Dehumidification characteristics due to variation of packing density in structured packed bed dehumidifier using liquid desiccants.

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Abstract

Packing density of a structured packing bed is an important parameter effecting heat and mass transfer during dehumidification performance in a liquid desiccant-based dehumidifier system. A numerical study was conducted to test the effects of variation of packing material density in a packed bed system type of dehumidifier on outlet air humidity. Commercially available packing material Mellpak 250 Y of packing density 250 m^2/m^3 was considered due to its superior qualities compared to existing materials and much lower air pressure drop. In order to conduct the study, 3 different packing densities were used in the range 200 to 300 m^2/m^3 using potassium formate as liquid desiccants under their optimum conditions. A parametric study was conducted using variable air and desiccant parameters i.e., air and desiccant inlet temperatures, air and desiccant flow rates and inlet air humidity. Dehumidifier performance variation due to packing density was evaluated in terms of moisture removal rate, dehumidifier effectiveness, enthalpy effectiveness and latent heat ratio. Changes in the wettability of the bed due to variation in packing density affects the performance indices. Higher packing density increases dehumidifier performance due to adequate distribution of solution across the fluid bed which increases the condensation rate. However, this enhancement is not uniform as the input parameters are varied for different packing densities. Resistance to air flow, liquid hold up, increase in air residence time inside the dehumidifier are different factors attributed to this dehumidification performance behaviour.

Keywords: Structured packed bed, packing density, dehumidification, liquid desiccants.

1. Introduction

The hydrophilic property of desiccants finds many uses in a variety of field such as engineering, chemical, agricultural and medical. When brought into contact with humid air, the desiccant in its solid or liquid form can absorb the moisture resulting in dry air. In vapour compression air conditioning systems, this dehumidification process is carried out by the lowering the air temperature to dew point for condensation and dehumidification of the air and then reheating the de-humified air to the required comfort zone. The desiccant cooling process, reduces the latent cooling load and allows the system to have a higher operating temperature which increases its coefficient of performance. Energy saving of upto 55% have been reported by Lim and Jeong [1][2] , when using desiccant based air conditioners relative to the conventional vapour compressors. The system can be integrated with a solar collector which also contributes to reduction of carbon footprint. According to reports by International Institute of Refrigeration in Paris, 45% portion of energy in the household and commercial buildings is being is used by the air-conditioning systems. This renewable energy supported system can pose as the solution to this problem. [3],

Liquid desiccants give higher performance relative to solid desiccants mainly due to having lower regeneration temperature. Lower air pressure drops, utilization of low-grade regeneration energy sources and potential to improve indoor air quality are advantages of liquid desiccant dehumidification systems. The liquid desiccants commonly used in industries are usually solutions prepared from halide salts, glycols or weak organic acids. More recently, material manipulation methods such as mixing of desiccants, addition of surfactants and nanomaterials to the base solution, ionic liquid desiccants have been seen to develop. These new desiccants although lower the air humidity by considerable amounts, it mostly comes at a higher cost. The behaviour of liquid desiccants can be controlled by variation of their concentration, temperature or both. The dehumidifier and regenerator are generally classified as adiabatic or non-adiabatic type. The adiabatic type offers higher mass transfer rate and ease of fabrication. Different contacting devices such as spray tower, packed bed and falling film are commonly seen. Among these, packed bed type provides the benefit of larger air-desiccant contact area for heat and mass exchange increasing the rate of de-humification of air and is still highly preferred. It consists of a packing bed with a chamber filled with sand, stone or phase change material (PCM) capsules known as packing materials. These packing fills increases the contact area. This type of dehumidifier/regenerator is compact in design and have higher efficiency relative to the other types. [4], [5].

Gandhidasan [6], predicted the pressure drop in packed bed dehumidifier system using calcium chloride liquid desiccant solution. He developed a model for both structured and random packings. Three structured packing types and four random packing materials were arbitrarily selected for the study. He concluded that structured packings have lower irrigated pressure drop and higher capacity relative to random packings. He pointed out that Mellapak 250 Y is able to provide the lowest pressure drop value among his selected material types.

Wahab et al. [7] experimentally investigated the dehumidifier performance using different packing densities i.e 77,100 and 200 m^2/m^3 of structured packing. The orientation of stacks of absorber plates was 90°. With increasing air flow rate, inlet concentration and solution flow rates, packing density of 200 m2/m3 gave lower absorber effectiveness and higher effectiveness was obtained for increasing inlet air and desiccant temperature. Comparatively, performance was improved with lower packing densities under similar conditions.

Singh et al. [8] studied the heat transfer and pressure drop characteristics using different shapes of packing and developed a general corelation for Nusselt number and friction factor as function of Reynolds number, sphericity and void fraction based on experimental data.

Gorodilov and Pushnov [9] worked on the improving contact devices designs for better heat and mass transfer in wooden structured grid packings. They listed a number of methods along a number of empirical relations between different geometrical parameters. Finally, an equation for calculating the liquid film thickness at air-solution contact area was presented.

Du et al. [10] experimentally studied the void size distribution of packed bed for both random and structured particles and developed a void function distribution for packed beds as a function of Reynolds number, sphericity and void fraction. They found that, relative void size is independent of particle size, while void size distribution is significantly affected by particle shape. The developed co relations were in good agreement with literature.

Raj and Jaykumar [11], observed the effect of packing on dehumidification and humidification of a desalination system. He selected 15 different types of random packings to perform a numerical investigation. They reported that high surface area to volume ratio, low packing factor and small packing diameter functions improves dehumidification.

It is observed that previous studies, that wetting condition of the packing material and uniform spreading of the liquid desiccant are important factors for improvement of mass transfer in the packed bed. Pressure drop of the desiccant-air contact system governs the dehumidifier performance. These parameters are dependent on the geometrical aspects of the packed bed. In addition to these, sensitivity to fouling, liquid holdup, ease of handling high or low desiccant flow rate, resistance to corrosion and cost must also be considered while designing the packed bed to promote mass transfer. Although literature committed to research on these areas have been seen, they are less and requires further investigation. Therefore, the current work is a study dedicated to investigate the dehumidifier performance with respect to variations in packing density of the packed bed column for a better understanding of its hydraulic performance. Under a set of variable air and desiccant inlet properties, the de-humidifier performance is quantified using different parameters namely, moisture removal rate, moisture effectiveness, pressure drop and latent heat ratio. Based on literature findings, Mellpak is chosen as the material of the packed bed and organic desiccant potassium formate is used as the liquid desiccant.

2. Numerical analysis

2.1 Range of parameters

As mentioned in the objective the aim of this work is to investigate the effect of packing density of the packed bed on dehumidifier performance. Table 1 gives the range of packing material od dehumidifier system and the operating inlet parameters. Fig. 1 shows the Dimensional view of the packed bed considered for this study.

Table 1. Simulation settings for the packing material and operating conditions

Parameters of system	Range/size/type	Parameter	Range
Dehumidifier size (m) *(Diameter x height)*	0.254 x 0.60	Air humidity ratio (g_{wv}/kg_{da})	21.6 - 27.2
Particle shape	Triangular/diamond/ sinusoidal	L/G ratio	2 - 5
Packing density (m^3/m^2)	100 - 300	Mass flow rate of desiccant (kg/m^2-s)	0.554 - 2.77
		Solution concentration (% wt.)	55 – 75

2.2 Physical model description

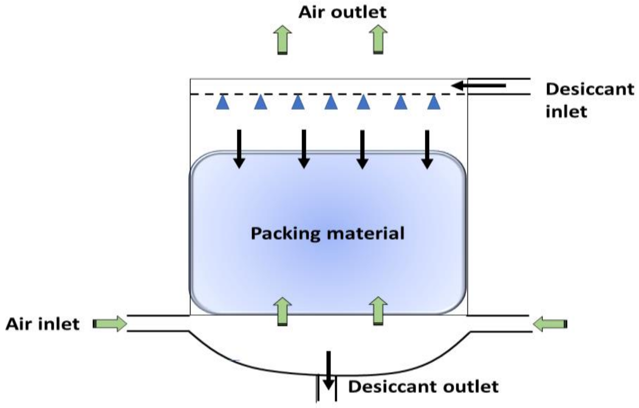

Fig 1: Schematic overview of a typical dehumidifier set-up.

A finite element method (FEM) model is developed to observe the heat and mass transfer phenomena in the dehumidifier due to packing density variations. The study is conducted by varying a number of inlet parameters as mentioned above to predict the effect on dehumidifier efficiency. Three different types of structured packing namely, Sulzer Mellpak 250Y, Gempak 3A and Montz B1are considered for the study due to having lower pressure drop as seen from literature (Gandhi). Their commercially defined packing density and void fraction values are as depicted in table.

Table 2: Physical characteristics of selected packing materials for study

Structured packing	Type	Packing density m^2/m^3	Free volume m^3/m^3	C1	C2	C3
Sulzer	Mellpak 250Y	250	0.850	1	1	0.32
Gempak	3A	262	0.930	3	2.3	0.28
Montz	B1 200	200	0.98	2	4	1

Mellpak 250Y packing is made of groves and perforated surfaces where the adjacent elements are rotated at 45°. Channels of triangular cross section forms the packed bed structure. Gempak is composed of lanced and perforated surfaces of standard type with 3-inch crimp height. Both packing structures have 45° crimp angle with sharp crimp apex. In contrast to the previous two types, the Montz B1 packings are sinusoidal type instead of sharp cornered. It has unperforated surface with closely spaced tiny projections in the form of a matrix.

2.3 Mathematical model

Simulations were formed under conditions that closely follow the experimental conditions of Bhowmik et al, for tropical climatic conditions. For simplicity, the channels are considered to be made of identical elements of similar dimension in each case, facing identical test conditions. The dehumidifier is divided into 250 parts and the heat and mass transfer equations were solved for each segment. Counter flow conditions for desiccant solution and air stream are taken along the dehumidifier height with desiccant falling along the packing material surface due to gravitational forces. During initialization, following assumptions were made,

i. Slug flow of air and desiccant.
ii. The process is adiabatic.
iii. The properties of the air and liquid desiccant solution are assumed to be constant.
iv. The heat and mass transfer area is equal to the packing material specific area.
v. The concentration gradient and temperature gradient exist only in the z-direction.
vi. Non uniformity in air motion is neglected.
vii. Constant thickness of desiccant film

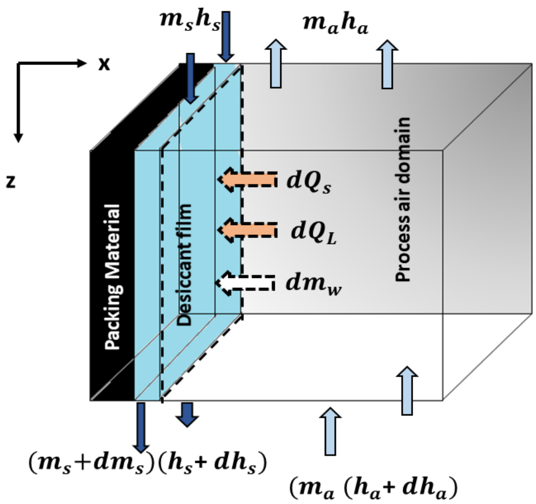

Fig 2: Differential segmentation of a packed bed counter flow dehumidifier system.

2.4 Governing equations

The desiccant solution is uniformly spread across the packing material and force acting on it making it flow downwards is gravity. The gravitational force is opposed mainly by vapour pressure drop, buoyancy and drag. The total area wetted by the desiccant solution is given by,

$$a_{wv} = a_t(1 - e^{-1.45\left(\frac{\sigma_c}{\sigma_L}\right)^{0.75} Re_L^{0.1} Fr_L^{-0.05} We_L^{0.2}}) \qquad \text{(Eq.1)}$$

The gradient in air temperature along the dehumidifier column is given as

$$\frac{dT_a}{dz} = \frac{h'_G a_t\,(T_L - T_L)}{G(c_{p,a} + Y c_{p,v})} \qquad \text{(Eq.2)}$$

The heat transfer coefficient $h'_G a_t$,for simultaneous heat and mass transfer and the gas phase heat transfer co-efficient h_G , and mass transfer co-efficient are expressed as Eq. (3), Eq. (4), Eq. (5) and Eq. (6)

$$h'_G a_t = \frac{-G c_{p,v} \frac{dY}{dz}}{1-exp\left(\frac{G c_{p,v} \frac{dY}{dz}}{a_t h_G}\right)}; \quad \text{(Eq.3)}$$

$$h_G = F_G M_a \left(c_{p,a} + Y c_{p,v}\right) \frac{Sc^{0.667}}{Pr^{0.667}}; \quad \text{(Eq.4)}$$

$$F_G = K_G P \quad \text{(Eq.5)}$$

$$K_G = 5.23 \left(\frac{a_t D_G}{R T_a}\right) \left(\frac{G}{a_t \mu_G}\right)^{0.7} \left(\frac{\mu_G}{\rho_G D_G}\right)^{0.3333} \left(a_t D_p\right)^{-2} \quad \text{(Eq.6)}$$

The change in air humidity across the dehumidifier is calculated as

$$\frac{dY}{dZ} = -\frac{M_W F_G a_W}{G} ln \frac{1-Y_i}{1-Y} \quad \text{(Eq.7)}$$

Here, the interfacial gas phase concentration is found as

$$ln \frac{1-Y_i}{1-Y} = ln \frac{1-\left(\frac{P_S}{P_t}\right)}{1-\left(\frac{P_a}{P_t}\right)} \quad \text{(Eq.8)}$$

Change in desiccant flow rate, solution concentration, and temperature across the differential segments of the dehumidifier are expressed as,

$$\frac{dL}{dz} = G \frac{dY}{dz}; \quad \text{(Eq.9)}$$

$$\frac{dx}{dz} = -\frac{G}{L} x \frac{dY}{dz} \quad \text{(Eq.10)}$$

$$\frac{dT_L}{dz} = \frac{G}{c_{p,L} L} \left\{ \left(c_{p,a} + Y c_{p,v}\right) \frac{dT_a}{dz} + \left[\left(c_{p,v} \left(T_a - T_0\right) - c_{p,L} \left(T_L - T_0\right) + \varphi\right) \frac{dY}{dz} \right] \right\} \quad \text{(Eq.11)}$$

2.5 Performance parameters:

- **Moisture removal rate:** It gives the amount of moisture transferred from air side to the desiccant solution per unit time which is calculated as in Eq. 1

$$MRR = \dot{m}_a (\omega_{a,in} - \omega_{a,out}) \quad \text{(Eq.12)}$$

- **Moisture effectiveness:** It gives the actual variance in specific humidity relative to maximum possible humidity change across the dehumidifier under the ideal operating conditions. It is calculated as in Eq. 12

$$\varepsilon_m = \frac{\omega_{a,in} - \omega_{a,out}}{\omega_{a,in} - \omega_{T_d,sat}} \quad \text{(Eq.13)}$$

- **Enthalpy effectiveness:** It gives the actual variance in specific humidity relative to maximum possible humidity change across the dehumidifier under the ideal operating conditions. It is calculated as in Eq. 12

$$\varepsilon_h = \frac{h_{a,in} - h_{a,out}}{h_{a,in} - h_e}, where, h_e = (C_{p,da} + C_{p,v}\omega_a)T_a + L_{\omega e} \quad \text{(Eq.14)}$$

- **Latent heat ratio:** It is the ratio of laten heat to sum of total sensible heat and latent heat involved during the dehumidification process as represented in Eq. 15

$$LHR = \frac{Q_{lat}}{Q_{lat} + Q_{sen}} = \frac{1}{1 + \frac{1}{\varepsilon_m} \times L^*} \qquad \text{(Eq.15)}$$

$$where, L^* = \frac{\Delta T_{sa}}{\Delta \omega_{sa}} \times \frac{C_{pa}}{h_{fg}}, and \Delta T_{sa} = \left|T_{a,i} - T_{s,i}\right|; \Delta\omega_{sa} = \omega_{a,i} - \omega_{s,i}; \omega_s = \omega_e$$

- **Pressure drop:**

Pressure drop across the dehumidifier is given as

$$\Delta P_d = 0.125 f_0 \frac{\rho_G u_G^2 a_t}{\epsilon^{4.65}}; \qquad \text{(Eq.16)}$$

Where, friction factor is $f_0 = \frac{C_1}{Re_G} + \frac{C_2}{Re_G^{0.5}} + C_3$; and Reynold's number is $Re_G = \frac{\rho_G D_P u_G}{\mu_G}$

$D_P = \frac{6(1-\epsilon)}{a_t}$ is the equivalent diameter.

Irrigated pressure, due to surface tension force is given as

$$\frac{\Delta P_{irri}}{\Delta P_{dry}} = \left(\frac{a_L + a_t}{a_t}\right)\left(\frac{\epsilon}{\epsilon - h_a}\right)^{4.65} \qquad \text{(Eq. 17)}$$

Where, diameter of the falling liquid drop is $d_L = C\sqrt{\frac{6\sigma_1}{(\rho_L - \rho_g)g}}$; and area of the liquid drop $a_L = 6\frac{h_a}{d_L}$.

Pressure drop at flooding is calculated as,

$$\Delta P_f = \frac{\rho_L g}{2988 h_b}\sqrt{249 h_b\left(\sqrt{X} - 60\epsilon - 558 h_b - 103 d_L D_P\right)} \qquad \text{(Eq.18)}$$

Constant C depends on structure of packing. Value of C is 0.8 and 0.4 for structured and random packing respectively. Where flooding coefficient, X in the above equation can be calculated as follows:

$$X = 3600\,\epsilon^2 + 186500\,\epsilon h_b + 32300 d_L a_t \epsilon + 191800 {h_b}^2 + 95030 d_L a_t h_b + 10610 {d_L}^2 {a_t}^2 \qquad \text{(Eq.19)}$$

2.6 Validation of the model

The experimental dataset of Fumo and Goswami [12]. is used to validate the developed numerical model and the results obtained are compared using lithium chloride as desiccant solution. The inlet conditions are as given in literature [12]. It can be seen that the numerically predicted outcome of the model closely follow that of experimental investigation with good agreement. Specific air humidity ratio, desiccant concentration (ξ), temperature of air (**T_a**) and solution at outlet (**T_L**) showed a minimum deviation of ±1 % and maximum of ± 6.18 % from literature. MRR was within an acceptable error of 8.42 %.

Table 3. comparison of the numerically predicted results of the model with established literature. [12]

Experimental results from literature.					Predicted outcome of model				
ω_a kg_{wv}/kg_{da}	ξ **(wt. %)**	**T_a°C**	**T_L°C**	**MRR (g/s)**	(ω_a) kg_{wv}/kg_{da}	ξ **(wt.%)**	**T_a°C**	**T_L°C**	**MRR (g/s)**
0.0104	0.345	31.3	32.3	0.32	0.0107	0.35	30.33	30.87	0.295
0.0108	0.346	32.2	32.6	0.4	0.01083	0.347	30.4	31.23	0.385
0.0112	0.337	32.8	32.6	0.42	0.01108	0.344	34.63	31.36	0.415
0.0113	0.342	32.2	32.7	0.38	0.01109	0.343	30.42	31.3	0.348
0.011	0.343	32	32.5	0.39	0.01159	0.344	30.42	30.98	0.367
0.0114	0.33	32.4	32.2	0.36	0.012043	0.330254	31.19	30.97	0.33
0.0112	0.337	32.5	32.6	0.38	0.011893	0.337226	31.22	31.09	0.36
0.0107	0.347	32	32.5	0.41	0.01022	0.34717	30.31	31.13	0.38

3. Results and discussion

The discussed system of equations is used in a HCOOK solution – air contact system using two different three packing materials namely, Mellpak 250Y, Gempak 3A and Montz B1 type with varying packing densities. The base properties of material and packings are taken from literature [6]. To study the effect of packing density on dehumidification it is varied in the range 100-300m^3/m^2 for each case under ideal identical input design parameters taken from literature [13]. Solution flow rate is taken 1.383 kg/m^2-s, L/G ratio is taken as 2.5, inlet air temperature is 35°C, inlet solution temperature is 25°C, concentration of desiccant solution is 0.65%wt., inlet air humidity is 0.0272 kg$_{wv}$/kg$_{da}$.

3.1 Effect of variation of packing density in different packing materials.

The dehumidifier performance was evaluated in terms of from mainly moisture removal rate (MRR) and pressure drop on the air side (PD). Figure 3, the interdependency of the design parameters on packing density is seen. It is observed that on variation of packing density, for all the three cases, pressure drop is seen to rise with increase in packing density. The effect of packing density is more pronounced in Montz B1 type of packing material, whereas in Mellapak 250 Y and Gempak A3, the drop in pressure is considerably much less. In contrast, moisture removal rate (MRR) was enhanced due to packing density increase slightly exponential manner in each case. Montz B1 gave the highest MRR value followed by Gempak A3 and Mellapak 250 Y materials. Theoretically, denser columns provide higher contact area improving condensation rate as mentioned by Wahab et al. [7] who tested dehumidifier performance using three different packing densities 77, 100 and 200 m^2/m^3 for structured corrugated sheets and TEG as desiccant solution. Lowest pressure drop with Mellapak 250 Y was reported by Gandhidasan [6]. The other parameters such as moisture effectiveness (ε_m), enthalpy effectiveness (ε_h), latent heat ratio (LHR) is also seen to increase with packing density. Better distribution of liquid, increase in air-desiccant contact area and time inside the absorber, decrease in wetting angle improving the wetting condition of the bed, together contribute to this higher performance of the system under constant operating conditions. However, variation of the inlet parameters may change the performance characteristic curves.

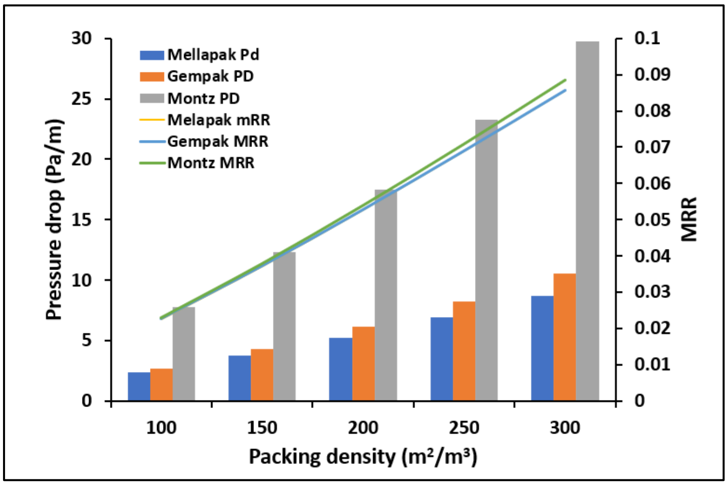

Fig 3: Comparison of variation in packing densities for different packing materials

Thus, further studies were conducted where Mellapak 250 Y type packings are chosen to study the effect of variations of different inlet parameters with varying packing density. The findings are detailed below. The constant parameters considered during the study are taken from literature and selected as follows: $\dot{m}_L$ is 1.38 kg/m^2-s, L/G ratio is 2.5, T_a is 35°C, T_L is 25°C, solution concentration is 65% by wt. and specific humidity is 0.0272 kg$_{wv}$/kg$_{da}$. The results obtained are discussed as graphical representations of output parameters mainly, the MRR, moisture effectiveness (ε_m), moisture enthalpy (ε_h), LHR and pressure drop.

3.2 Effect of variation of inlet specific humidity ratio on varying packing density

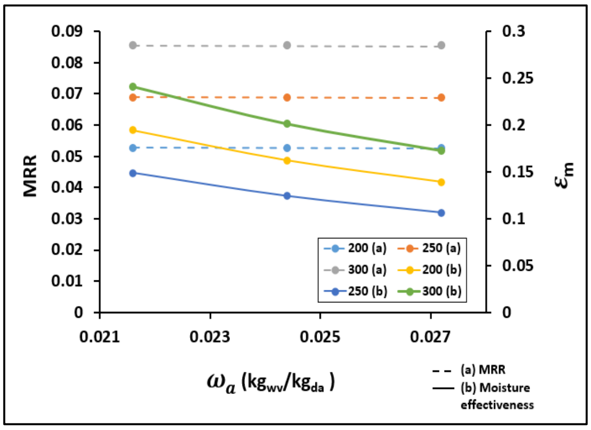

Fig 4(a): Effect of varying on MRR and (ε_m)

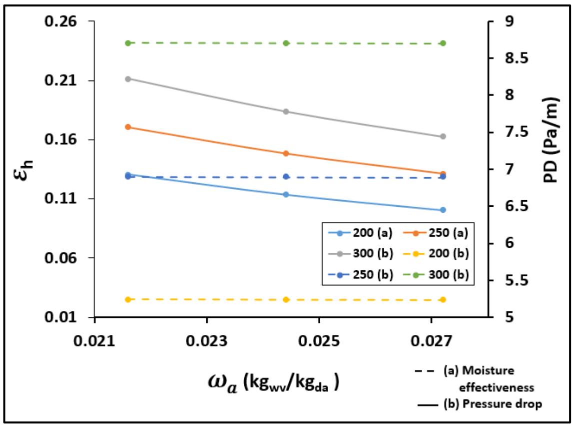

Fig 4(b): Effect of varying (ε_h) and PD.

The MRR and moisture effectiveness (ε_m) values are plotted against varying specific humidity ratios (ω_a) of inlet air stream and the trend is observed for three different packing densities of 200, 250 and 300 m^2/m^3. Other parameters such were kept constant at the values mentioned earlier. As observed from the doubly Y axis plot of Fig. 4(a), with MRR on the left side and moisture effectiveness (ε_m) on the left, the (ε_m) gradually decreases with increase in (ω_a) values in the range of 0.145 - 0.173 kg$_{wv}$/kg$_{da}$ for the three different packings. The values of (ε_m) were highest for packing density of 200 and lowest for packing density of 250 denoting an increasing decreasing pattern. This is due to adequate wetting of material contact surface, thereby increasing the interaction between air and solution. The increasing (ω_a), the air pressure *(P_a)* decreases resulting in variation of performance. The variation of specific humidity did not have much effect on MRR and straight lines can be observed. This is because the difference in vapour pressure was considerably lesser at the selected constant parameters of design. The highest values were obtained for highest packing density of 300 and deceases with decreasing packing density with a variation of 0.01.
Variation of enthalpy effectiveness (ε_h) was also found to have similar trend behaviour as MRR but with higher amount of variation depicting a decreasing trend for increasing specific humidity ratio. But no effect was observed for pressure drop which showed minute variations. Highest pressure drop was observed for packing density of 300 and lowest for 200, with a variation of approximately 1.24 and values were seen in the range of 5.24 to 8.707 Pa/m. This was due to variation in wetting area. LHR and (ε_h) did not show much changes and were approximately 0.148 and 0.37 receptively having nearly ± 1.45 deviations.

3.3 Effect of variation of concentration on varying packing density

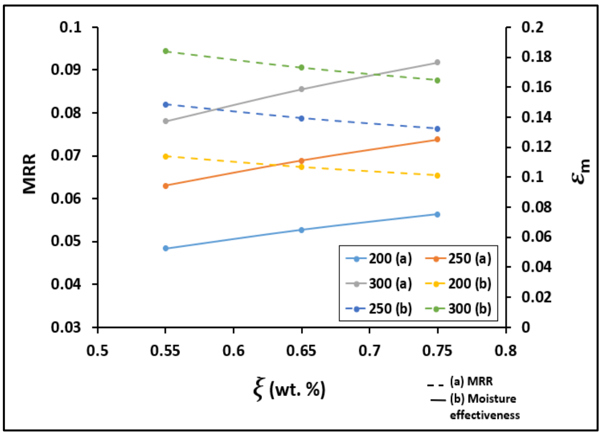

Fig 5(a): Effect on MRR and (ε_m)

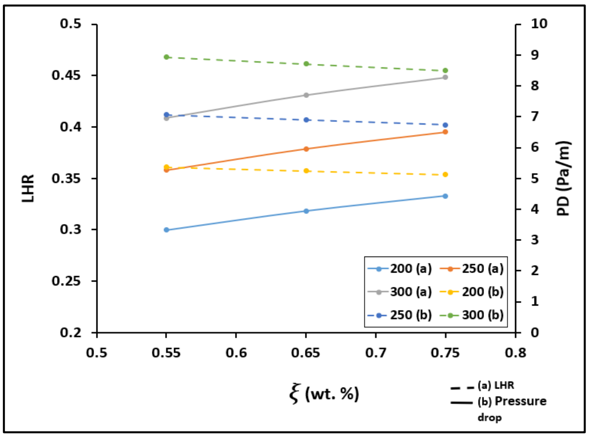

Fig 5(b): Effect on LHR and PD

For the study of effect of variation of solution concentration (ξ), three concentration of 55, 65, 75 wt. % were considered for the HCOOK desiccant solution to keep the range near optimum of 64.5 % as given by Wen et al. [14]. Two double Y axis graphs were plotted for MRR and moisture effectiveness (ε_m), LHR and pressure drop for varying concentrations as illustrated in Fig 5(a) and 5(b). The variations in trends were observed at constant specific humidity of air (ω_a), solution flow rate $(\dot{m}_L)$ and air flow rate $(\dot{m}_a)$ at inlet, and temperature of air (T_a) and desiccant solution (T_L). It can be seen that MRR improves with increase in concentration (ξ) of solution and packing density and the value is seen to improve by 55.55 % for this study. This is due to lower surface vapour pressure at higher concentrations values. Lower vapour pressure increases the driving force for mass transfer enhancing the condensation rate. Moisture effectiveness (ε_m) decreases with solution concentration (ξ) but increases with packing density. Better distribution of solution across the bed results in better dehumidifying rates. Best results were reported at low concentration and higher packing density values. LHR also improved with higher concentration values and packing density of bed and obtained range of values is 0.296 to 0.448 under the given operational conditions. Concentration (ε_m) variation had however minute effects on pressure drop across the dehumidifier as can be seen from the fig 5b. This can be attributed to sufficiently well distribution of solution with low resistance to air at the given adequate air flow rate.

3.4 Effect of variation of solution flow rate on varying packing density

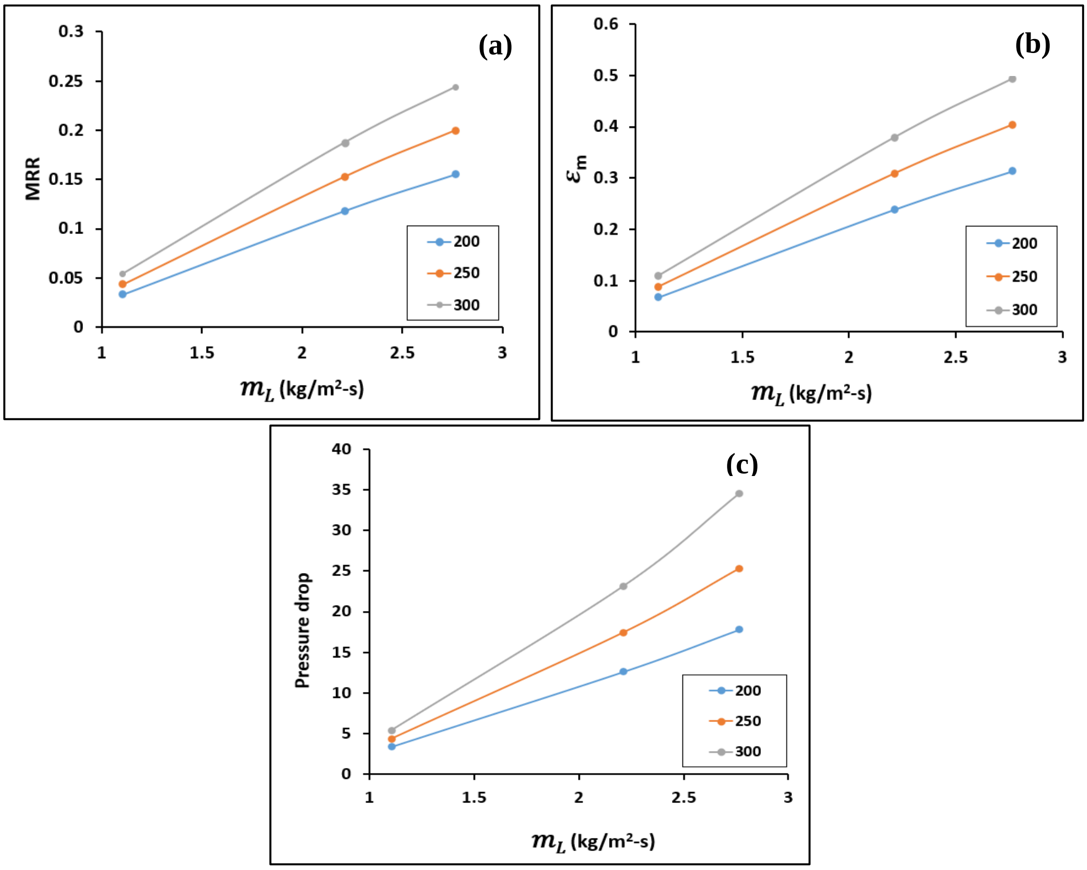

Fig 6: Variation of solution flow rate for different packing densities. (a) Effect on MRR (b) Effect on (ε_m) (c) Effect on PD

Fig 6 (a), (b), (c) shows the variation of MRR, moisture effectiveness (ε_m) and pressure drop (PD) for three different packing densities with changing solution flow rates $(\dot{m}_L)$ at dehumidifier inlet. It can be seen that all three parameters increase as solution flow rate $(\dot{m}_L)$ is increases from 1.1064 to 2.766 kg/m^2-s. This is due to sufficient wetting of the packed bed. It is observed that at lower flow rates $(\dot{m}_L)$, difference in packing density has minimum effect on MRR, moisture effectiveness (ε_m) and pressure drop and the values improves gradually for all three cases as flow rate $(\dot{m}_L)$ is increased. Higher values of packing density of packed bed give better performance for all three parameters. The lower variations at low flow rates are due to lesser amount of concentrated solution available at air-solution contact interface, which reduces the dehumidification as saturated solution is not replaced quickly in relative to humid air flow. Increment of flow rates provides larger amount of concentrated solution to interact at the interface. MRR value increases to 0.244 from 0.033 under the given operating condition as packing density was increased from 200 to 300 and flow rate was increased from 1.1064 to 2.766 kg/m^2-s. Effectiveness of the dehumidifier (ε_m) increases by 25 % as packing density was increased from the manufacturer value of 250 to 300. On the other hand, increment of solution flow rate had an adverse effect on pressure drop of the packed bed unit. The range of pressure drop lies in the range 3.371 – 34.589 Pa/m for the given operational conditions. pressure was seen to drastically drop as packing density was increased. This is due to increase in liquid hold up which increases the hydraulic resistance to air flow. At lower packing densities, the magnitude of the spacing between packing is sufficient to allow free air moment during the draining of liquid along the material surface. The gap reduces at higher densities and high solution flow rate blocks the air path due to over filling of the void spaces with liquid.

3.5 Effect of variation of air flow rate on varying packing density

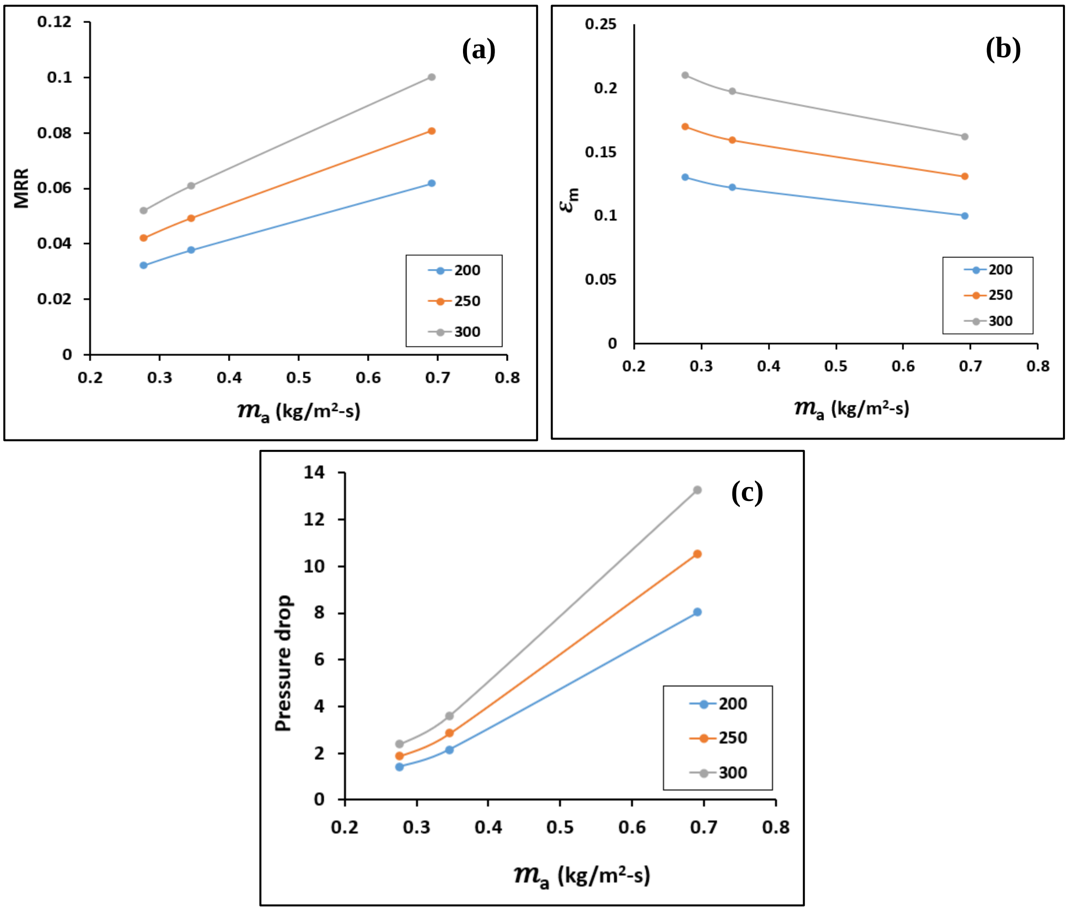

Fig 7: Variation of air flow rate for different packing densities. (a) Effect on MRR (b) Effect on (ε_m) (c) Effect on PD

For observing the effect of air flow rate $(\dot{m}_a)$, it is decreased from 0.6915 to 0.2766 kg/m^2-s for the three different parameters. Although MRR was seen to increase with increasing flow rates, but the effect is less. Higher packing density, provides sufficient contact surface area for air and desiccant interaction which compensated the decrease in air residence time inside the dehumidifier. This causes condensation rate to improve with packing density. Enthalpy effectiveness (ε_h) is seen to deteriorate with higher air flow rates and gradually improves as air flow rate $(\dot{m}_a)$ is reduced. This decrease may be explained due to decrease in residence time of air inside the dehumidifier. As the air is still considerably humid, at the outlet, the effectiveness of the absorber is reduced. Dehumidification is best at high packing density of 300 at low air flow rates. The drop in effectiveness is 55% when both packing density is decreased from 200 to 300 and air flow rate is increased to 0.2766 kg/m^2-s from 0.6915 kg/m^2-s. The drop in air side pressure is lesser as compared to variations with solution flow rate. Overall better results for MRR and (ε_h) were obtained with higher packing and decreases gradually. Lowest pressure drop is obtained for low packing density and low air flow rate.

4. Conclusions

A numerical comparative study using finite element method is conducted on packing density variation of structured packed bed for dehumidification of air for air conditioning purpose using HCOOK liquid desiccant solution. Three different base materials namely Mellapak, Gempak and Montz B1 were compared for different packing densities in the range 100 – 300 and dehumidification performance was numerically observed under a set of constant operating parameters for counter flow configuration. Mellapak showed best performance and better results were obtained as packing density was increased. However, increase in packing density causes an increase in pressure drop. The pressure drop is more rapid in case of Montz B1 as compared to Mellapak 250 Y and Gempak A3 materials.

Mellapak material is concluded as a better choice of the three and further parametric study was conducted by variation of different input parameters namely, inlet air humidity, solution concentration, solution flow rate, air flow rate and L/G ratio, on different packing densities. Based on the numerical analysis and comparison of dehumidification performance, the following conclusions have been drawn which were in acceptable agreement with the experimental findings of literature [7], [9]:

- With variation of humidity in the range 0.0216 – 0.0272, moisture effectiveness and moisture enthalpy decrease gradually while MRR and PD remain almost unaffected. Higher packing densities yielded better results at lower air humidity ratios but interestingly, lowest value of moisture effectiveness is seen for packing density of 250 instead of 200 as is seen in other cases.
- As solution concentration increases, higher values of MRR and LHR are obtained but moisture effectiveness is seen to fall. Pressure drop is benefited and the decreases slightly at higher concentration.
- MRR and moisture effectiveness increases with increase in solution flowrate at the cost of increasing pressure drop on the air side and a balance in solution flow rate must be determined.
- Decrease in air flow rate, decreases the MRR but improves moisture effectiveness as well as considerably lowers the air side pressure drop.
- Increase in L/G ratio increases the MRR and moisture effectiveness but exponentially increases the air pressure drop.
- Dehumidifying rates and effectiveness of the dehumidifier should simultaneously considered while selecting the design parameters of the desiccant based dehumidifier system.

Greek Symbol		***Suffix***	
ϵ	Void Fraction	L	Liquid
σ	Density (kg/m^3)	G/a	Air
u	Dynamic viscosity (Pa.s)	C	Critical
σ	Surface tension (N/m)	Sat	Saturation
ρ	Density (kg/m^3)	t, tot	Total
ξ	Concentration (wt. %)	out	Outlet
ω	Specific humidity	in	Inlet

Nomenclature.

a	Total Specific surface area (m^2/m^3)
D_p	Equivalent diameter, m
D	Diffusivity (m^2/s)
g	Acceleration due to Gravity (m/s^2)
F	F type mass transfer coefficient ($kmole/m^2.s$)
h	Volumetric heat transfer coefficient ($kW/K.m^3$)
h_a	Static liquid holdup
K	Mass transfer coefficient ($kmol/m^2.s.Pa$)
L	Liquid Flow rate ($kg/m^2.s$)
Re, Fr, We	Reynolds, Froude, Weber number
P	Pressure (Pa)
R	Ideal gas constant (kJ/kmole.K)
T	Temperature in (°C)
x/ξ	Concentration in Fraction of weight
Y/ω	Specific humidity (kg/kg of dry air)

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