Experimental study on dehumidification performance of liquid desiccant system with aqueous HCO_2K solution

DOI : 10.36909/jer.ICIPPSD.15533

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ABSTRACT

The liquid desiccant systems are one of the promising technologies in dehumidification applications. The experimental study on dehumidification performance of a counter flow structured packing liquid desiccant system is done with Aqueous HCO_2K as working fluid. The HCO_2K solution at different mass flow rate of air and solution is tested. The airflow rate is varied from 0.187 kg/s to 0.272 kg/s and the solution flow rate is varied from 0.053 to 0.115 kg/s. The output parameters, specific moisture change, moisture removal rate, dehumidification effectiveness and latent heat removal capacity varied in following ranges 3-4.2 g/kg of dry air, 2.4-3.1 kg/h, 0.12-0.21 and 1.7-2.1 kW respectively. Particularly when air flow rate increases from 0.187 kg/s to 0.272 kg/s the moisture removal performance improves about 11% whereas when the solution flow rate increases from 0.055 to 0.115 kg/s, improvement in moisture removal performance about 20%. The results imply that increase in solution flow rate always have the positive impact on dehumidification performance. The increase in airflow rate has the

negative impact on specific moisture removal and effectiveness, but the impact is positive in case of the moisture removal rate and latent heat removal capacity. The Overall results show a promising dehumidification performance and further improvement is possible by incorporating a cooling system.

Keywords: Liquid desiccant, Dehumidification, Potassium formate (HCO_2K)

NOMENCLATURE

w_{in}	Air humidity ratio at entry of the dehumidifier g/kg of dry air
w_{out}	Air humidity ratio at exit of the dehumidifier in g/kg of dry air
w_{eq}	Equilibrium humidity ratio of the water vapour in liquid desiccant g/kg
$\dot{m}_{air}$	mass flow rate of air in kg/s
T_{sol}	Temperature of solution in °C
MRR	Moisture removal rate in kg/h
$\dot{m}_{sol}$	mass flow rate of solution in kg/s
ε_d	Dehumidification effectiveness

INTRODUCTION

Humidity control is recognized as a vital issue in industrial, agricultural, and residential sectors specifically in hot and humid climates. Conventional vapor compression systems for air conditioning consumes most of its input power to handle the latent heat load. Also the refrigerants like HFCs have negative impacts on environment(Chen et al. 2019).The air conditioning load can be reduced about to 3-20% by incorporating insulations over the roof and wall. But the reduction in humidity in the building is not possible with these passive measures (Shwehdi et al. 2015). The limitations associated with vapor compression systems urged researchers to survey new alternative technologies, which are environment-friendly, energy efficient and promising technologies for air conditioning applications. Over the years, liquid desiccant systems have gained significant interest as they utilize the desiccant material a hygroscopic substance to dehumidify the air and provide favorable comfort conditions by improving the indoor air quality while reducing the power consumption of vapor compression air conditioners specifically. Liquid desiccant systems are more promising than solid desiccant systems as they provide more advantages and control flexibility over solid desiccants (Shehadi 2018). Many works related to liquid desiccant system integration with other conventional systems has been reported that C.O.P of the combined systems is found to be increased (Yamaguchi et al. 2011). The internally cooled counter flow dehumidifier offers better dehumidification ability than adiabatic systems. The internally cooled system shows the higher dehumidification efficiency at lower solution flow rates whereas adiabatic system shows better performance in larger solution flow rates (Liu, Liu, and Zhang 2019). LiCl and LiBr solutions show the higher dehumidification ability but are expensive. Cost effective desiccants like Magnesium chloride $MgCl_2$ and Calcium chloride $CaCl_2$ solutions are able to dehumidify the air to considerable extent. Alternatives like HCO_2K, $Ca(NO_3)_2$ and H_2PO_2 provide better dehumidification performance and are less corrosive (Giampieri et al. 2018). Experimental results indicated that 70.3% HCO_2K solution had almost the same vapor pressure as 35% LiCl solution but absolute moisture removal of HCO_2K solution was found be slightly higher than LiCl solution and the proposed correlation mentioned will be valuable for the application of HCO_2K solution in any LDCS (Wen et al. 2021). Additionally, the thermal properties including the density and vapor pressure of HCO_2K solution were measured and fitted as polynomials and the obtained data will be helpful for studying the performance of dehumidifier/regenerator utilizing HCO_2K solution.(Wen et al. 2019). A proposed polymer hollow fibre integrated desiccant dehumidification system was experimentally investigated and showed comparable dehumidification performance with respect to other porous media integrated liquid desiccant dehumidification system using potassium format (Chen et al. 2018). The effect of various operating inlet parameters on the outlet and performance parameters for the Celdek packed dehumidifier using calcium chloride as desiccant is investigated experimentally and found that the dehumidification performance of the system is affected by solution and air flow rates significantly (Kumar and Asati 2016). Optimization algorithms namely Genetic algorithm, simulated annealing, geometric programming, and particle swarm optimization are studied for a cost saving objective, where Genetic algorithm and particle swarm optimization provides better optimal solutions. Such algorithms also can be applied for liquid desiccant technology to find the optimum operating parameters in energy saving aspect (Ubeku and Odiase 2014). Thermal flume simulations study performed in high rise building for a VRF air conditioning system. The temperatures and air distribution at different locations are found by the simulation study. Such simulations can be effective in examining the performance of liquid desiccant system for predicting the temperature and velocity distribution inside the dehumidifier (Zhang et al. 2019). The exergy analysis is performed in air conditioning system with different refrigerants, where the exergy efficiency is increased to 13.2 % when R404 A is replaced with R600A. The exergy analysis also can be performed for liquid desiccant systems to evaluate the actual performance and exergy destruction of the system (Ozbek 2016).The parabolic trough type concentrated solar collector in a small scale is studied with different thermal fluids such as *therminol, dowtherm and paratherm* etc., to evaluate the heat transfer effectiveness. The use of such heat transfer fluid can improve the performance of liquid desiccant system. Particularly liquid desiccant regeneration unit can be integrated with solar collectors with these effective heat transfer fluids (Ullah et al. 2021). Solar based desalination is studied in the plate type collector associated with air flow enhancement. Where the study implies that counter current air flow enhances the desalination performance about 30%. Moreover, the recycling of condensed air improves the performance about 3.6 times. Since the desalination process is similar to that of liquid desiccant regeneration process, the study helps in understanding the effect of air flow (Mousa and Mjalli 2018). The recent numerical study of spray type liquid desiccant system reported that increase in solution flow rate and decrease in air flow rate improves the specific moisture removal. But when the moisture removal increases, the temperature rise in the air and solution also increases which can be avoided by adding cooling system (Ijas et al. 2021). The literature study implies that there is a lot of scope to utilize the liquid desiccant system in dehumidification and air conditioning applications. Recent studies mentioned that potassium format as one of the ecofriendly well performing liquid desiccants. At the same time more studies required to address the performance of the liquid desiccant system with potassium format. Hence, this study aims to evaluate the dehumidification performance of the aqueous potassium format solution experimentally and to find the effect of flow rates of the air and desiccant solution.

EXPERIMENTAL METHODOLOGY

An experimental study is performed on liquid desiccant system to study the effect of mass flow rates of air and desiccant solution on dehumidification performance. An existing experimental setup is being used which is installed in hydraulics lab NIT Calicut, Kerala India. The study is aimed to perform only dehumidification performance. So, there is no cooling system incorporated with the liquid desiccant system. The testing is done under the climatic condition of the location where the setup is installed, which is a warm humid outdoor condition. The details of experimental setup and study parameters are explained in following sections.

EXPERIMENTAL SETUP DETAILS AND WORKING PRINCIPLE

The Figure 1.a shows the schematic diagram of the experimental setup and the Fig.1.b shows the photographic view of the setup. The Experimental setup is a counter flow packed type dehumidifier. The entire dehumidifier body is made of GI sheet. Inside the dehumidifier body, the structured packing made of ABS (Acrylonitrile butadiene styrene) is provided as replaceable. The air inlet is provided at the bottom of packing and the outlet is located at the top of the packing. The solution inlet is provided as spray type at the top of the dehumidifier packing and the outlet is provided at the bottom. A dual inlet single outlet variable flow blower (310 W) is fitted at the inlet to supply the air to the system. The blower speed can be varied such that air flow rate will vary from 350 – 550 CFM. Similarly, a non-corrosive submersible pump (40 W) is provided to supply the liquid desiccant solution. A ball valve is provided to control the solution flow rate. Two plastic tanks (25 liters each) are provided to store the strong solution and collect the weak liquid desiccant respectively. The strong liquid desiccant is supplied by the pump to the top of the dehumidifier packing through the sprayers. The liquid is sprayed over the packing. Meanwhile the outdoor humid air is sent through the blower from the bottom of the packing. The air and solution interact o the surface of the structured packing. Due to the water vapor pressure difference between the solution and the humid air, the moisture from the humid air transfers to the solution. The dehumidified air leaves the dehumidifier at the outlet. During the dehumidification, solution becomes weak due to absorption of the moisture.

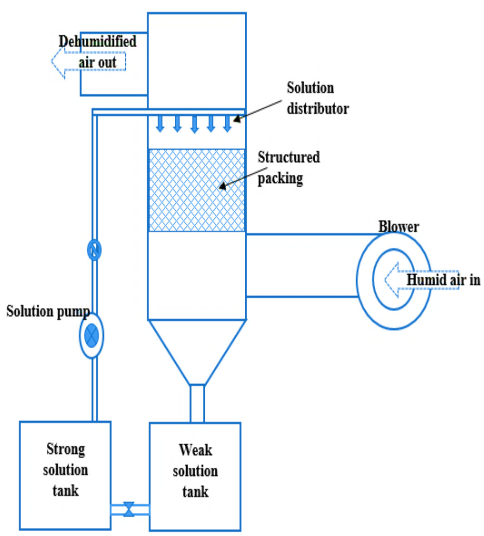

Figure 1a Schematic diagram of the experimental setup

Figure 1b Photographic view of the experimental setup

The weakened solution is being collected in the tank which is provided at the bottom of the dehumidifier. During the process of dehumidification there will be a slight increment in temperature of solution. This is due to exothermic reaction by absorbing the moisture. The weakened solution can be regenerated with the same system to concentrate it and the concentrated strong solution can be stored in storage tank and it can be used for further dehumidification cycle. The temperature, humidity and velocity of the air and the temperature, flow rate and concentration of the solution are measured as the primary parameters. The instrument details are provided in the Table 1.

Table 1 Instrument used and operating ranges, accuracy and resolution of the instrument

Instrument	Parameter	Range	Accuracy	Resolution
Testo 480 Anemometer	Temperature	0- 50^{o}C	± 0.6 ^{o}C	0.1^{o}C
	Relative humidity	0 - 100 %	±1.8%	0.1%
	Velocity	0-20 m/s	±0.03 m/s	0.01 m/s
Hydrometer	Specific gravity	1-2	±0.1	0.1

The vapor pressure of aqueous potassium format solution is calculated by the following equation provided by (Longo and Fedele 2018)

$$ln(p) = (17.864 + 2.7856/T - 2.564/T^2) + (-3659.7 - 306.42/T - 812.21/T^2).X + (249986.0 + 93118.0/T + 24973.0/T^2).X^2 \quad (1)$$

where, p - the vapour pressure of the solution in mbar; T - temperature of the solution in K; X - the salt mass fraction;

PERFORMANCE PARAMETERS TO BE STUDIED

The following parameters are evaluated to define the performance of dehumidification.

Specific humidity change (Δw): The difference of humidity ratio of the air between entering and leaving the dehumidifier (g/kg of dry air).

$$\Delta w = w_{in} - w_{out} \quad (2)$$

Dehumidification effectiveness (ε_d) : Ratio of actual moisture removed to the maximum moisture can be removed by the liquid desiccant.

$$\varepsilon_d = \frac{w_{in} - w_{out}}{w_{in} - w_{eq}} \quad (3)$$

The term w_{eq} is equilibrium humidity ratio is calculated as a function of vapour pressure of the liquid at particular solution concentration and temperature.

$$w_{eq} = 0.622 * \frac{P_{sol\ (X,T_{sol})}}{P_{atm} - P_{sol\ (X,T_{sol})}} \text{ kg/kg of dry air} \quad (4)$$

Moisture removal rate (MRR) (kg/h): Amount moisture removed from the air per hour. This value tells the actual moisture removed from the air over a period.

$$MRR = [\dot{m}_{air}(w_{in} - w_{out})] \times 3600 \text{ kg/h} \quad (5)$$

Latent heat removal capacity (kW): The heat removed due to removing moisture from the air is called as latent heat removal capacity.

$$Q_{latent} = \dot{m}_w h_{fg} \text{ or } [\dot{m}_{air}(h_{in} - h_{out})] \text{ kW} \quad (6)$$

h_{fg} is the latent heat of fusion of the water vapor at dry bulb temperature of air. The h_{in} and h_{out} are the enthalpies of air at taken inlet and outlet of the dehumidifier respectively.

These parameters are evaluated by varying the mass flow rate of air and solution flow rates when other operating conditions maintained as constants. The range of operating parameters and constant values are given in the Table 2.

Table 2 Operating Parameters

Parameters to be varied	Range	Reference value of the constant parameters
		DBT = 29°C ±1°C
		W_{in} = 19 g/kg of dry air ± 1 g/kg of dry air
		T_{sol} = 30°C ±1°C
		C_{sol} = 68% ±0.5%

UNCERTAINTY ANALYSIS

The uncertainty analysis is evaluated for the sample experiment readings using Propagation analysis method(Moffat 1988).If $a = f\ (x_1, x_2 \dots x_n)$; where $x_1, x_2, \dots x_n$ are the independent variables and $\partial c_1, \partial c_2 \dots \dots \partial c_n$ are the uncertainty of independent variables respectively. The resultant uncertainty (a_x) can be calculated by the following formula.

$$a_x = \sqrt{\left(\frac{\partial c_1}{\partial x_1}\right)^2 . \Delta a^2 + \left(\frac{\partial c_2}{\partial x_2}\right)^2 . \Delta a^2 + \cdots \left(\frac{\partial c_n}{\partial x_n}\right)^2 . \Delta a^2} \qquad (4)$$

The calculated uncertainty values are provided in the Table 3

Table 3: Uncertainty errors of the results

S.No	Parameters	Uncertainty
1.	Temperature	±0.6°C
2.	Relative humidity	±1.8%
3.	Velocity	±0.03 m/s
4.	Specific humidity	±0.615 g/kg of dry air
5.	MRR	±0.12 g/s
6.	Effectiveness	±0.004

RESULTS AND DISCUSSIONS:

The sample readings from the experimentation is provide in the Table 4. The table shows the values of specific moisture change (Δw) ranges from 2.6 to 4.2 g/kg of dry air. Other dehumidification performance parameters are also evaluated and the effect of mass flow rates of air and solution on these parameters is discussed in this section.

Table 4 Sample Readings

$T_{air\ in}$ °C	R.H.$_{in}$%	m_{air} kg/s	m_{sol} kg/s	$T_{sol\ in}$ °C	C_{sol} %	w_{eq} g/kg of dry air	$T_{air\ out}$ °C	R.H.$_{out}$%	w_{in}g/kg of dry air	w_{out}g/kg of dry air	Δw g/kg of dry air
29.4	75.5	0.187	0.115	29.1	70	9.8	29.6	59	19.6	15.4	4.2
29.8	72.6	0.187	0.093	29.2	69.8	9.7	30.4	56.6	19.3	15.5	3.8
29.8	73	0.187	0.055	30.2	69.5	10.0	31.5	54	19.4	15.7	3.6
29.9	73.9	0.225	0.115	30.1	69	11.0	31.9	54.2	19.8	16.2	3.6
29.8	74.2	0.225	0.093	29	71	9.6	30.6	58.7	19.7	16.3	3.4
29.4	74.8	0.225	0.055	29.1	71.5	9.8	29.8	61.9	19.6	16.4	3.2
29.5	71.8	0.272	0.115	30.2	70.8	9.1	30.7	56.8	18.9	15.8	3.1
30.2	70.9	0.272	0.093	30.1	70	9.3	31.2	58.3	19.5	16.7	2.8
29.1	76.2	0.272	0.055	30.3	71	9.4	30.9	60.8	19.8	17.2	2.6

The Figure 2 shows the specific humidity change with the variation in solution flow rate and air flow rate. The Δw is increasing with the increase in solution flow rate but decreases with the increase in air flow rate. Also, from the Figure 2 it is understood Δw decreases with increase in airflow rate for a single constant flowrate. Because at lower air flow rates, air gets enough time to interact with the solution. So the Δw reaches higher values in lower air flow rates. Since the solution is the moisture absorbing medium, the Δw keeps increasing with the increase in solution flow rates. The maximum Δw reaches up to 4.2 g/kg of dry air when a solution flow rate its maximum (0.115 kg/s) and air flow rate at its minimum value (0.187 kg/s)

The Figure 3 shows the moisture removal rate performance with the variation of air and solution flow rates. The moisture removal rate is the actual amount of moisture removed from the air during dehumidification over a time. Basically, MRR is a function of air flow rate, so the MRR has the increasing trend with increase in air flow rate. Since the MRR is a product of both air flow rate and Δw, some cases the variation of MRR depends upon the Δw also. But in higher air flow rate with the higher air solution flow rate MRR reaches the higher value up to 3.1 kg/h. So, the solution flow rate has the significant part in affecting the moisture removal rate also.

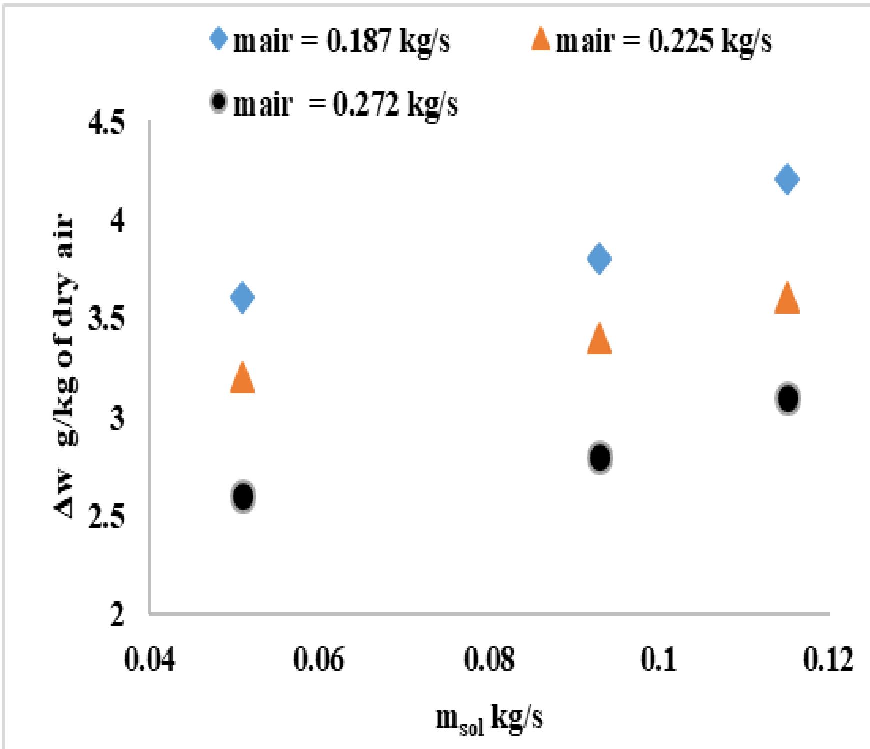

Figure 2 Specific moisture change (Δw)

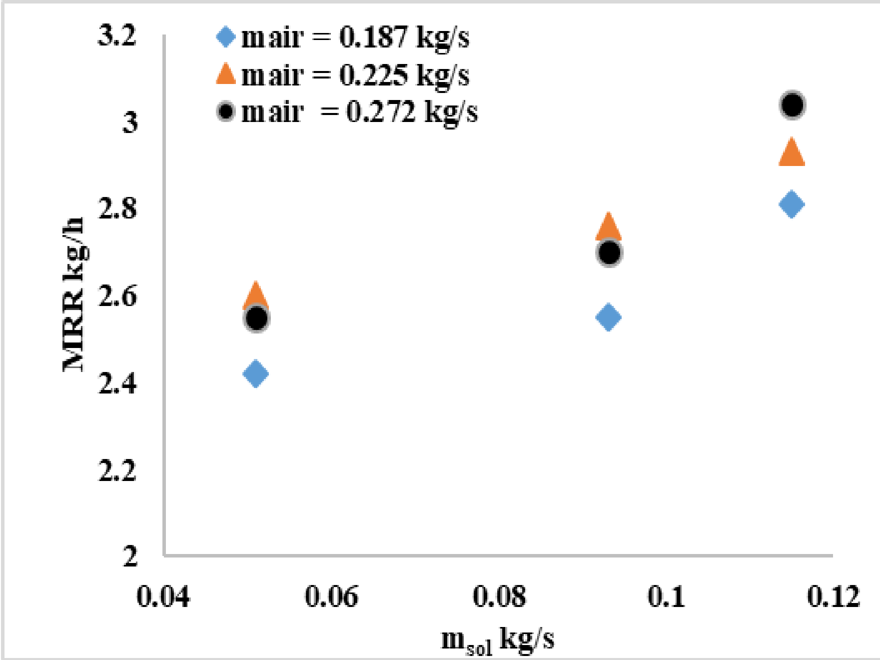

Figure 3 Moisture removal rate (MRR)

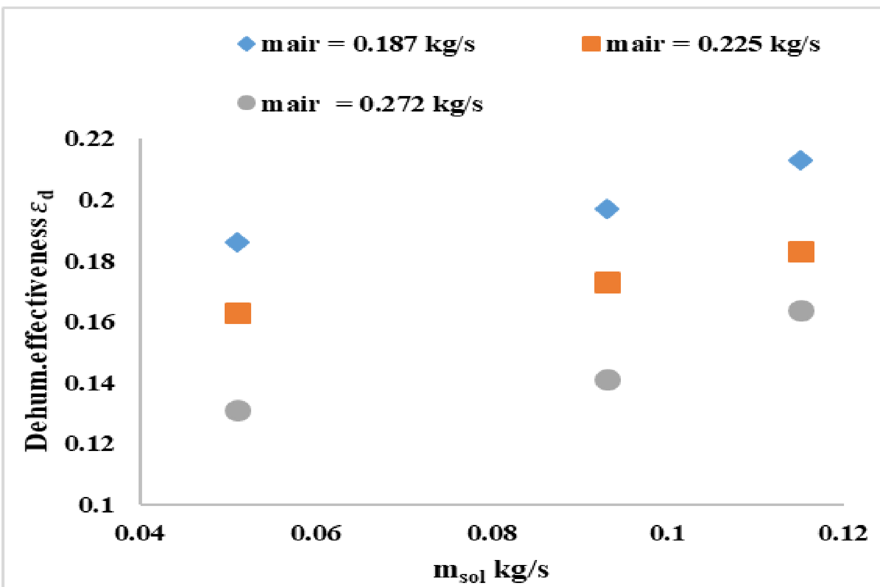

Figure 4 Dehumidification effectiveness

The Figure 5 shows the dehumidification effectiveness of the system with respect to solution and air flow rates. Dehumidification effectiveness is the ratio of the actual dehumidification to the maximum possible dehumidification. The system shows the effectiveness within the range of 0.12 to 0.21. the effectiveness is following the similar trend like Δw as it is a direct function of specific moisture change. So in similar way like Δw the effectiveness increase with the solution flow rate and decreases with the increase in air flow rate. Since the cooling system is not incorporated the effectiveness is not up to the mark. The effectiveness is also depending on other parameters such as packing type spraying and distribution of solution. So there is further scope to improve effectiveness by improving the design of the system.

The effect of mass flow rates of air and solution on latent heat removed shown in Figure 5.the latent heat removed is the heat removed by removal of moisture from the air. The latent heat is evaluated without accounting the sensible heat during the dehumidification. Since the latent heat removal is a function of MRR it follows the similar trend with the variation of flow rates of air and solution. The latent heat removal increases with both solution and air flow rate. The latent heat value reaches up to 2.1 kW for an air flow rate of 0.272 kg/s (550 CFM), which is equal to 0.6 TR of cooling capacity. Still at the same time there is a temperature rise in air up to 2℃ due to exothermic reaction of solution during moisture absorption. The heat can be addressed as sensible heat added during the process of dehumidification. Anyway, this temperature rise can be eliminated when the solution is used at low temperatures or by incorporating a dedicated cooling systems such as vapour compression refrigeration or evaporative cooling systems.

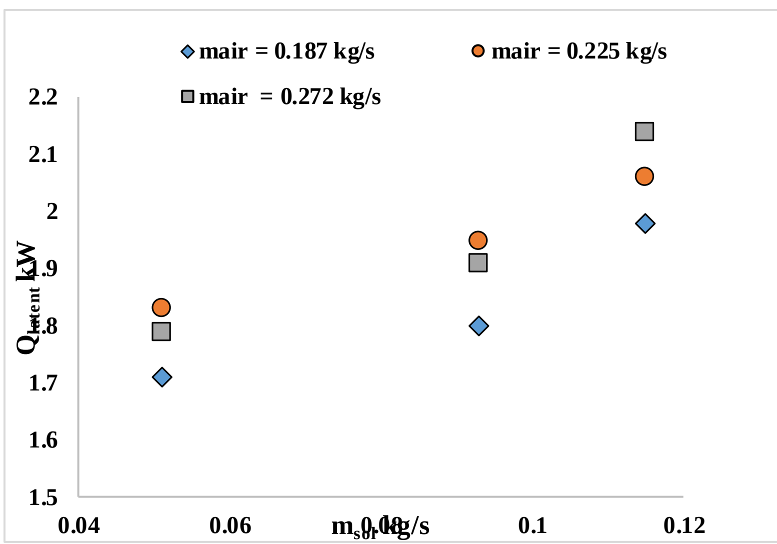

Figure 5 Latent heat removal capacity (Q_{latent})

CONCLUSION

The main purpose of the study is to evaluate the dehumidification performance of the liquid desiccant system with aqueous HCO_2K. The experimentation is done on structured packing counter-flow type dehumidifier. Mainly this study aimed to evaluate the dehumidification performance under the effect of solution flow rate and air flow rate variations. The following points are inferred from the current study. The specific moisture change (Δw), which is the primary parameter of dehumidification performance, reached up to 4.2 g/kg of dry air. The Δw increases with the increase in solution flow rate but decreases with increase in air flow rate. This is due to the reason that, at lower air flow rates there is sufficient time for interaction of air with the solution which leads in good moisture transfer from air to solution. Particularly the Δw reaches the maximum value (4.2 g/kg of dry air) at lowest air flow rate (0.187 kg/s) and highest solution flow rate (0.115 kg/s).The moisture removal rate is directly proportion to the mass flow rate of the air. But in some cases the moisture removal rate is lesser for the air flow rate 0.272 kg/s than that of 0.225 kg/s. This is due to the reason that at lower air flow rates the specific moisture change is better than higher air flow rates. So the specific moisture change is dominating in lower airflow rates. But when solution flow rate increases the MRR keep increases. At higher solution flow rate with higher air flow rate MRR reaches the maximum value of 3.1 kg/h. So, the increase in solution flow rate always increasing the moisture removal performance. The dehumidification effectiveness follows similar trend like specific moisture change (Δw) as it is a direct function of Δw. The effectiveness increases with the solution flow rate and decreases with air flow rate. The effectiveness lies in the range between 0.12 to 0.21. The effectiveness can be further improved with incorporating a solution cooling system. The latent heat removed is discussed which is evaluated without accounting the sensible heat added during dehumidification. The latent heat removal capacity (Q_{latent}) following a similar trend of moisture removal rate. The Q_{latent} increases with the increase in both solution flow rate and air flow rate. Q_{latent} reaches up to 2.1 kW which is a significant value without cooling system. Anyway, the sensible heat addition is not accounted here, by adding a cooling system the sensible heat can also be reduced and latent heat removal capacity can be further improved. Overall, the studied liquid desiccant dehumidification system with aqueous potassium format shows a significant dehumidification performance. The system still has the scope to improve the performance by adding the cooling system. The results particularly the latent heat removal shows feasibility that the system can be extended as an air conditioning system by incorporating a vapor compression or any other conventional cooling system.

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