PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Influence of desiccant concentration and temperature on moisture absorption using a multistage dehumidifier

Ana Tejero-González[a]; Shiva Kumar[b];
Sampath Suranjan Salins[c]; S.V. Kota Reddy[d]

[a] School of Engineering, University of Valladolid, Valladolid, Spain, ana.tejero@uva.es CA
[b] Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, India, shiva.kumar@manipal.edu
[c] School of Engineering and IT, Manipal Academy of Higher Education, Dubai Campus, UAE, sampath@manipaldubai.com
[d] Department of Mechanical Engineering, VIT-AP University, Vijayawada, Andhra Pradesh, India, vc@vitap.ac.in

Abstract:

Moisture control is essential for appropriate indoor air quality, mainly in humid regions. Liquid desiccant dehumidification system is among the latest techniques used to minimize the humidity indoors and maintain thermal comfort, requiring less energy than dehumidification through conventional refrigeration. In the current work, a four-stage dehumidifier is constructed, which consists of a dynamic packing soaked in the solution containing the desiccant. The linear motion of packing is induced by a cam spring follower mechanism powered by a motor. Celdek 7090 is used as packing along with Calcium Chloride of different concentrations as desiccant. Experiments are conducted for varying air velocity, desiccant concentration, and inlet dry bulb temperature. Input parameters are noted and performance parameters such as coefficient of performance, moisture removal rate, dehumidification efficiency, and humidity and temperature drops are evaluated. Results indicate that an increase in the desiccant concentration yields larger dehumidification, though 40% desiccant concentration led to adverse effects on the system components and hindered the flow. Rise in the inlet temperature slightly raised the dehumidification. System gave maximum moisture removal rate, dehumidification efficiency, and coefficient of performance equal to 4.83 g/s, 72.74%, and 4.35 respectively. Results also showed that increasing air velocity reduced the dehumidification efficiency. Air quality check conducted on the exit air, it is found that air quality is good and meets ASHRAE standards.

Keywords:

Multistage dehumidifier; desiccant; coefficient of performance; dehumidification effectiveness; air quality.

1. Introduction

Due to the rise in the world's population, there is a significant increase in the energy consumption. Air conditioning (AC) alone comprises 50% of the overall building energy utilization [1]. It is thus critical to improve the energy efficiency when controlling the temperature and humidity within the occupied spaces. In AC, the temperature is maintained below dew point temperature to remove moisture by condensation [2]. Due to water collection, there is a risk of growth of the mold and bacteria, with the consequent undesirable health effects. Therefore, to remove more moisture, reheater is required [3]. Desiccant dehumidification is an alternative approach which can provide high air quality and meet thermal comfort conditions [4]. Liquid desiccant dehumidification system (LDDS) is an alternative option where that dehumidifies the air with the use of liquid desiccant. Humid air is driven through the duct and interacts with the packing, where there moisture condensates [5]. This is due to the vapor pressure difference between the desiccant and the air. As the concentration of the desiccant increases, there is a drop in the vapor pressure of the desiccant and the moisture diffuses from the higher to the lower concentration [6]. Some of the packings which are commercially available are Celdek and Aspen packing. Celdek packing gives high wettability value. Wettability is the desiccant holding capacity of the packing. Lithium bromide (Li Br) and Lithium Chloride (Li Cl) are commonly used desiccants which yielded good dehumidification, but they are corrosive [7]. This issue can be overcome using less corrosive desiccants such as Calcium Chloride (Ca Cl_2) and potassium formate (HCO_2K) [8]. Thickness of the packing and desiccant concentration are decisive on the dehumidification performance [9].

https://doi.org/10.52202/069564-0029

Outside climate is another factor which determines the dehumidifier performance. In the majority of the systems, the packing is static, single stage, and the type of flow between the air and the desiccant is either counter or cross flow [10]. Counter flow can result into higher performance. Some articles in the literature focus on multistage and dynamic dehumidifiers.

Air can be driven through one or more packings. Similarly, the packing may be static or dynamic. Dong et al. [11] studied a corrugated, S-shaped, PVC, and a globular shaped, polypropylene packing. the performance of the dehumidifier was evaluated for the inlet air flow rate and temperature. In terms of the moisture effectiveness, corrugated packing gave better results than S-shaped packing. Globular packing gave the least performance among all. Wang et al. [12] worked on a counterflow liquid desiccant dehumidifier which used structured packing with wettability of 650 m^2/m^3. Experiments were conducted for variable packing height, climatic conditions, and air velocity. The system gave a moisture effectiveness of 0.6 and moisture removal rate of 0.9 g/s. Jain et al. [13] built a dehumidifier unit which comprised a cooling tower, heat exchanger, regenerator and control unit. The desiccant used by the unit was $Ca\ Cl_2$ and Li Cl, and the desiccant concentration and air flow rate were varied. Results indicated that change in the specific humidity of Lithium Chloride and Calcium Chloride was found to be 5.86 and 1.77 g/kg. Bouzenada et al. [14] developed a desiccant air conditioning system which used $Ca\ Cl_2$ as desiccant. Operating parameters such as air temperature, humidity and air velocity were varied and found that absorption mass rate varied linearly with the inlet air humidity. Results indicated that the system gave a vapor pressure of 20 Pa. Lu et al. [15] worked on LDDS where the inlet air humidity ratio and temperature were varied. Experimental test rig was developed and found that outlet desiccant and air temperature increased with the inlet conditions. Solution fraction increase gave a drop in the outlet humidity. Seenivasan et al. [16] compared the performance of single and two stage dehumidifiers. Air flow rate were varied and found that there was a drop in the dehumidification effectiveness. There was a rise in the condensation rate with the increase in the desiccant flow rate. Also, the performances varied with the desiccant concentrations and found that moisture removal rate increased significantly. Results inferred that two-stage dehumidifier performed better than single stage dehumidifier. Cheng et al. [17] worked on a multistage dehumidifier and conducted experiments for different number of packing stages. The system used Li Cl solution which interacted with the humid air in cross flow direction. Results indicated that dehumidification efficiency was mainly affected by air flow rate and solution flow rate, and the system gave a dehumidification efficiency of 80%. Li et al. [18] performed an experimental study on a multistage planar membrane dehumidifier both counter and parallel flow arrangements. Nafion 212 membranes were used, and the inlet operating conditions were initially maintained at 27ºC, then varied. Performance parameters were obtained by varying the temperatures, relative humidity, and air flow rate. Results indicated that counter flow dehumidifier gave better performance compared to the parallel type.

After reviewing the literature, it is found that most of the papers used counter and cross flow types, while desiccant used were Li Cl and $Ca\ Cl_2$. Celdek packing is widely used, which gave high wettability. Few works focused on the variation of the climatic conditions and the solution flow rate. Most research focus on single stage static dehumidifiers, while research related to multistage dynamic dehumidifiers is scarce. Also, the study of the influence of the desiccant concentration variation and the climatic conditions on the system performance are limited. To overcome these gaps, a multistage reciprocating dehumidifier is constructed where the desiccant concentration and inlet climatic conditions were varied to obtain the performance parameters such as moisture removal rate and moisture effectiveness. Energy efficiency is also studied and expressed in the form of the COP.

2. Methodology

Figure.1 shows the psychrometric process in the desiccant dehumidification system.

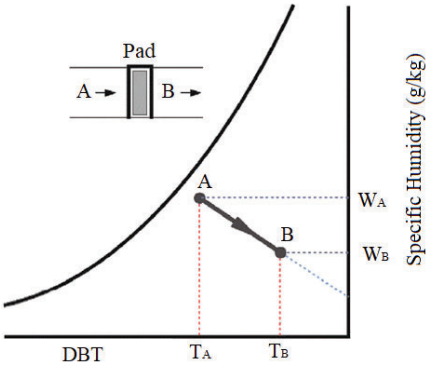

Figure.1. Psychometric process representing dehumidification.

The air gets dehumidified as it passes through the reciprocating packing system. W_A, T_A are the air specific humidity and temperature at the inlet, while W_B, T_B are the air specific humidity and temperature at the outlet. In the dehumidification process, the temperature of air increases as the specific humidity drops.

The moisture removed from the air (MRR) is given by equation (1), which is evaluated by the product of air flow rate and difference in specific humidity.

$$MRR = (\omega_i - \omega_o)\,\dot{m}_a \tag{1}$$

The dehumidification efficiency given in equation (2) is defined as the ratio of the difference between the inlet and outlet specific humidity to the inlet specific humidity and equilibrium specific humidity.

$$\varepsilon = \frac{\omega_i - \omega_o}{\omega_i - \omega_{eq}} \tag{2}$$

The mass transfer coefficient is defined as the product of the MRR to the product of the surface area and the specific humidity difference of average and equilibrium points. It is given by equation (3).

$$K = \frac{MRR}{A\,(\omega_{av} - \omega_{av,eq})} \tag{3}$$

The Coefficient of Performance (COP) is defined as the ratio of the enthalpy difference or heating effect to the total energy required. It is shown in equation (4).

$$COP = \frac{HE}{Energy\ consumed} \tag{4}$$

All the performance parameters are determined using equations (1) to (4) and represented in section 3 in the form of graphical representation.

2.1. Multistage dehumidifier test rig construction and operation

Figure 2 shows the experimental test rig constructed. It mainly consists of an absorber unit where the dehumidification process is carried out, composed by four packings at different positions that reciprocate inside the desiccant solution.

The evaporator of a vapour compression refrigeration system is integrated in the absorber to regulate the desiccant temperature. Celdek 7090 is used for the multistage packing, which rotates thanks to a 0.3HP motor that powers a cam spring follower mechanism. A blower drives the air through a 25cm×25cm and 2.5 m length duct, where it interacts with the packing soaked with desiccant. As the air gets dehumidified, the desiccant concentration drops due to the water condensation. To regain the due concentration, the desiccant is driven to a preheater tank, where it is heated up to approximately 65°C, then driven to the heater tank equipped with an electric coil that supplies 1 kW. A separator consisting of baffled structured plates enables the mass transfer and the hot desiccant is pumped to a contact device system. The contact device consists of four further reciprocating packings where air interacts with the hot desiccant, removing the moisture and cooling it. The desiccant at the original concentration is pumped to a radiator where it is further cooled, then supplied to the absorber unit. The connection of the different systems is represented in Figure 3.

In this system, the reciprocating packing gets dipped inside to increase the wettability. The reciprocating action is enhanced due to cam follower mechanism powered by a 0.3 HP motor. Air is blown by a 0.5 HP blower and interacts with the $CaCl_2$ desiccant, which leads to moisture condensation. High desiccant concentration has low vapor pressure; hence the air moisture diffuses towards the concentrated desiccant. Low concentration desiccant is driven through a regenerator to regain the original concentration. The regenerator consists of a preheater, separator, heater and a contact device. Weak desiccant is preheated using the waste condenser heat from a VCR cycle. It is driven through the heater where the desiccant is heated to the boiling temperature, then enters the separator to eliminate moisture from the solution. The separator contains baffle plates and is insulated using Asbestos covering. This completes a first stage of dehumidification. The desiccant moves into the contact device where it is in contact with the reciprocating packing. Due to the vapor pressure difference between hot desiccant and the fresh air entering the contact device, a second stage dehumidification takes place. In the second stage regeneration, due to the packing action, the temperature of the desiccant slightly drops down. The high temperature concentrated desiccant is made to pass through the radiator to reduce the temperature drastically and the warm desiccant enters the absorber unit where the temperature of the desiccant is in equilibrium temperature due to the evaporator coil. Table.1 gives the operating conditions of the system.

https://doi.org/10.52202/069564-0029

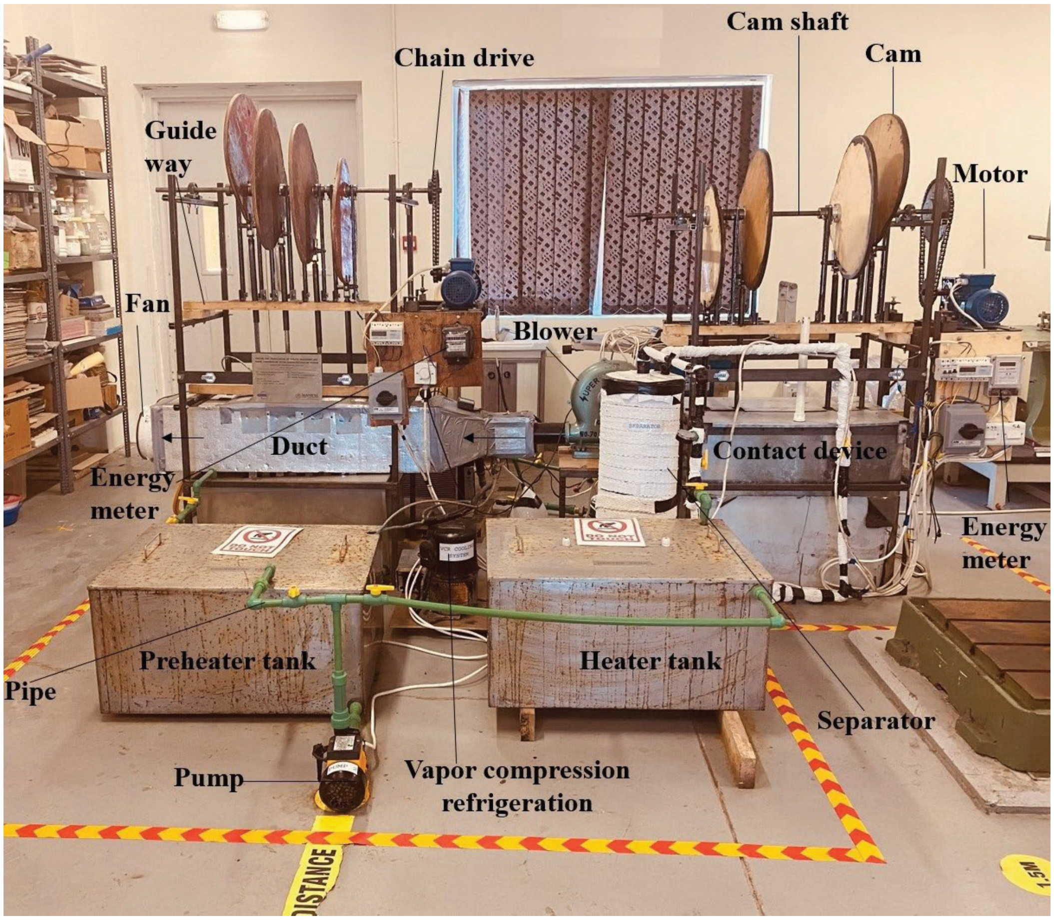

Figure.2: View of the multistage dehumidifier test rig

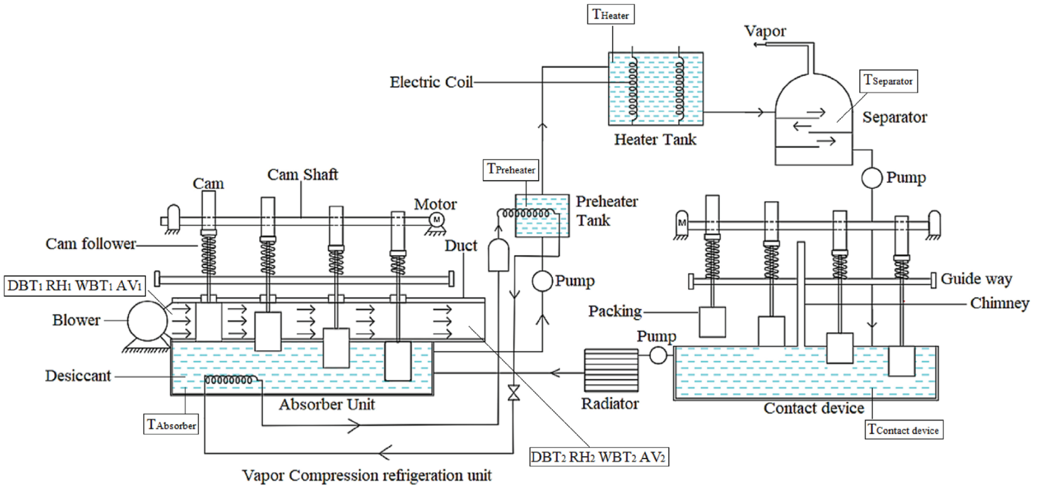

Figure.3: Scheme of the multistage dehumidifier test rig

Table.1. Experimental conditions and parameters studied

Packing, wettability, type of flow and fluids	Inlet conditions	Measuring parameters	Performance parameters
Packing: Celdek 7090, Wettability: 632 m²/m³ Type of flow: cross flow Fluids: Air and Calcium Chloride desiccant Cam shaft speed: 10 rpm	Inlet temperature: 30 to 42ºC Mass flow rate: 0.23 to 0.62 kg/s Desiccant concentration: 20%, 30% and 40%	Outlet temperature, relative humidity, wet bulb temperature	Moisture removal rate, COP, dehumidification efficiency, mass transfer coefficient

2.2. Measuring instruments

Several instruments are used to measure the operating parameters. A refractometer is used to measure the concentration of the salt. It measures the salinity range between 1 to 100% and has a resolution of 1%. The desiccant flow is measured using a flow meter which has a range of flow between 10 to 120 LPM and has a pressure value of 20 bar. Dry bulb temperature is measured using Pt100 thermometers with a range from -20 to 80°C, accuracy ± 0.1˚C, and resolution of 0.1˚C. To measure the wet bulb temperature, a Pt100 thermometer with similar specification is used, where the bulb is covered with a soaked cloth. Capacitive hygrometers are used to measure the relative humidity, which has a range of 0 to 99%. Anemometer measures the air velocity of air which has the range of 0.3 to 30 m/s and resolution 0.1 m/s. Tachometer measures the cam shaft speed of rotation which has range of 10 to 9999 rpm and resolution 0.1 rpm. Energy meter measures the total energy consumed by the unit during the operation period. It has voltage of 220 V, frequency 50 Hz and current 80 A.

3. Results and discussion

Experiments have been conducted by varying the mass flow rate of air and desiccant concentration. For a particular concentration, mass flow rate of air is varied from 0.23 kg/s to 0.62 kg/s with an increment of 0.1 kg/s. Air and desiccant conditions such as air temperature, specific humidity, desiccant concentration, and air velocity are measured at the inlet and exit of the system.

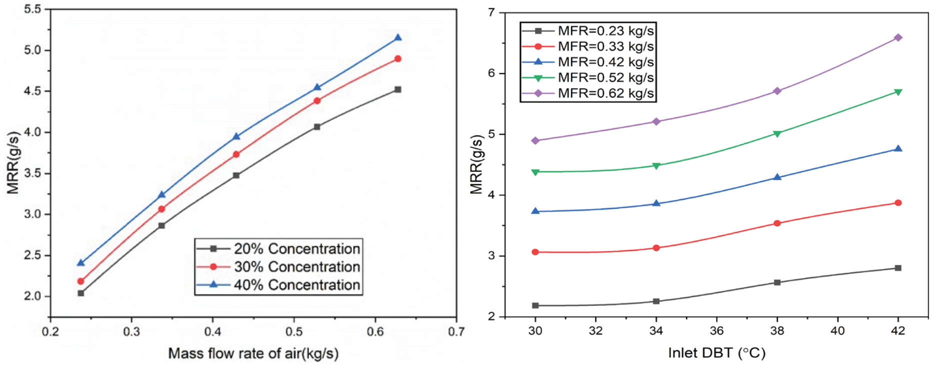

Figure. 4. Variation of MRR with mass flow rate of air and inlet DBT

Figure 4 shows the variation of MRR with the flow rate for different desiccant concentrations. As the concentration and mass flow rate increases, MRR also increases. Higher air velocities have higher mass flow rates. Even though difference in the humidity ratio decreases for higher mass flow rates, increased mass helps to remove more moisture per time unit. This increases the MRR (g/s). As the concentration is increased, vapour pressure difference between air and the desiccant also increase. Higher vapour pressure difference increases the ability to remove more moisture. Hence, 40% concentration desiccant absorbs more moisture than 20 %.

Figure 4 also shows the variation of MRR with the inlet air temperatures. For any value of fixed air relative humidity, as the air temperature increases, humidity ratio also increases. This increases the dehumidification capacity of the air sample. Hence, as the inlet air temperature increases, higher MRR is observed. The results show that for 0.52 kg/s air flow rate, MRR increases by 11.79% for 40% desiccant concentration, as compared to that of 20% concentration. Similarly, when the inlet temperature varies from 30 to 42°C, MRR increases by 30.2%.

https://doi.org/10.52202/069564-0029

3.1. Outlet DBT

Figure 5 shows the variation of the exit DBT with the mass flow rate and the inlet DBT for different desiccant concentrations. Higher concentrated desiccant can absorb more moisture from the air, or, in other words, higher heat of condensation is released. This heat increases the temperature of both the air and the desiccant. This leads to a rise in the exit air temperature for all tested cases. As the mass flow rate of the air increases, the amount of moisture being condensed reduces, which in turn reduces the exit air temperature.

Figure 5 also depicts the variation of the exit DBT for different air inlet temperatures. Higher inlet temperature increases the temperature rise for any fixed air mass flow rate. This is because higher inlet temperature is responsible for higher dehumidification, hence enhanced heat transfer rate, which also increases the air temperature. From the tested values, it is observed that the air exit temperature is 4.5% higher for 40 % desiccant concentration than for 20% concentration and 0.52 kg/s air flow rate. When the inlet temperature varied from 30 to 42°C, exit DBT raises by 83%.

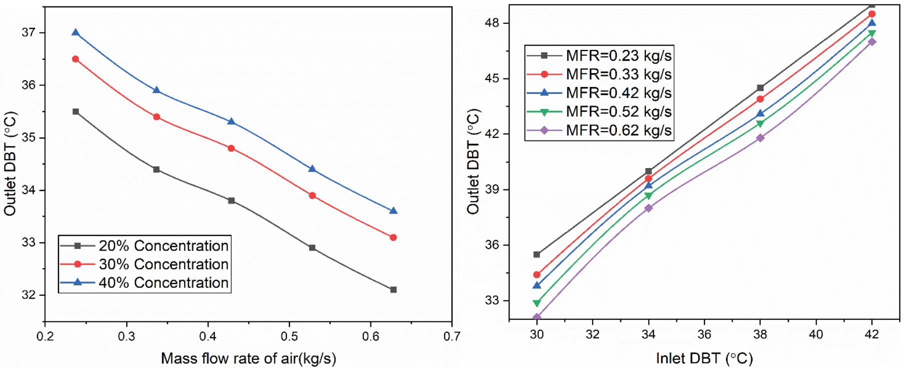

Figure. 5. Variation of outlet DBT of air with mass flow rate and inlet DBT

3.2. Dehumidification or moisture effectiveness (DE)

Dehumidification or moisture effectiveness (DE) is the ratio of moisture absorbed by the desiccant to the difference between the inlet and equilibrium moisture. Equilibrium moisture is the moisture contained by the air sample at the desiccant inlet conditions. It is clearly seen from figure 6 that higher desiccant concentrations show higher moisture effectiveness. This is because as the concentration increases, dehumidification also increases. For a constant value of equilibrium moisture, higher DE will be observed. As the mass flow rate of the moisture increases, DE value decreases resulting in reduced DE.

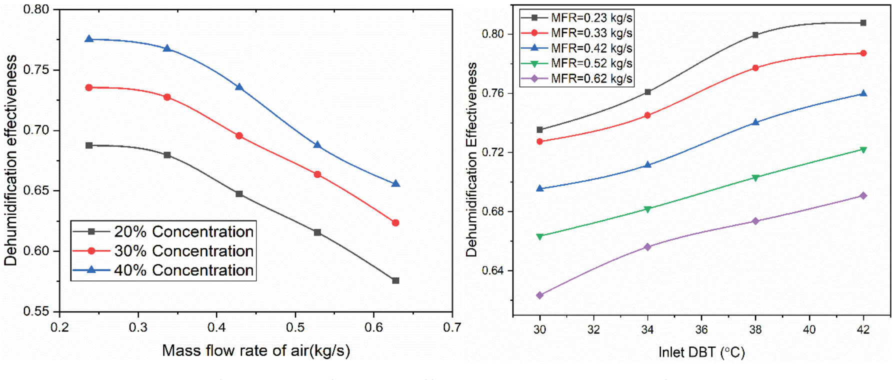

Figure. 6. Variation of Dehumidification effectiveness with mass flow rate and inlet DBT

Figure 6 also depicts the variation of DE for various inlet air temperatures. As the air inlet temperature increases, DE also increases. Similarly, as the inlet temperature increases, dehumidification capacity of air sample increases. For any constant RH condition, specific humidity values are higher for higher temperatures. This increases the dehumidification capacity. Hence higher temperature will have higher tendency for dehumidification. When the concentration is increased from 20% to 40%, DE increases 11.5% for 0.52 kg/s air flow rate. For the same air mass flow rate, when the inlet temperature increases from 30 to 42°C, DE increases by 10.6%.

3.3. COP

COP is the ratio of enthalpy change due to the dehumidification to the total energy input to the system. Total energy input includes the work supplied to the blower and the motor that runs the cams. It is observed from figure 7 that desiccant concentration significantly influences the COP, as the dehumidification values increase when increasing the desiccant concentration. Furthermore, as the air mass flow rate increases, COP tends to rise. Even though energy input to the blower increases for higher mass flow rates, the increased enthalpy difference contributes to higher COP values. It is also seen that higher inlet temperatures tend to enhance the COP. This is mainly due to the higher moisture absorbing capacity of the air sample at higher temperatures with fixed RH conditions. Concerning the energy requirements, these are independent from the inlet temperatures. Consequently, higher inlet DBT increases the enthalpy difference and hence the COP. The experimental results reveal that when the desiccant concentration is enhanced from 20 % to 40%, COP rises by 48%. Similarly, when the inlet temperature increased from 30 to 42°C, the COP is increased by 45% for 0.53 kg/s air flow rate.

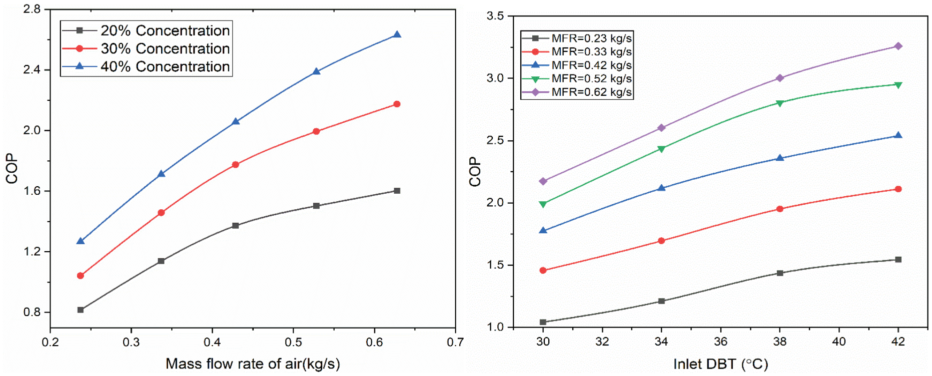

Figure 7. Variation of COP with mass flow rate and inlet DBT

4. Conclusions

Experimental investigations are conducted in a reciprocating multistage dehumidification unit to assess the dehumidification performance for different $CaCl_2$ desiccant concentrations and different air inlet temperatures. The results obtained can be summarized as follows:

- Multistage reciprocating dehumidification shows better performance as compared to that of a single stage stationary type, with higher values of MRR and moisture effectiveness.
- Increasing the concentration from 20 to 40% increases the MRR, DE, and COP by 17.6%, 13.2% and 53.6%, respectively, for 0.23 kg/s air flow rate.
- When the inlet temperature increased from 30 to 42°C, the performance parameters MRR, DE, and COP increased by 27.2%, 34.5% and 49 %, respectively, for 0.23 kg/s air flow rate.
- When the mass flow rate is increased from 0.23 kg/s to 0.72 kg/s, the DBT, humidity ratio, and DE decrease by 9.5%,7.2%,16.1%; whereas the MRR and the COP increase by 80% and 95%, respectively, for 20% desiccant solution and inlet temperature of 34°C.

Hence, it is seen that a multistage reciprocating dehumidification unit offers benefits such as higher performance with reduced desiccant consumption, as the desiccant remains stationary unlike the conventional dehumidification systems. As the four pads are intermittently in contact with air, pressure drop and energy consumption are lower. This contributes to more sustainable dehumidification technologies with minimum energy consumption and environmental pollution.

Acknowledgments

Authors are thankful to the lab support provided by the School of Engineering & IT, Manipal Academy of Higher education, Dubai, UAE.

Nomenclature

$\dot{m}$	mass flow rate, kg/s
T	temperature, °C
ΔT	temperature difference, °C
RH	relative humidity, %

K mass transfer rate, kg/(m^{2}s)
w specific humidity, g/kg
HE Heating Effect, W

Greek symbols

ε dehumidification effectiveness or efficiency, %

Subscripts and superscripts

a air
av average
eq equilibrium
i inlet
o outlet

References

[1] Naik BK, Muthukumar P. Experimental investigation and parametric studies on structured packing chamber based liquid desiccant dehumidification and regeneration systems. Build Environ 2019;149:330-348.

[2] Salins SS, Reddy SVK, Kumar S. Assessment of process parameters in a dehumidification process using biomass-based wood shaving as a packing material. Indoor Built Environ 2022;31(2):496-509.

[3] Ou X, Cai W, He X. Model-based optimization strategy for a liquid desiccant cooling and dehumidification system. Energy Build 2019;194:21-32.

[4] Qasem NAA, Zubair SM. Performance evaluation of a novel hybrid humidification-dehumidification (air-heated) system with an adsorption desalination system. Desalination 2019;461:37-54.

[5] Salins SS, Kota Reddy SV, Shiva Kumar. Experimental Investigation and Neural network based parametric prediction in a multistage reciprocating humidifier. Appl Energy 2021;293.

[6] Kavasoğullari B, Cihan E, Demir H. Novel Packing Materials for Open Liquid Desiccant System. Energy Procedia; 2016.

[7] Zegenhagen MT, Ricart C, Meyer T, Kühn R, Ziegler F. Experimental Investigation of A Liquid Desiccant System for Air Dehumidification Working with Ionic Liquids. Energy Procedia; 2015.

[8] Wu A, Li C, Zhang H. The primary research on liquid desiccant dehumidifier with cooling capacity using compression heat pump system. International refrigeration and air conditioning Conference. 2006.

[9] Mohamed ASA, Ahmed MS, Hassan AAM, Hassan MS. Performance evaluation of gauze packing for liquid desiccant dehumidification system. Case Stud Therm Eng 2016;8:260-276.

[10] Sampath SS, Kumar S, Kota Reddy SV. Influence of Different Desiccants, Flow Type and Packings on the Liquid Desiccant Dehumidification System: A Review. Intl J Air-Conditioning Refrig 2020;28(1).

[11] Dong C, Qi R, Lu L, Wang Y, Wang L. Comparative performance study on liquid desiccant dehumidification with different packing types for built environment. Sc Tech Built Environ 2017;23(1):116-126.

[12] Wang L, Xiao F, Zhang X, Kumar R. An experimental study on the dehumidification performance of a counter flow liquid desiccant dehumidifier. Int J Refrig 2016;70:289-301.

[13] Jain S, Tripathi S, Das RS. Experimental performance of a liquid desiccant dehumidification system under tropical climates. Energy Convers Manage 2011;52(6):2461-2466.

[14] Bouzenada S, Frainkin L, Léonard A. Experimental investigation on vapor pressure of desiccant for air conditioning application. Procedia Computer Science; 2017.

[15] Lu, J., Wang, M., Li, Y. and Yang, L., 2017. Numerical study on dehumidification performance of a crossflow liquid desiccant air dehumidifier. Procedia Engineering, 205, pp.3630-3637.

[16] Seenivasan D, Selladurai V, Arjunan TV. Experimental studies on the performance of dehumidifier using calcium chloride as a liquid desiccant. Int J Energy Technol Policy 2018;14(1):49-63.

[17] Cheng X, Rong Y, Zhou X, Gu C, Zhi X, Qiu L, et al. Performance analysis of a multistage internal circulation liquid desiccant dehumidifier. Appl Therm Eng 2020;172.

[18] Li, C.H., Chen, C.Y., Yang, T.F., Li, W.K. and Yan, W.M., 2020. Experimental study on heat and mass transfer of a multistage planar dehumidifier. International Journal of Heat and Mass Transfer, 148, p.119104.

https://doi.org/10.52202/069564-0029