. dehumidification system examined in the present study comprised a multi-layer flat plate heat and mass exchanger between ambient P_{air} containing moisture and cooled and concentrated L.D. solution. The dehumidification system presented in the study, reports substantial surface contact and interval between L.D. solution and P_{air} and curtails the air side pressure drop and solution carryover with the P_{air} as the two exhibits an interfacial film contact despite direct intermixing which is a significant drawback of the packed bed and spray tower L.D. dehumidification systems. The system also delivers thorough film development of L.D. solution over the entire plates and getting the advantage over the falling film dehumidifiers. The weakened L.D. solution has been heated into a solution heating tank consisting of heating coils and further re-energized in the regenerator. Potassium format has been utilized as an L.D. material with a concentration of 40 % and 35 % by wt. Three sets of the velocity of $P_{air,}$ i.e., 0.9, 0.7, 0.5 m/s have been studied. Experiments were performed by changing the concentration of the L.D. solution and P_{air} velocities. The performance of the L.D. dehumidification system investigated in this study has been reported in terms of L.D. dehumidification effectiveness and moisture absorption rates (M.A.R.).

Keywords: dehumidification, regeneration, liquid desiccant, effectiveness, moisture absorption rate.

I. INTRODUCTION

To control the latent load is significant in space cooling applications mainly in industrial dehumidification, warehouses, multiplexes and grain stores. In such cooling applications, dehumidification generally occurs through conventional vapour compression systems (VCS). In these systems, P_{air} is cooled under its dew point temperature and again heat up to suitable room temperature for space cooling. This process makes the VCS system very much energy consumption and lowers its coefficient of performance [21]. Also, the efficiency of evaporative coolers is mainly governed by relative humidity ratio (RH) of the ambient air. Thus, the moisture level in the ambient air escalates the latent load on VCS as the evaporative coolers are inefficient in hot and humid climates like India. L.D. dehumidification provides a better solution to VCS as it separately controls the latent load and very much energy efficient. Desiccant materials possess great attraction towards the water vapour of the moist air. The difference in surface vapour pressure L.D. solution and moist P_{air} act as the driving force to move moisture content of P_{air} to L.D. solution. Also, re-energising of these L.D. materials needs low-grade energy which can be readily available in the form of solar energy. The advantages of L.D. systems like low regeneration temperature requirement, storage of diluted desiccant solution during non-sunshine hours and potential to eliminate harmful microbial contamination from P_{air} that can affect the health of an individual makes these systems more promising than VCS. Possibilities of using L.D. in dehumidification systems are first investigated by Bichowsky and Kelley [1]. Considerable research has been done from the last two decades in the area of LD air conditioning technology, and improvement could be seen in practising the commercialization of these systems. Fumo and Goswami (2002) experimentally investigated and modelled a packed bed absorber for mass and heat transfer with the use of polypropylene packing [5]. The authors found that LiCl desiccant solution wets the polypropylene packing in a non-uniform manner due to the high surface tension of the solution. Khoukhi *et al*., (2006) made an experimental investigation for the twin-rotor desiccant air conditioning system [10]. Liu *et al.,* [14]; Liu and Jiang [13] established an analytical correlation for the coupled mass and heat transfer for a packed bed desiccant cooling system by assuming a minimal change in the concentration of the desiccant solution and Lewis number used as one. Liu *et al.,* (2006) experimentally investigated the performance of a cross-flow dehumidifier by using structured packing and LiCl as a desiccant solution [15]. They represented the results in the form of moisture absorption rate and performance of the absorber for different values of the desiccant solution and Pair flow rates, temperatures and concentration of the desiccant solution and temperature and humidity ratio of P_{air}. A compilation of the experimental performance of various L.D. cooling systems has been made by Jain and Bansal (2007) [8] and represented an overview and present scenario of the cooling technology based on the L.D. system. Hwang *et al.,* (2008) suggested that the absorption cycle is better than the adsorption cycle and thermal COP of the L.D. system is higher than that of the solid desiccant system [7]. Wang *et al.*, (2009) made a comparison for performance and economic viability for different types of L.D. systems and found that carryover of desiccant droplets with the P_{air} is an unavoidable problem related to an L.D. system and should be removed with some appropriate methods [26].

For wetting the surface of the dehumidifier to increase the mass and heat transfer between the L.D. solution and the P_{air}, the surface tension of the solution plays a critical role in it. Lof investigated experimentally and suggested the earliest L.D. cooling system by using TEG as the material for a desiccant solution and found that the desiccant system performed more effectively in hot and humid climates [16]. A packed bed L.D. cooling system was developed by Patnaik *et al.,* (1990) with the use of LiBr as a desiccant solution and found that by using such systems, cooling capacities of 3.5 to 14 kW may be achieved [22]. Hassan and Hassan (2008) made a comparison for the performance of calcium chloride and calcium nitrate by taking the different composition of two. The results showed that low stability of calcium chloride could be enhanced by adding calcium nitrate in it and the composition of 20% and 50% by weight of calcium nitrate and calcium chloride respectively deliver maximum possible vapour pressure depression [6]. Kumar *et al.,* (2009) made an investigation for the performance of the L.D. system and developed new cycles for the enhancement of the system performance and studied the significance of various design parameters on the performance of absorber and regenerator. Mist filters are used to avoid the carryover of the desiccant droplet with room air, but it increased the pressure drop of incoming air which in turn required more maintenance [11]. Ertas *et al.,* (1994) determined the properties of LiCl and $CaCl_2$ with three different compositions (70-30, 50-50, 30-70%) respectively and found that 50-50 % composition of Lithium chloride and calcium chloride gives the best results for the dehumidification system [4]. Longo and Gasparilla (2005) made a comparison between the conventional L.D. solution of LiBr and LiCl with a novel L.D. solution of $KHCO_2$ and concluded that $KHCO_2$ has poor dehumidification performance but have better performance in regeneration process than LiCl and LiBr. They also proposed $KHCO_2$ as a better choice over conventional desiccant materials due to less corrosive and cost-effective qualities [17]. Kaushal and Sharma (2019) has been experimentally investigated a flat plate L.D. cooling system and optimized the operating parameters to enhance the performance of the system using Taguchi method [9, 25]. Mehla and Yadav (2017) has made an experimental investigation to utilise the evacuated tube collector to regenerate the solid desiccant wheel to optimise the system performance. They also made use of phase change material to further enhance the system effectiveness and COP [19]. Cuce (2017) experimentally investigated a novel liquid desiccant base evaporative cooling system by using two different process air velocity levels. They found average reduction in the process air temperature of 5.3ºC with an average dehumidification effectiveness of 63.7%. Several research works have been done in recent years to analyse the performance of different types of L.D. air conditioning systems [2]. Saman and Alizadeh (2002) proposed a new kind of absorber which is internally cooled with the help of evaporative cooler. In this system, the secondary air stream is used with water spray to cool the L.D. solution, which is flowing in the adjacent channel [23]. Niu *et al.,* (2010) analysed the effect of different ambient air ratios on the performance of the dehumidification system [20]. A new two-stage LD cooling system was developed by Xiong *et al.*, [27]. Thermal COP rises from 0.24 to 0.73 as compared to the conventional cooling system by using $CaCl_2$. Elmer *et al.,* (2016) experimentally investigated a novel integrated liquid desiccant system using HCOOK as L.D. and average COP of 0.72 has been achieved [3, 28].

According to the literature review, it has been found that most of the study has been conducted on the packed bed and falling film dehumidifier/regenerator in which solution falls vertically inside the dehumidifier in a falling film mode but no study revealed the performance L.D. solution flows horizontally over the flat plate of a flat plate dehumidifier. Also, the inclined flat plate in concern of dehumidification characteristics has received little attention. In the present study, dehumidification performance of moist P_{air} in a horizontally inclined flat plate dehumidification system using potassium format as an L.D. solution is studied experimentally. The objective of this study is to analyse the effect of different inlet conditions on the performance of the horizontally inclined flat plate dehumidification system.

Nomenclature

		Subscripts	
ω	humidity ratio (g/kg)	a	air
$\Delta\omega$	change in humidity ratio (g/kg)	in	inlet port
m	mass flow rate (kg/s)	out	outlet port
T	temperature (°C)	eqm	equilibrium
p	partial pressure (kpa)	d	dehumidifier
h	specific enthalpy (kJ/kg)	r	regenerator
φ	mole fraction of solute particle	s	solution
x	concentration of desiccant solution	*Abbreviations*	
ε	effectiveness	HCOOK	potassium formate
Å	rate of moisture absorption	LiCl	lithium chloride
		LiDS	LD solution

II. EXPERIMENTAL SET-UP AND METHODOLOGY

The prime components associated with the existing experimental test rig of L.D. dehumidification system are:

– The absorber
– The regenerator
– Solution heat exchanger
– Cooling tower

The absorber comprises of five flat plates which are divided into five channels. The channels are divided through baffles but interconnected with a small opening at the end of channels. The ambient air to be processed enters into the dehumidification unit through the inlet port with the help of an induced draft fan which has varying speed. The salt solution of potassium format having a concentration of 40% and 35 % by wt. is used as L.D. solution. Initially, the L.D. solution has been stored into the storage tank at a certain height and below atmospheric temperature with the help of cooling tower. After achieving the required temperature for the dehumidifier, the valve of storage tank opens, and the desiccant solution starts flowing through pipes and enters into the absorber. The L.D. solution flows over the plates of the absorber, making a thin film of 1mm at meagre flow rates of 0.080 kg/s. The ambient P_{air} flows over the desiccant solution film creating an interfacial contact between the two. The P_{air} then exits from the outlet port of the absorber and sent to the space to be conditioned. In this process, no intermixing of two films has been observed, which reduces the air side pressure drop related to packed bed dehumidifiers. Surface vapour pressure of the L.D. solution is preserved below the P_{air} so that vapours get condensed into the desiccant solution from P_{air}. Acrylic sheets have been used as the fabricating material for the dehumidification system to restrict the corrosive nature of the halide salts. The weakened L.D. solution collected at the other end passed through the solution heat exchanger and preheated before entering the regenerator. The regenerator has the same configuration as that of the dehumidifier. The weak L.D. solution after heated up by an electric heater in a storage tank flows through the regenerator. The storage tank for heating the solution has the capacity of 300 litres and consists of two electric heaters of 1 kW rating, which heat the solution to 60 °C. The concentrated LiDS leaving the regenerator also passes through the solution heat exchanger to precool and again cooled with the help of cooling water circulates through the cooling water cycle. Some other components of the dehumidification system are cold solution pump in the dehumidifier, hot solution pump for regenerator and one water pump for cooling tower, desiccant solution storage tanks. The schematic diagram showing the details of the experimental set up which is used in the present study for dehumidification and regeneration of P_{air} are given in the Fig. 1.

Fig. 2 reveal the schematic of the side view of the dehumidification unit. It shows the interfacial contact between the P_{air} and L.D. solution films. The thickness between two layers of the dehumidifier has been kept at 10mm for the proper contact between P_{air} and L.D. solution films. Sensors for measuring temperature and RH of P_{air} are placed at both ports of the absorber. The outlet temperature of L.D. solution is also monitored at regular interval of time.

Fig. 3 shows the graphic illustration of the set-up and process detail. In the dehumidification mode, the ambient moist air enters through inlet port with the help of an induced draft fan mounting at the outlet port of the system. The L.D. solution stored in an overhead storage tank flows through the pipes after the opening of the valve and starts spreading over the entire plate and makes a thin film. The flow rate of the solution is kept at a minimum possible level for the continuous flow of L.D. solution over the plates and also to provide P_{air} and solution in contact for a significant time. The main reason for the dividing of the flat plate into five channels is to offer a long path for the P_{air} flow.

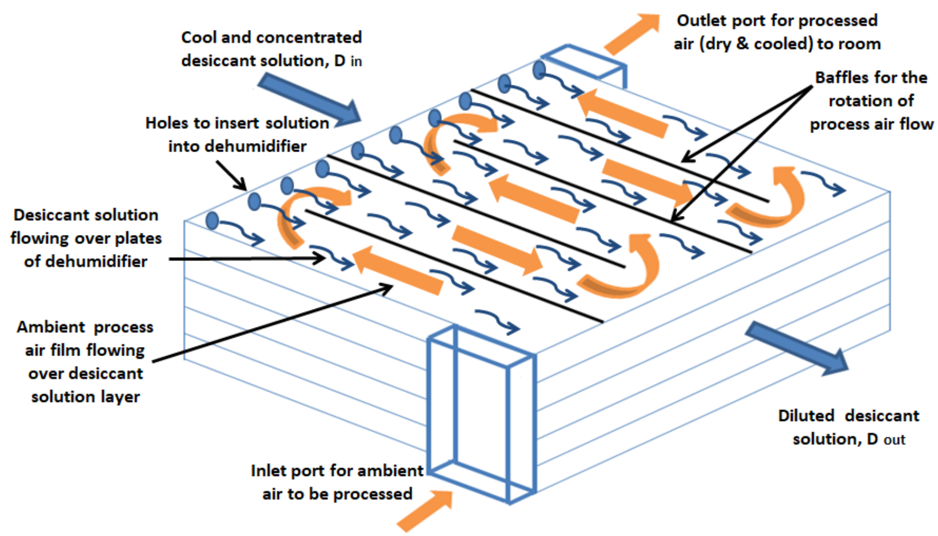

Fig. 1. Schematic diagram of multi-layer flat plate dehumidifier/regenerator.

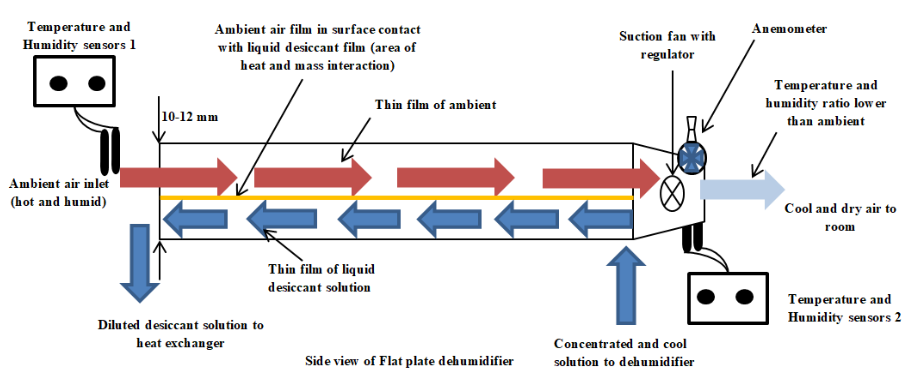

Fig. 2. Schematic diagram of a side view of the dehumidifier.

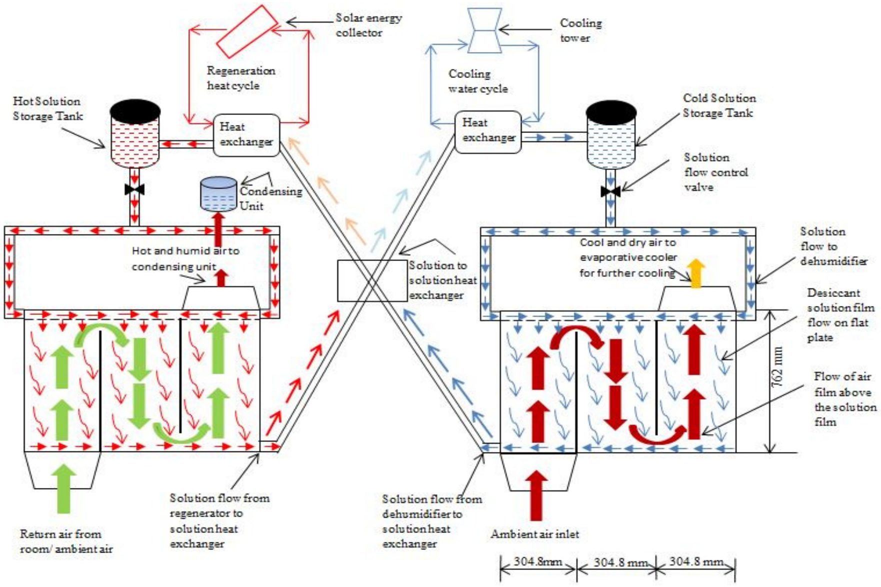

Fig. 3. Schematic diagram of the dehumidification system set-up.

III. MEASUREMENTS

The experiments were performed by adopting experimental research methodology. In the investigation, moisture removal rate (MAR) and effectiveness of the dehumidification system has been studied by varying the input settings to the dehumidifier. Two sets of experiments are done to examine the dehumidification effectiveness and MAR throughout the study. The variable input conditions include the L.D. solution concentration, the flow rates, temperature, and RH of P_{air}. Fig. 4 demonstrates the pictorial view of the complete experimental setup. All the Experiments are conducted in the thermal engineering laboratory of the mechanical engineering department at NIT-Kurukshetra, Haryana (India).

Fig. 4. Experimental setup for the dehumidification system.

IV. PERFORMANCE PARAMETERS

The parameters required to analyse the performance of the dehumidification system are mentioned below:

Dehumidification Effectiveness $(\varepsilon_d) = \frac{\omega_{a,1}-\omega_{a,2}}{\omega_{a,1}-\omega_{eqm}}$ (1)

where ω represents the humidity ratio of P_{air}. Sub fix *a,* 1, and *a,* 2 represents the P_{air} entering at and leaving the dehumidifier, respectively. In contrast, ω_{eqm} is the equilibrium specific humidity for the LiDS and can be calculated by

$$\omega_{eqm} = \frac{0.622\{p_s(\varphi,T)\}}{\{p-p_s(\varphi,T)\}} \quad (2)$$

Moisture absorption rate $(Å_d) = m_{a,1}(\omega_{a,1}-\omega_{a,2})$ (3)

The moisture absorption rate is the rate at which moisture is removed by L.D. solution from P_{air} in the dehumidification process, and $m_{a,1}$ is the mass flow rate of P_{air}. Vapour pressure for the LD solution at a particular concentration and temperature, is taken from [24].

V. MEASUREMENTS AND DEVICES

The properties of P_{air} and L.D. solution during the dehumidification process are measured using the instrumentation described in Table 1.

Table 1: Measuring instruments and accuracy.

S. No.	Device	Measured property	Accuracy
1.	Anemometer	Velocity of Pair	± 2 %
2.	Hygro-thermometer	RH and temperature of the Pair	± 2 %
3.	RTD PT 100	LD temperature	± 0.3 oC
4.	Hydrometer	LD specific gravity	± 0.05
5.	Stopwatch	Operational time	± 0.01 s
6.	Rota meter	LD flow rate	± 0.45 lpm

VI. UNCERTAINTY ANALYSIS

In the present study, the root means square method given by Kline and McClintock [18] is used for uncertainty analysis. The association for uncertainty examination has been described below:

$$\Delta x = [\left(\frac{\partial m}{\partial z_1}\right)^2 (\Delta z_1)^2 + (\frac{\partial m}{\partial z_2})^2 (\Delta z_2)^2 + \cdots + \left(\frac{\partial m}{\partial z_n}\right)^2 (\Delta z_n)^2]^{\frac{1}{2}} \quad (4)$$

Where x is the reliant variable and Δx is its total uncertainty and m is a function of the independent variable z_1, Δz_1 is the absolute uncertainty. The relative uncertainty is given by:

$$\frac{\Delta x}{x} = [\left(\frac{\partial m}{\partial z_1}\right)^2 \left(\frac{\Delta z_1}{y}\right)^2 + \left(\frac{\partial m}{\partial z_2}\right)^2 \left(\frac{\Delta z_1}{y}\right)^2 + \cdots + \left(\frac{\partial m}{\partial z_n}\right)^2 \left(\frac{\Delta z_1}{y}\right)^2]^2 \quad (5)$$

Based on the above interactions, a comprehensive error calculation has been made through uncertainty analysis. Overall accuracy within ±9.3 % for ε_d has been observed.

VII. RESULTS AND DISCUSSIONS

The prime objective of the present study is to decrease energy consumption associated with room air conditioning. The system provides dehumidification of moist air in an eco-friendly and cost-effective manner. In this section, two sets of experiments are done in which two levels of the desiccant solution is taken, i.e., 40 % and 35 %, and three levels of airflow rate are taken, i.e., 0.9 m/s, 0.7 m/s and 0.5 m/s. The effect of these parameters on ε_d and MAR is studied, and results are discussed below. In Tables 2 and 3, the performance variables of the system are shown in the specific range. Figs. 5-8 graphically summarised the variation of RH, temperature, M.A.R and dehumidification effectiveness w.r.t time for the three velocities settings, i.e. 0.9, 0.7, 0.5 m/s of P_{air} and 40 % by wt. concentration of the LD solution.

Table 2: Performance variables in dehumidification process with 40 % and 35 % by wt. Concentration.

S. No.	L.D. flow rates (kg/s) avg.	P_{air} velocity (m/s)	L.D. Conc. (χ) (%)	HR, air, in (g/kg)	HR, air, out (g/kg)	Δ HR (Δ ω) (g/kg)	M.A.R (g/s)	Effectiveness (ε)
1	0.080	0.9	40	20.17-21.54	18.16-18.82	1.76-2.91	0.007-0.011	0.087-0.135
2	0.080	0.7	40	20.65-21.60	17.44-18.02	2.96-3.70	0.009-0.011	0.144-0.172
3	0.080	0.5	40	20.82-21.79	16.12-16.23	4.43-5.21	0.010-0.014	0.210-0.301
4	0.080	0.9	35	21.55-22.35	20.28-21.06	0.99-1.47	0.003-0.005	0.045-0.065
5	0.080	0.7	35	21.71-22.64	19.64-20.43	1.52-2.51	0.004-0.007	0.069-0.112
6	0.080	0.5	35	20.88-21.97	17.60-18.65	3.03-3.53	0.006-0.007	0.139-0.164

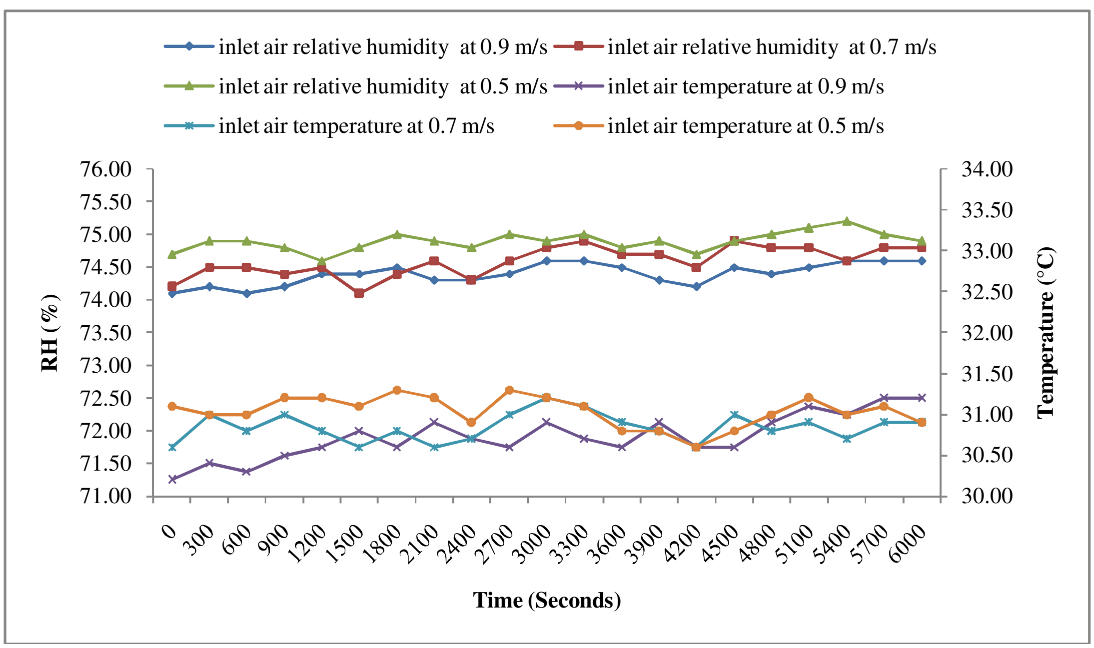

Fig. 5. Variation in RH and temperature of P_{air} at inlet port for dehumidification process w.r.t time.

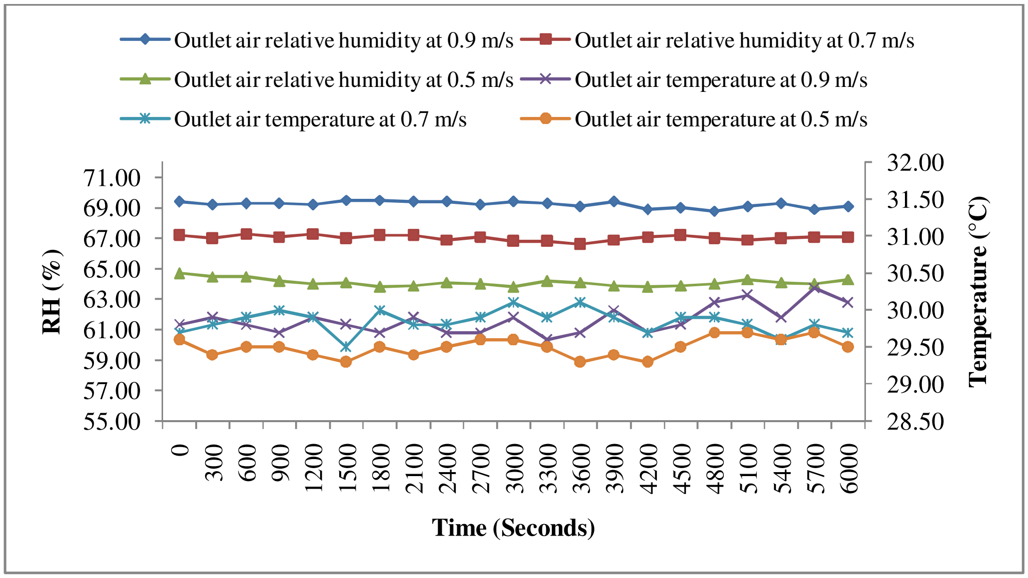

Fig. 6. Variation in RH and temperature at the outlet port of P_{air} for dehumidification process w.r.t time.

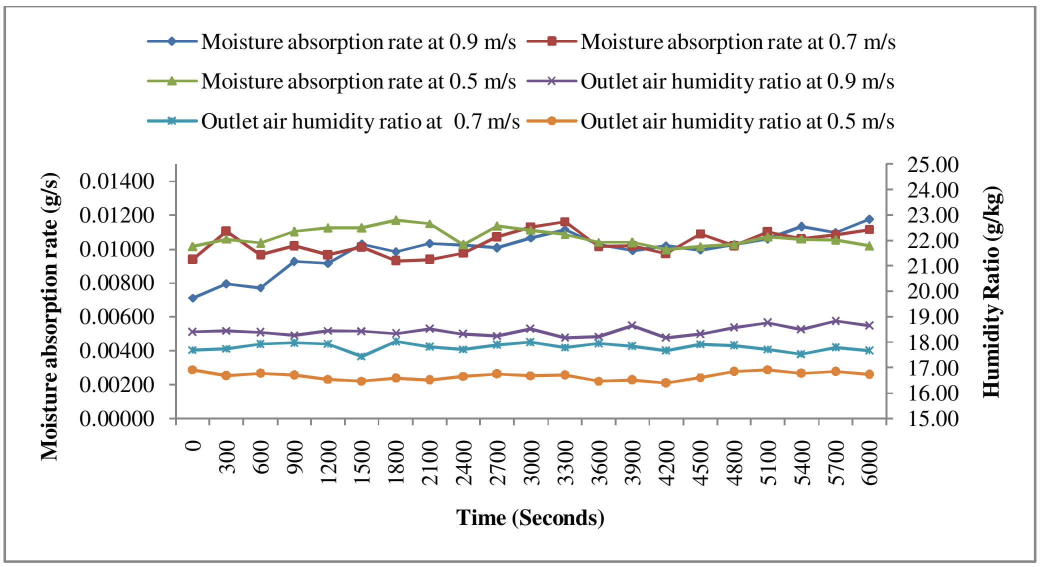

Fig. 7. Variation in M.A.R and outlet humidity ratio of P_{air} for dehumidification process w.r.t time.

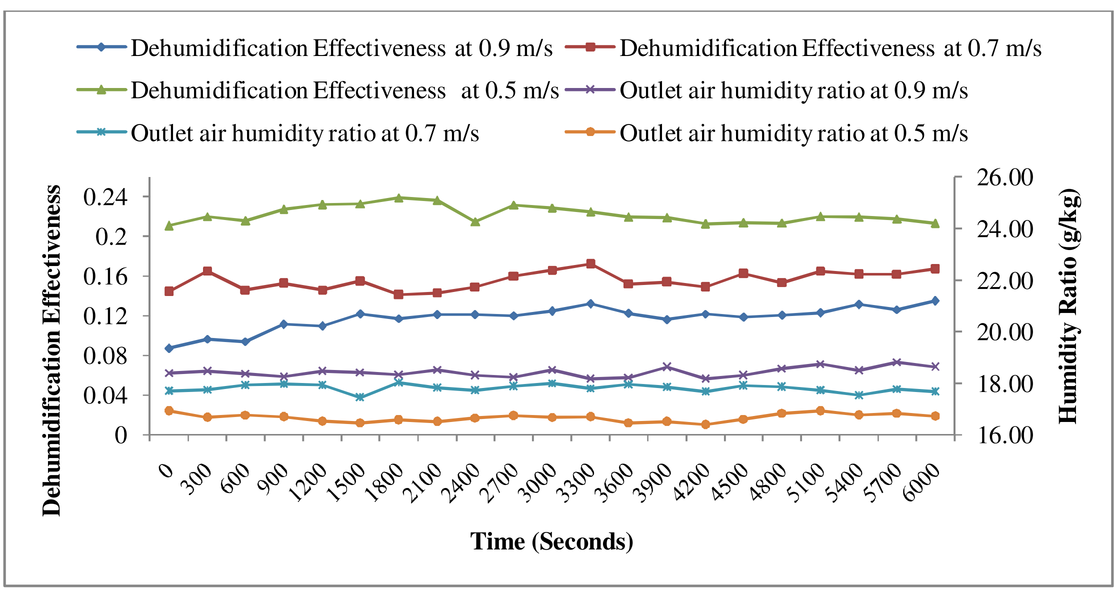

Fig. 8. Variation in the effectiveness and outlet humidity ratio of P_{air} for dehumidification process w.r.t time.

Three velocities and two concentration levels has been examined as inlet conditions for the experimental analyses of the dehumidification system. The reference P_{air} velocities are 0.9, 0.7 and 0.5 m/s and L.D. solution concentration are taken as 40 % and 35%. Fig. 4 shows the difference in the RH and temperature of three velocities for 40 % concentration of L.D. solution. At inlet port, the RH and temperature are independent of the flow rate of P_{air}. The inlet RH and temperature is in the range of 74.10 % to 75.20 % and 30.20 ℃ to 31.30 ℃ respectively. It has been clear from Fig. 6 that there is a significant decrease in the value of RH and found in the range of 4.70 % to 11.10 %. The maximum amount of RH up to 11.10 % or 5.21 g/kg for the velocity of 0.5 m/s has been observed. Change in RH occurred due to the decrease in the flow rate of P_{air} which increased the time of contact between L.D. solution and the incoming air so that the extra moisture is absorbed by the desiccant solution from the incoming moist air in case of the velocity of 0.5 m/s w.r.t. 0.7 and 0.9 m/s. Figs. 7 and 8 show the variation in moisture absorption rate and effectiveness of the dehumidification system w.r.t humidity ration and time. It is clear from the graphs that the system is more effective by decreasing the flow rate of incoming P_{air}. The absorption rate is in the range of 7.1 % to 11.6 % and maximum at 3300 sec for the velocity of 0.7 m/s. This change is due to the low flow rates of Pair and low generation of latent heat of condensation at that point. The overall high absorption rates are achieved with a velocity of 0.5 m/s. The effectiveness of the system also depends on the flow rates of the $P_{air,}$ and it has a maximum value of 0.239 at 1800 sec where the humidity ratio has a value of 16.58 g/s for the Pair velocity of 0.5 m/s. The humidity ratio also has a minimum for a velocity of 0.5 m/s, which is the range of 16.39 to 16.92 g/s.

Fig. 9-12 graphically represented the variation for dehumidification process in RH, temperature, moisture absorption rate and dehumidification effectiveness w.r.t time for the three sets of velocities for 35 % concentration of the L.D. solution.

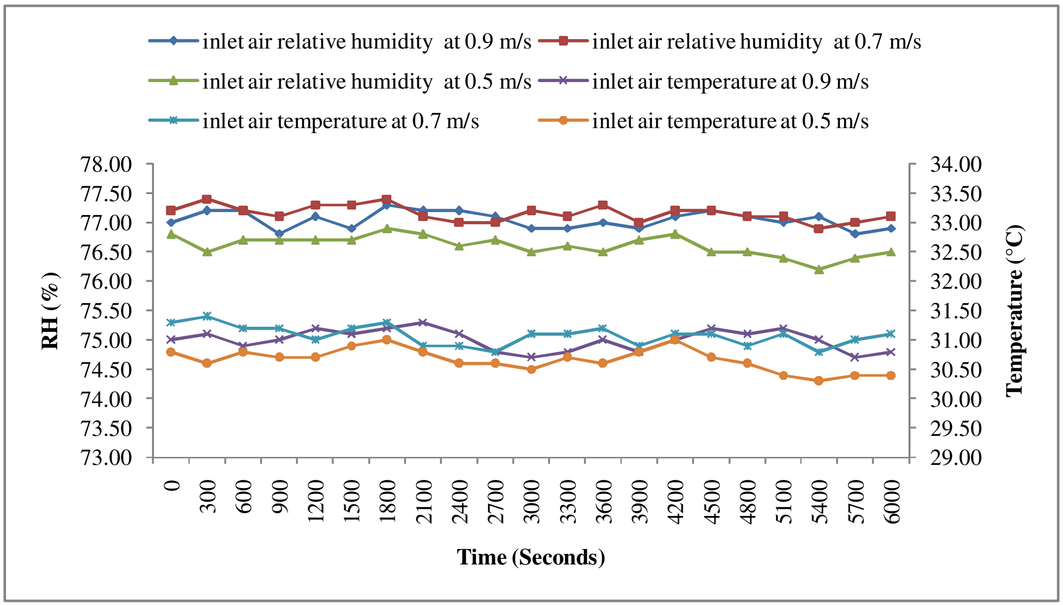

Fig. 9. Variation in RH and temperature of P_{air} at the inlet for dehumidification process w.r.t time.

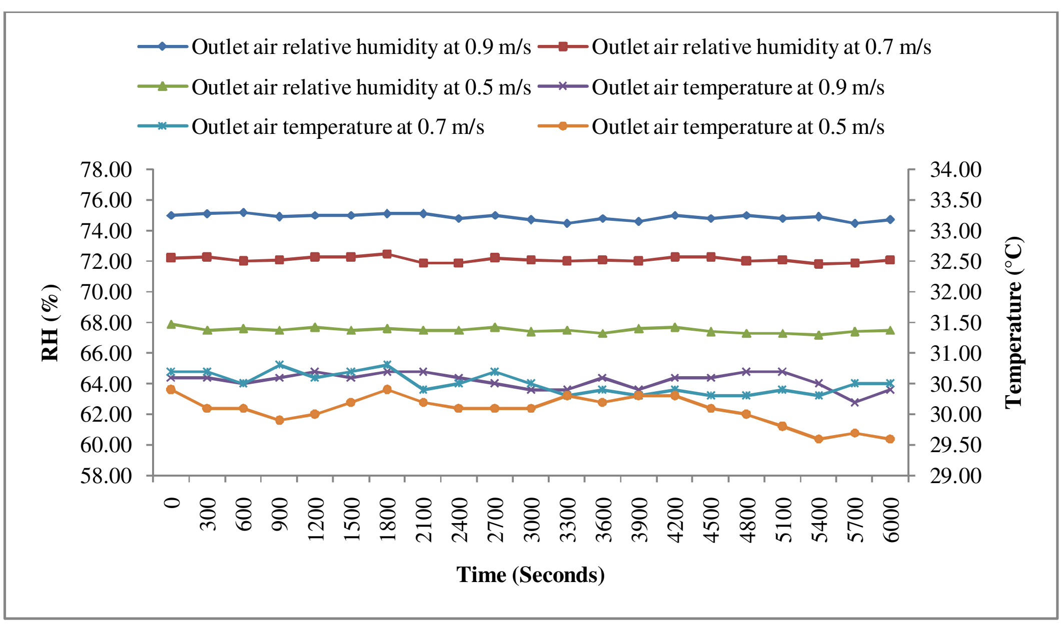

Fig. 10. Variation in RH and temperature of P_{air} at the outlet for dehumidification process w.r.t time.

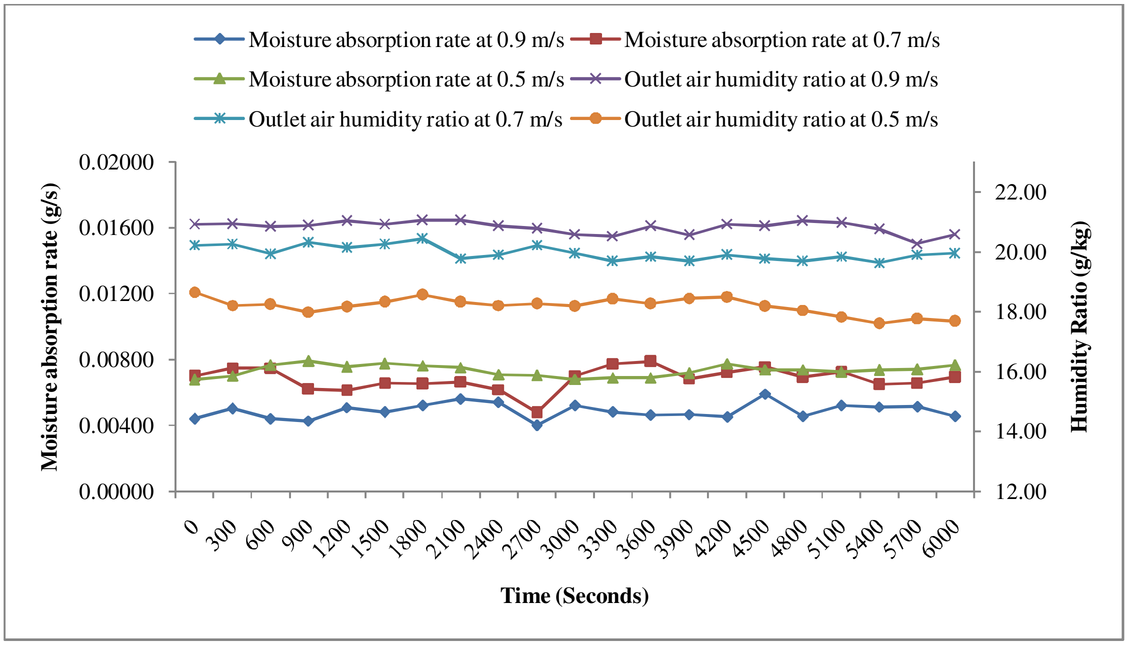

Fig. 11. Variation in M.A.R and outlet humidity ratio of P_{air} for dehumidification process w.r.t time.

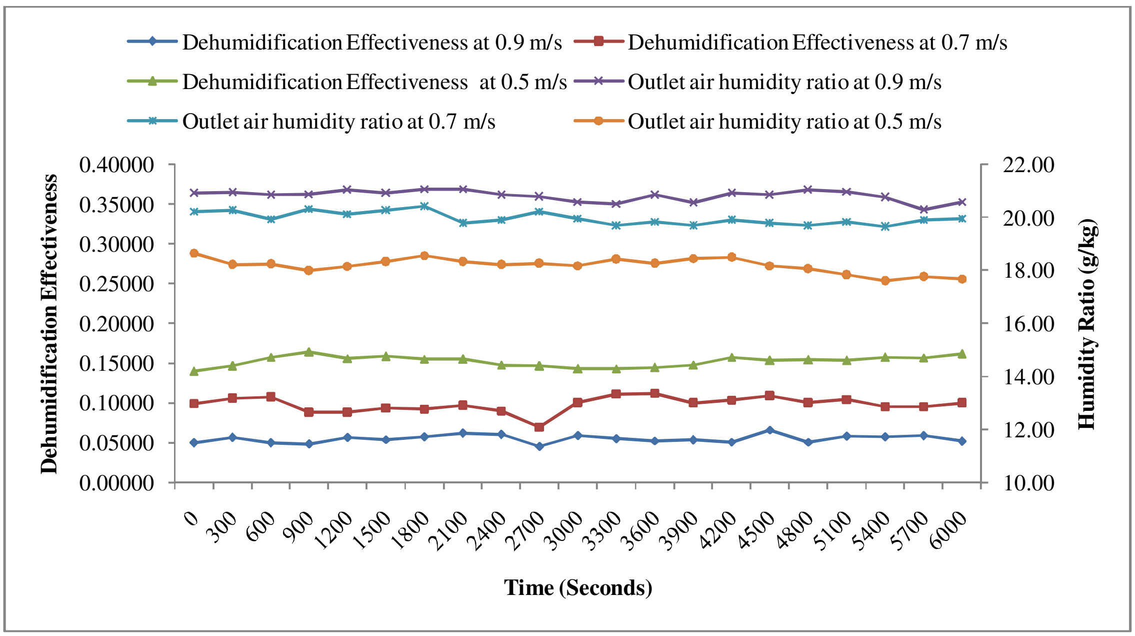

Fig. 12. Variation in the effectiveness and outlet humidity ratio of P_{air} for dehumidification process w.r.t time.

The second case for the dehumidification process has an L.D. solution concentration of 35 % and has the same sets of velocities. Figs. 11 and 12 show the difference between inlet and outlet RH and temperature of the three given velocities. The minimum RH is at 5400 sec having value 67.20 % or 17.60 g/s. The maximum difference between the inlet and outlet RH is 9.20 % or 3.53 g/s, which is reasonable but quite lower than the values obtained with the desiccant solution concentration of 40 %. The moisture absorption rate depends on the inlet RH or ambient air conditions, equilibrium humidity solution temperature and concentration. The moisture removal rate and effectiveness are varied between 4.3 % to 7.9 % and 0.04 to 0.16, respectively. The effectiveness has a maximum value at 0.16 at 6000 sec for Pair having a velocity of 0.5 m/s.

The investigation of the performance parameters achieved through experimental studies performed by various researchers are determined by the variables such as L.D flow rate, concentration and temperature, and process air humidity ratio and temperature. Table 3 represents the experimental outcomes achieved by different researchers using liquid desiccant solution to dehumidify the process air.

Table 3: Experimental outcomes achieved by different researches.

Study	L.D. used	Process variables						Parameters measured		
		L.D. (flow rate) (kg/s)	X_{IN} (conc.) (%)	$T_{L,IN}$ (°C)	P_{air} (flow rate) (kg/s)	$T_{a,IN}$ (°C)	ω_{in} (g/kg)	ΔT (°C)	$\Delta\omega$ (g/kg)	ε
[2]	HCOOK	—	74	24-26	0.0042-0.0070	38.6	42.5	-1.3	26.6	0.63
[5]	LiCl	6.124	34.6	30.1	0.89	30.1	18	1.2	-7.6	0.75-0.84
[12]	LiBr	0.018- 0.13	53-57	16.1- 34.1	3.67	23.6-35.4	1.4-18.7	—	-3 to -11	0.25
[17]	KOOH	0.09-1.23	72.8-74	21.9-24.8	0.48-0.52	22.6-35.8	8.8-20.7	—	-2 to -13.5	0.3
[3]	HCOOK	0.03	50	23 - 26	6.7	30	16	2.42 – 6.39	0.19 – 0.60	0.3 – 0.47
Present study	HCOOK	0.80	35-40	22 - 24	0.01-0.02	35.57	20.65 - 22.64	1.45	4.62- 6.43	0.19 – 0.3

VIII. CONCLUSION AND FUTURE SCOPE

The experimental investigation performed in the present study examined the performance of an innovative multi-layer flat plate L.D. dehumidification system. During the investigation, interfacial contact between the thin layer of L.D. solution, flowing over plates of the dehumidifier and ambient P_{air} has been observed which eradicates the complications related to the conventional packed bed and spray tower dehumidifiers. The experimental investigation has been conducted by changing the concentration of L.D. solution, i.e. 40 % and 35 % by wt. Three sets of velocities of $P_{air,}$ i.e. 0.5, 0.7, 0.9 m/s have been examined. Through experimental studies, the conclusion has been made that in the dehumidification process, L.D. solution concentration of 40 % and P_{air} velocity of 0.5 m/s provides the most promising outcomes. The maximum variation obtained between the H.R, $_{in}$ and H.R, $_{out}$ was 5.20 g/kg, and the maximum dehumidification effectiveness achieved was 0.239 in case of 40 % concentration of L.D. solution with P_{air} velocity of 0.5 m/s. Scope of future investigation would comprise the practice of different desiccant materials with the present dehumidification system. The system can be investigated to analyse the process air behaviour by using different L.D. materials in near future.

Conflict of Interest. No potential conflict of interest was reported by the authors.

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