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Humidity Control Using Liquid Desiccant system driven by Solar Energy.

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Abstract: *The major purpose of the present research is to develop and implement a simplified model that carries out the performance investigation of each component of a flat-plate liquid-desiccant dehumidifier and regenerator allowing for complete simulation of the mass and heat balance equations using ambient and inlet conditions. In the current work, the model was accomplished in Engineering Equation Solver (EES). A performance evaluation study of the liquid desiccant conditioning system with calcium chloride as liquid desiccant was investigated. The presented system uses as a heat source for the purpose of reusing the desiccant solution again after the absorption process. The results show that the water temperature, desiccant solution inlet concentration and inlet air probabilities have a strong effect on the dehumidifier and regenerator performance. Increasing the desiccant concentration entering the conditioner improves the water transfer performance in the humidifier, but inversely affect moisture desorption in the regenerator part. The calculations of the component models match well the desiccant solution mass balance between the dehumidifier and regenerator which should be aimed for system steady operation. Conditioner thermal* $COP_{th,c}$ *of 0.4854 and regenerator thermal* $COP_{th,r}$ *of 0.2861 are achieved respectively under steady inlet conditions at* $CaCl_2$ *concentration ratio 37.2%, process air temperature of 25℃, 50% relative humidity and 30℃ solution temperature.*

Keywords: *Liquid desiccant, Dehumidifier, humidity ratio, moisture adsorption, Solar energy.*

I. INTRODUCTION

At present-day, the proportion of energy used by the air-conditioning (A/C) systems in commercial buildings and household accounts for about 45% whereas they account for almost 15% of the world total energy consumption [1]. Vapour compression (VC) systems contribute a senior proportion of AC systems in use, although they are not only having low efficiency with high humidity but also use refrigerants which are one of the major reasons of ozone layer depletion. Therefore, research about alternative A/C systems has led to the thermal driven AC systems development, which use solar energy or waste heat as renewable energy applications cooling techniques.

In liquid desiccant (LD) air conditioning system, moisture is extracted from air in the absorber or dehumidifier. LD turns into dilute through absorption of air moisture and requires to be regenerated by through the regenerator. Desiccants are hygroscopic materials that have a great affinity for water vapor which have the capability of absorbing and adsorbing great amount of water vapor. They dehumidified air without lowering the air temperature below its dew-point [2]. The driving force of water vapor transfer between air and the desiccant solution is the difference in vapor pressure between the air and the desiccant surface. When the desiccant surface vapor pressure is less than that of air, the moisture is attracted by the desiccant and when air vapor pressure goes lower than the desiccant surface, moisture get released from desiccant [3]. Once the desiccant is filled with moisture, sustainable heat is used to return the desiccant to its dry state. This leads to replace the high electrical demand of the compressor in a conventional air conditioner by the need for thermal energy to regenerate the desiccant using solar thermal energy. Effectively, a desiccant system reduces the HVAC energy demand by reducing its latent cooling load required to dehumidify. The desiccants are available in both liquid and solid states. Each of liquid and solid desiccant systems has its own Pros and Cons.

There are several desiccant materials that are commonly used in LD systems like triethylene, aluminum silicate, aluminum oxides, silica gels, glycol, lithium bromide and lithium or calcium chloride solution with water, etc. In addition of having low regeneration temperature and utilization flexibility, LD have lower pressure drop on air side while solid desiccant are compact, less susceptible to carry over and corrosion [4].

Kim et al. investigated a liquid desiccant and evaporative cooling system application, in order to propose a simple empirical regenerator model which could be used for finding optimal regeneration temperature or flow rate of desiccant solution in the liquid desiccant system operation to minimize operating energy consumption [5]. D.B. Jani et al. focused on the effective use of desiccant cooling systems in comfort cooling that are used mostly the solid-based desiccant [6]. Minaal Sahlot and Saffa B. Riffat reviewed Liquid desiccant systems widely, while advanced desiccants were briefly reviewed. Hybrid of LD systems with other systems were also reviewed along with some successful case studies and they mentioned that the most commonly used salts for dehumidification systems were lithium and calcium chloride. Lithium chloride was commonly used due to its stability and low vapour pressure whereas calcium chloride was cheap and easily available. However, both salts have corrosive nature and need precaution before utilizing. They can also be mixed in convenient ratios to get a more efficient and cost saving LD. Internally cooled dehumidification systems help to reduce the heat drainage, which can improve the performance of the system [7]. Hongyu Bai, Jie Zhu, Junze Chu, Xiangjie Chen, Yuanlong Cui and Yuying Yan investigated the flat-plate membrane-based liquid desiccant system performance through mixing lithium and choloride calcium using theoretical and experimental approaches. A mathematical model was established to predict the system performance. It was noticed that the regeneration energy can be reduced by either providing a high concentration solution or increasing the content of calcium choloride in the mixture. Compared with the pure lithium choloride solution, the mixed solution system COP improved up to 30.23% by increasing $CaCl_2$ proportion to 30% of the concentration solution [8].

The main objective of this study is to analyze the performance of the system and achieve the solution balance between regenerator with that of the conditioner to allow continuous operation of the system by desorping amount of moisture from the desiccant solution in the regenerator that is equal to the moisture absorbed from air in the conditioner, otherwise some problems will occure such as the dilution of desiccant solution as a resultt of mass imbalance during time. A simulation model of the system using computer program (EES program) is developed to study the air absolute humidity which is affected by various parameters such as inlet air and desiccant solution flow rates, temperatures, cooling water and heating water temperatures while the heat and mass transfer processes across the conditioner and regenerator are analyzed.

II. SYSTEMS DESCRIPTION

The components of the proposed solar-assisted LDAC are illustrated in figure 1. The system consists of two main components; the dehumidifier (absorber), and the regenerator (desorber). They are low flow, falling-film, parallel-plate and heat and mass exchangers. The regenerator is used to desorb the moisture gained in conditioner in order to reuse the desiccant solution. The presented system uses $CaCl_2$ as a desiccant and solar energy as a heat source, heat energy from the sun transferred to the water through the heat pipe evacuated tube. Hot water flowed thereafter into a heat exchanger to heat water that has passed through a heat exchanger and the heat flow is reduced to the hot water tank and then flowed back to the collector with hot water pump.

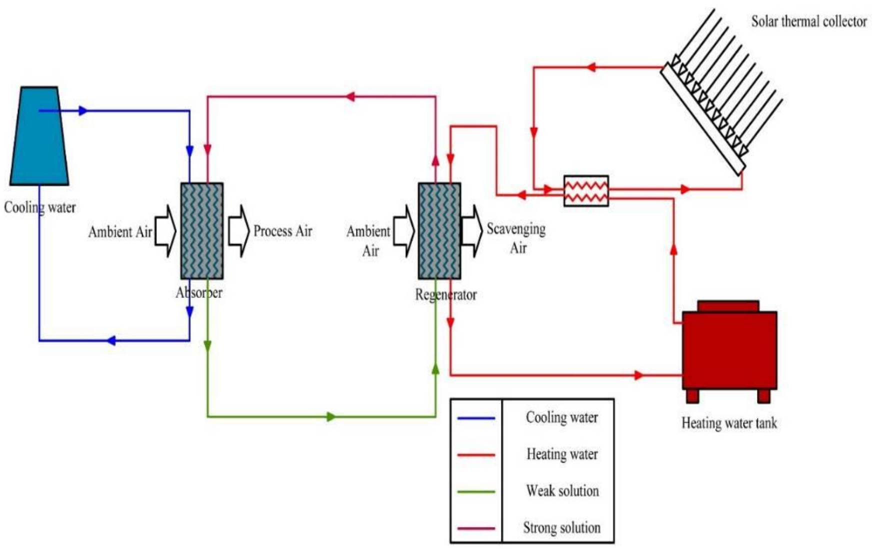

Figure 1. Simplified schematic of solar driven liquid desiccant air.

The mass transfer driving force of moisture between the air stream and the desiccant solution is the vapour pressure difference between the desiccant solution and the process air stream which is controlling the moisture absorption and desorption processes as illustrated in figure 2.a. At beginning, Air is flow across the desiccant streams falling down on the plates inside the conditioner and brought into contact with the strong desiccant solution where it gets dehumidified transferring both moisture and heat to desiccant solution. The moisture absorbed from the air dilutes the solution due to the vapour pressure difference between the air and the desiccant solution surface and then after the weak solution flows into the regenerator. This system uses an internally cooled parallel-plate for the conditioner as shown in figure 2.b. The cooling water flows inside narrow tubes inside each plate while a thin film of desiccant solution Pour over the outer surface of the plates. A cooling water source is needed for continuous process for the system. The cooling water lowers the equilibrium vapor pressure of the desiccant and reduces its temperature as a result, which improves the latent cooling, as well as decreasing the air stream temperature, letting for an amount of sensible cooling.

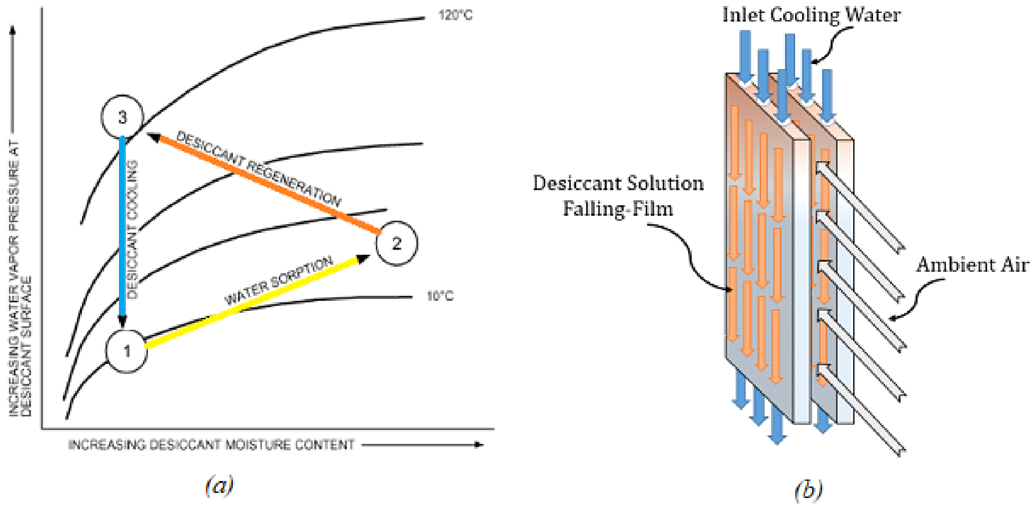

Figure 2. (a) Desiccant Cycle [9], (b) Internally cooled parallel plate falling-film conditioner.

Considering simple control volumes of dehumidifier and regenerator, mass and heat transfer governing equations have been obtained for the air and desiccant solution with some assumptions like that the system is operating in a steady state mode, only moisture is transferred between the air and the desiccant, the thickness of the desiccant falling film is very small, the conditioner and regenerator are adiabatic and there is no carryover of desiccant into the air stream. The conditioner deals with three working fluids; process air, desiccant solution and cooling water. As a result of direct and indirect contact between air, desiccant solution, and cooling water, heat and mass transfer takes place. Therefore, mass and heat balance equations that describe the operation of the conditioner is illustrated in figure 3.

III. MATHEMATICAL MODEL

The air is dehumidified in the process air stream, with absorbing moisture from air using the $CaCl_2$ desiccant solution, resulting in a lower outlet humidity ratio, the enthalpy of the outlet air stream is increased according to the heat transfer from desiccant to air, as well, the heat caused by evaporation and re-concentration of the salt solution.

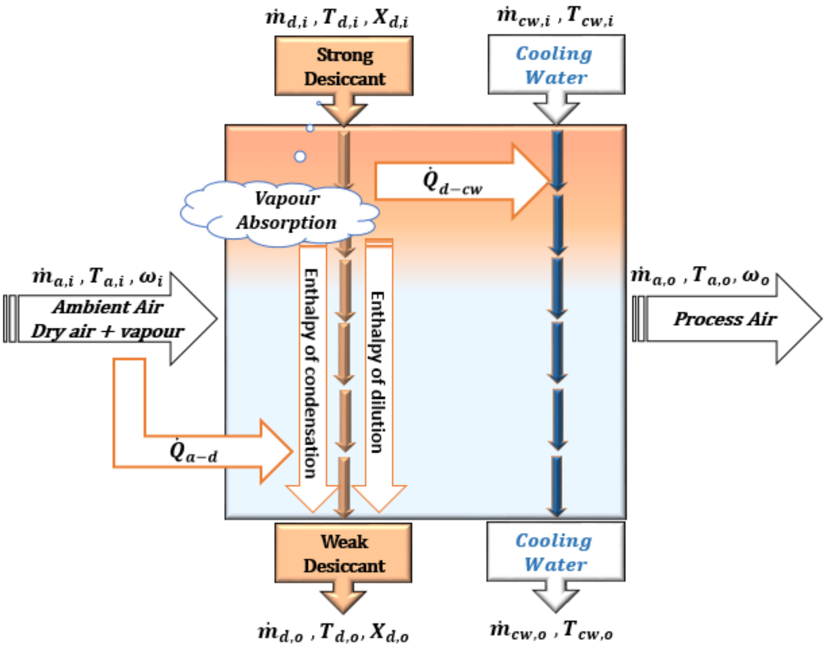

Figure 3. Schematic of mass and heat transfer in LD conditioner.

The mass and heat balance equations across the dehumidifier are clarified as:

$$\dot{m}_{a,i} * \omega_i = \dot{m}_{v(a-d)} + \dot{m}_{a,i} * \omega_o \quad (1)$$

Where $\dot{m}_{a_{i,c}}$ is the conditioner air mass flow rate, $\dot{m}_{v_{(a-d)}}$ is water vapor absorbed from air, $\omega_{i,c}$ and $\omega_{o,c}$ are the air absolute humilities into and out of the conditioner.

$$\dot{m}_{a,i} * \; h_{a,i} \; = \dot{m}_{a,o} * h_{a,o} + \dot{m}_{v_{(a-d)}} * \left(h_{fg} + h_{dil}\right) + \dot{Q}_{a-d} \quad (2)$$

Where $h_{a,i,c}$ and $h_{a,o,c}$ are the enthalpies of dry air into and out of the conditioner, $h_{fg,c}$ is the vaporization latent heat of and $\dot{Q}_{a-d}$ is the heat transfer rate between the air and the desiccant.

The strong inlet solution absorbs water vapor from the air stream, lowering the concentration of the solution, where the thermal contact with the process air and cooling water, and the condensation and dilution of the absorbed water vapor energy is taking in consider when study the energy balance of the desiccant solution. So the heat transferred from air to desiccant, the condensation and dilution enthalpies and the enthalpy of the inlet solution is equal to the output solution enthalpy in addition to the heat transferred from desiccant to cooling water as illustrated in following equations:

$$\dot{m}_{d,o,c} \; = \dot{m}_{d,i,c} + \dot{m}_{v_{(a-d),c}} \quad (3)$$

$$\dot{m}_{d,i,c}\, h_{d,i,c} + \dot{Q}_{(a-d),c} + \dot{m}_{v_{(a-d),c}} * \left(h_{fg,c} + h_{dil,c}\right) = \dot{m}_{d,o,c}\, h_{d,o,c} + \dot{Q}_{d-cw} \quad (4)$$

Where $\dot{m}_{d,i,c}$ and $\dot{m}_{d,o,c}$ are the conditioner inlet and outlet desiccant mass flow rate, $h_{d,i,c}$ and $h_{d,o,c}$ are the enthalpies of inlet and outlet solution across the conditioner.

Bouzenada investigated three effectiveness values to describe the conditioner, the dehumidification effectiveness, and the desiccant cooling water effectiveness [10], theses parameters are defined as follows:

$$\varepsilon_{deh,c} = \frac{\omega_{i,c} - \omega_{o,c}}{\omega_{i,c} - \omega_{eq,c}} \quad (5)$$

$$\varepsilon_{h,c} = \frac{h_{a,i,c} - h_{a,o,c}}{h_{a,i,c} - h_{eq,c}} \quad (6)$$

$$\varepsilon_{cw} = \frac{T_{d,i,c} - T_{d,o,c}}{T_{d,i,c} - T_{cw,i}} \quad (7)$$

Where $\omega_{eq,c}$ is the equivalent humidity ratio out of conditioner which occurs when the air is in equilibrium with the inlet desiccant concentration and inlet cooling water temperature, $h_{eq,c}$ is the minimum (equivalent) outlet enthalpy which occurs when the air is at the inlet cooling water temperature and has a humidity ratio of $\omega_{eq,c}$.

The regenerator is the other main component in LDAC systems, it is similar to the dehumidifier. However, the basic function and process of the two units is opposite to each other. It can be also modeled with a set of equations in the same approach. The air entering the regenerator is humidified by carrying out the vapor water from the weak solution due to heating it, resulting in a higher outlet humidity ratio. Whereas the enthalpy of the waste air stream is increased according to the heat transfer from desiccant to air, as well, the heat caused by evaporation and re-concentration of the salt solution.

The thermal cooling coefficient of performance of the conditioner is defined as the ratio of useful cooling to the heat consumption of regeneration [11], and defined as:

$$COP_c = \frac{\dot{m}_a * \left(h_{a_i} - h_{a_o}\right)}{\dot{m}_{hw_i} * Cp_{hw_i} * (T_{hw_i} - T_{hw_o})} \quad (8)$$

While the thermal coefficient of performance of the regenerator is described as the ratio of the water desorbed from the solution in terms of enthalpy to the heat absorbed in the regenerator,

$$COP_{reg} = \frac{\dot{m}_{v_{(d-a)}} * h_{fg_r}}{\dot{m}_{hw_i} * Cp_{hw_i} * (T_{hw_i} - T_{hw_o})} \quad (9)$$

IV. RESULT AND DISCUSSION

The previous analysis clarifies the dependence of the absorption process on operational parameters. An analytical model solution is developed using EES software program for calculating the air and desiccant solutions exit parameters after feeding the inlet parameters into the program.

4.1. Analysis of conditioner

Figure 4 represents the effect of the conditioner inlet air humidity ratio on the moisture absorption rate. As displayed, when inlet humidity ratio is elevated, the moisture absorbed from air directly proportional increases. It turns out that the partial vapor pressure between process air and the solution is the governing factor of the mass transfer occurs. As the inlet air humidity ratio increases, the partial vapor pressure of air also increases which in turn improves the partial vapor pressure difference between the inlet air-stream and that on the solution surface performing the raise in the moisture absorbing capacity of the desiccant solution [12].

As a result, the outlet humidity ratio of air is increased after moisture transfer to solution which causing the solution concentration to be decreased due to water vapor absorption.

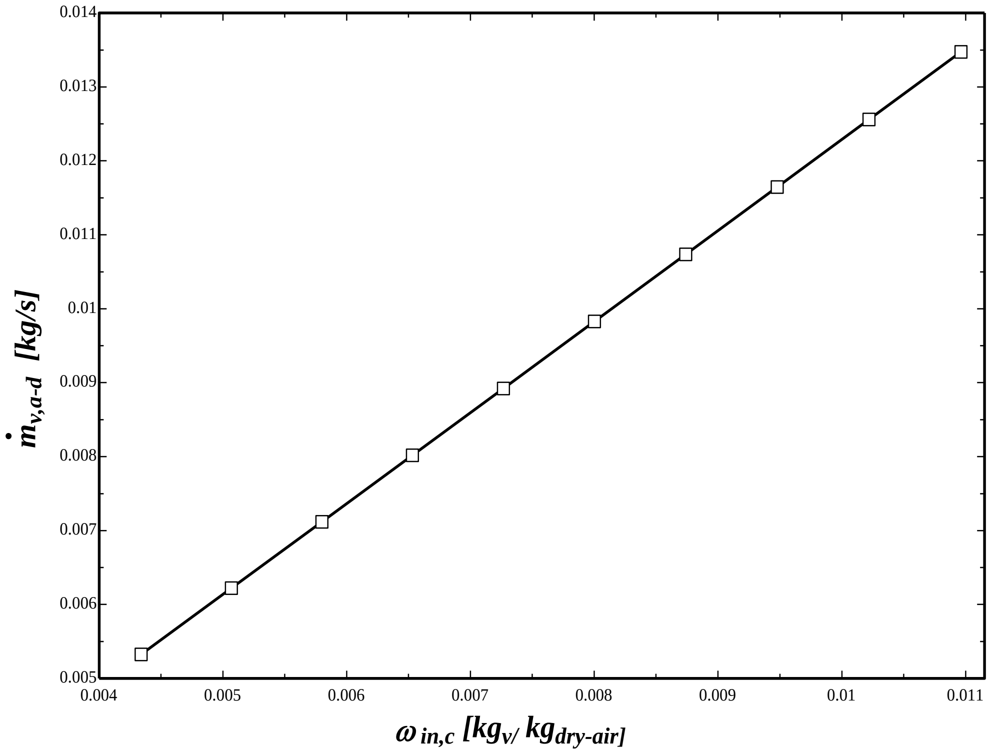

Figure 4. Effect of inlet humidity ratio on moisture absorption rate.

The effect of the inlet air temperature on the moisture absorption rate is described in figure 5. When the inlet air temperature is increased, the moisture absorption rate is increased also. That can be explained as that there is a fundamental relationship between dry bulb temperature of air and the moisture amount in it [13]. As the air temperature increases, the partial pressure increases and as a result the humidity ratio increases, which elevate the amount of moisture absorbed from air Consequently.

The moisture rate transferred from air to desiccant solution decreases with the increase of cooling water temperature. At higher temperature, the vapor pressure at solution surface is higher, and less moisture is driven from the air into the solution by the smaller vapor pressure difference. Figure 6 shows the effect of inlet cooling water temperature on the moisture removal rate. The results show strong dependence of desorption rate on inlet cooling water temperature since moisture removal rate declines from 0.012 kg/s to 0.00825 kg/s as inlet cooling water temperature increased from 15°C to 33°C.

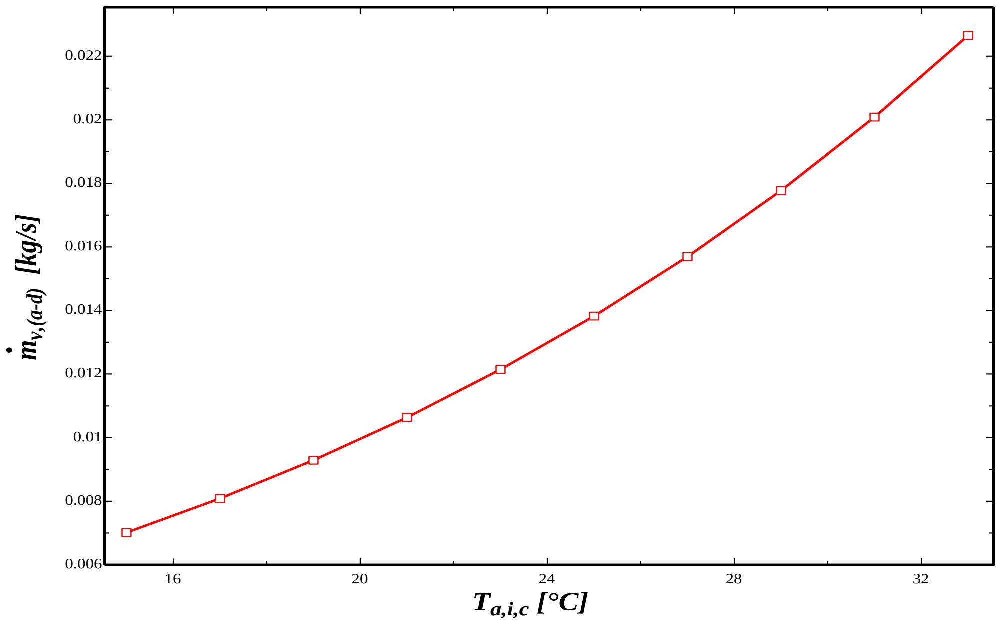

Figure 5. Effect of inlet air temperature on moisture absorption rate.

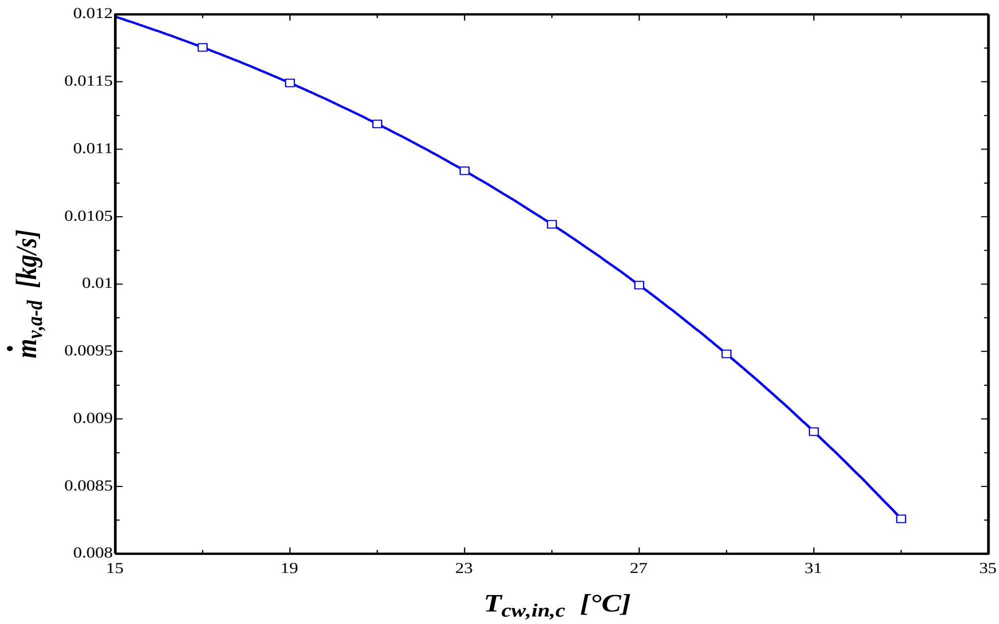

Figure 6. Effect of inlet air temperature on moisture absorption rate.

When the inlet desiccant solution concentration increases, the solution surface vapor pressure is decreased, leading to lowering outlet humidity ratio which in turn raises moisture removal rate, which reduces the mass transfer driving force between the desiccant and the moist air as presented in figure 7.

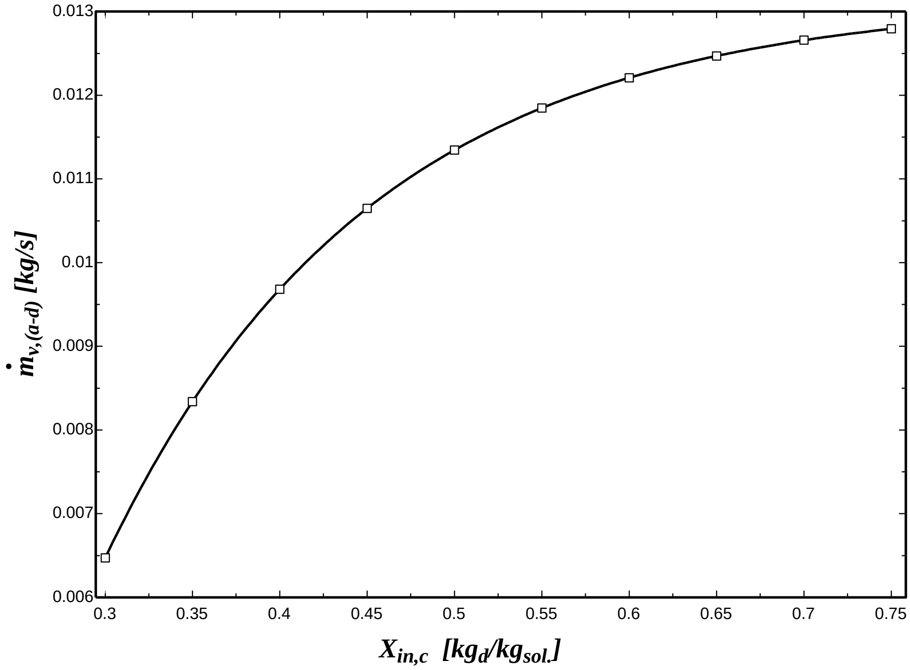

Figure 7. Effect of inlet desiccant concentration on moisture transfer rate.

4.2. Analysis of regenerator

On the contrary, the major function of scavenging air in the regeneration process is to carry over the water vapor from the desiccant solution as the weak desiccant solution becomes stronger by desorption process inside the regenerator. the moisture desorption rate decreases with the increase in the inlet air humidity. This is due to the increasing in partial vapor pressure according to the increasing of the inlet air humidity ratio which leads to the reduction in the difference between the partial vapor pressure of the inlet air stream and that on desiccant solution surface which in turn, results in a decreasing in the moisture desorption potential of air causes lowering in moisture desorption rate [14] as shown in figure 8.

While figure 9 shows that When the inlet air temperature increased, the desorption rate is increased consequently, desorption rate is increased respectively. This can be explained that when the scavenging air temperature is increased, the temperature of the desiccant solution inside the regenerator is also increased which in turn increases the partial vapor pressure on the desiccant surface. When the desiccant surface pressure is elevated, the desorption process potential is increased causing air to become more humid and strong desiccant solution is gained.

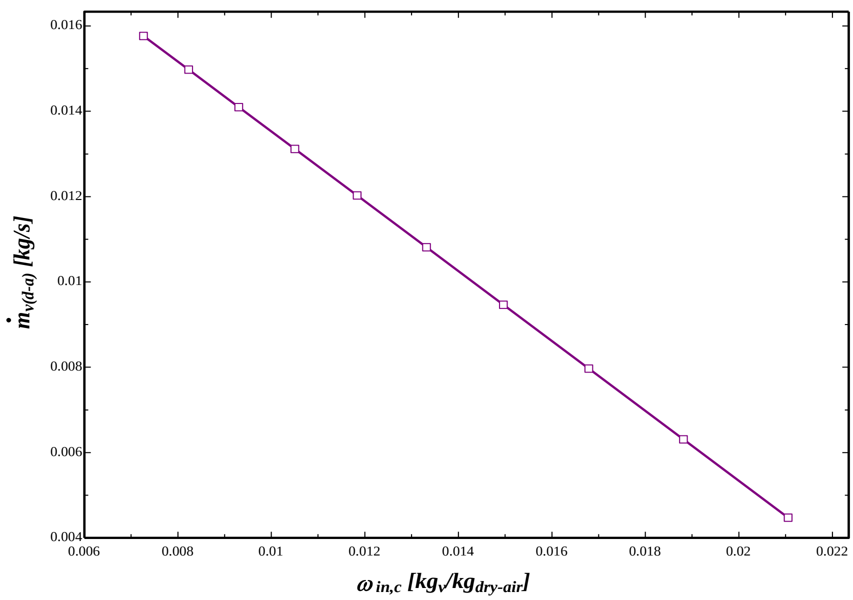

Figure 8. Effect of inlet air humidity ratio on moisture desorption rate.

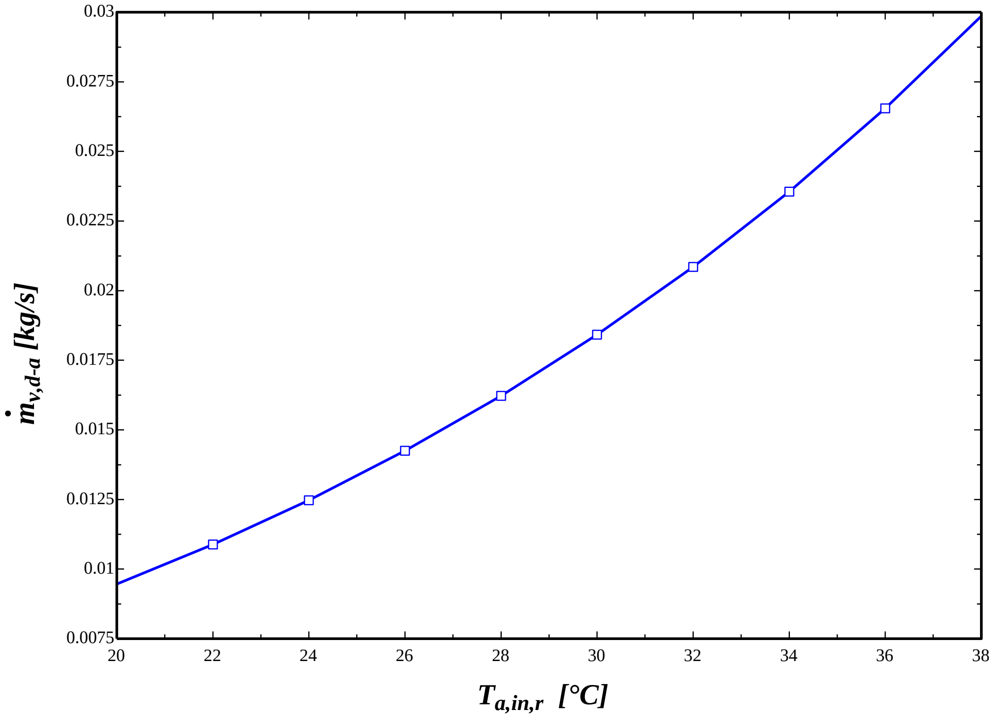

Figure 9. Effect of inlet air temperature on moisture desorption rate.

The heating water temperature is an important parameter for LDC systems, as it affects the performance of the overall system significantly. Figure 10 depicts the impact of the heating water temperature on moisture removal. When heating water temperature is increased, moisture adsorption rate is accordingly raised. This could be attributed to the increase in the desiccant solution to a higher temperature through the indirect contact with heating water. The increase in solution temperature results in a higher solution side vapour pressure and this leads to a greater vapour pressure differential between the solution and air, and thus an increase in mass transfer potential takes place [15].

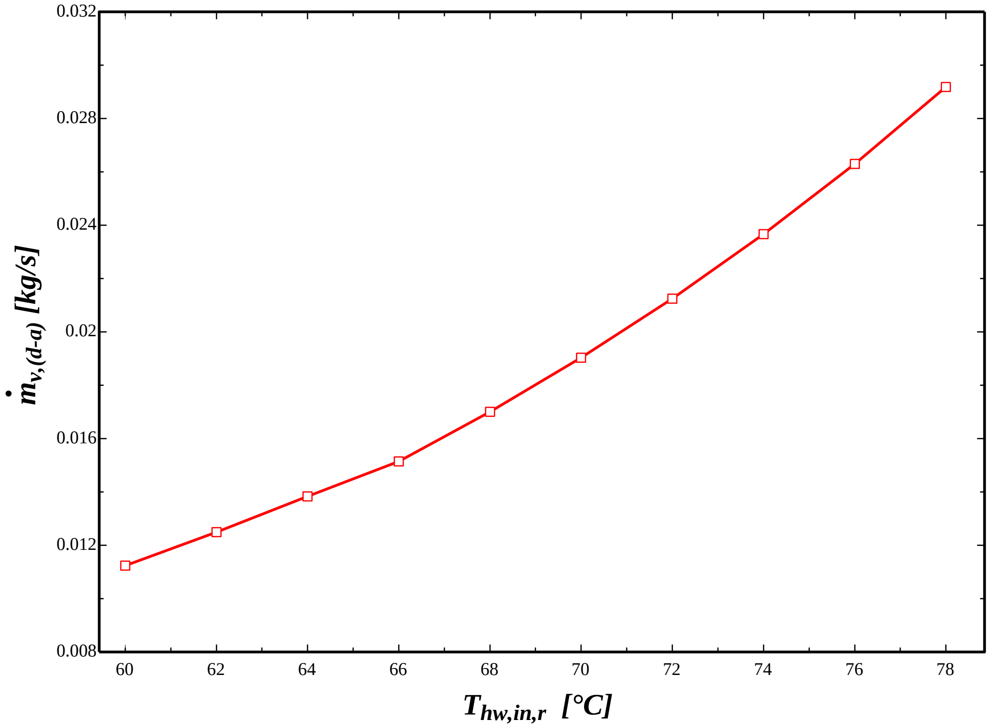

Figure 10. Effect of heating water temperature on moisture desorption rate.

Figure 11 observes decreasing in desorption rate across the regenerator while increasing the inlet concentration of desiccant solution. Desiccant solution with higher concentration ratio has lower vapour pressure which causes lower capability for moisture addition, the difference between the partial vapor pressure on the desiccant surface and scavenging air is decreased when the desiccant surface vapor pressure is decreased as a result [16].

The evident declines in the conditioner COP with cooling water temperature is observed in figure 12. It indicates that at higher temperatures the conditioner COP decreases while the regenerator COP is elevated with increasing the water temperature, this is due to increased conditioner heat needed, resulting from increased the required regeneration energy.

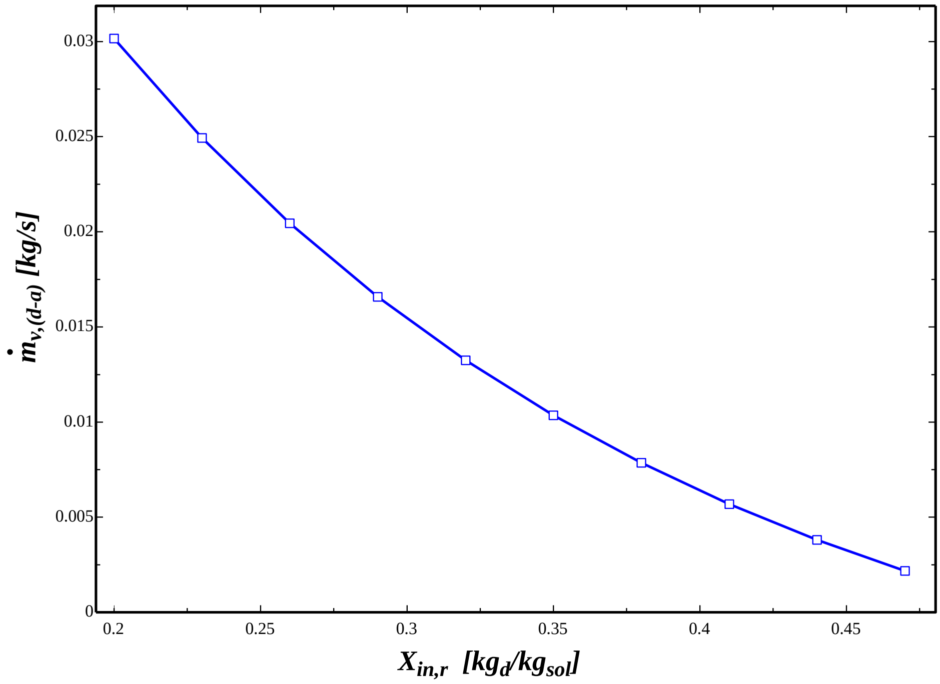

Figure 11. Effect of heating water temperature on moisture desorption rate.

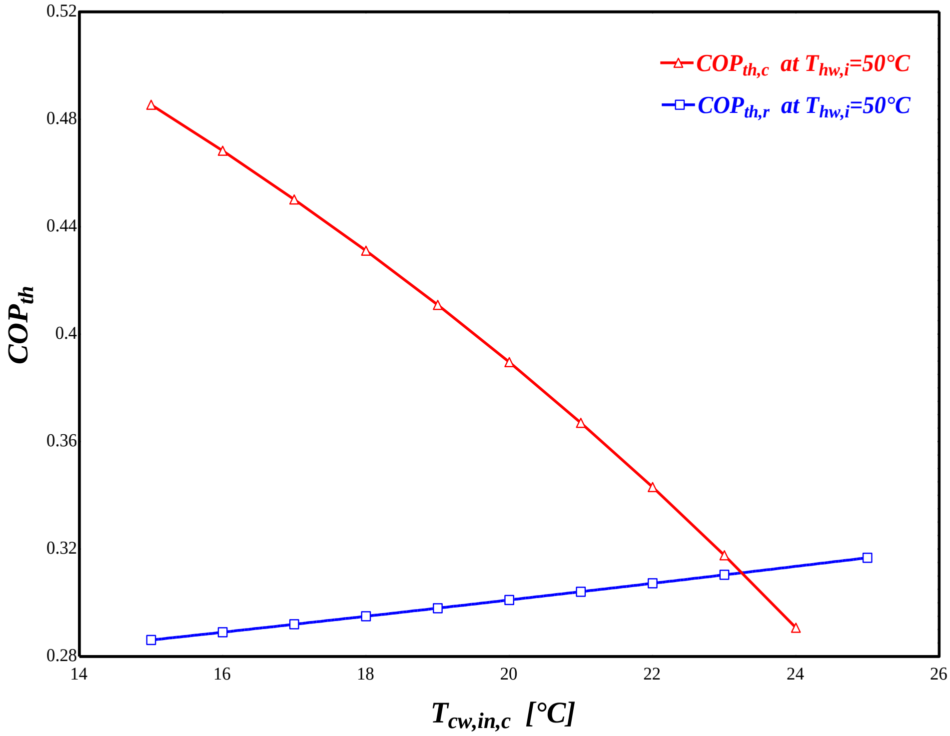

Figure 12. Effect of cooling water temperature on Coefficient of performance.

4.3. Achieving balance between conditioner and regenerator

To allow continuous operation for the system, the amount of moisture desorbed out of the desiccant solution in the regenerator should be equal to the moisture absorbed from air in the conditioner to maintain balance between two components.

At constant operating inlet conditions of $T_{a,i}$=25℃, $T_{cw,i}$=15℃, φ_i=50%, $T_{d,i}$=30℃ & $T_{hw,i}$=50℃, as illustrated in figure 13, a desiccant solution concentration ratio of 37.2% is obtained to achieve dehumidification and regeneration processes balance, where the dehumidifier moisture removal rate is equal to the regenerator moisture addition rate. Varying the inlet cooling water temperature impacts the inlet desiccant solution concentration required to achieve mass balance for the system. As shown in figure, at inlet conditions of $T_{a,i}$=25℃, φ_i=50%, $T_{d,i}$=30℃ & $T_{hw,i}$=50℃, when $T_{cw,i}$ raises to 50℃ the inlet concentration needed to achieve the balance reaches to 38.2% and increasing the inlet cooling water temperature as well to 20 ℃ brings the simulated concentration to be 40%.

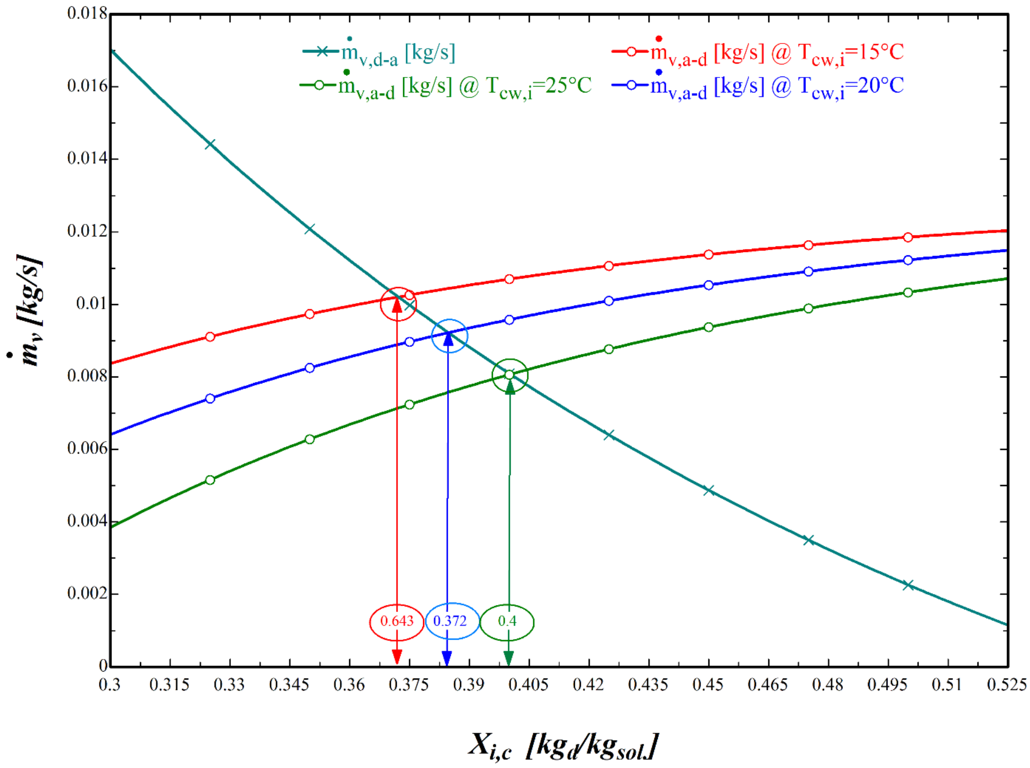

Figure 13. Effect of inlet solution concentration on moisture absorption and moisture desorption rate

Thus, measurements are required to facilitate the regenerator COP for the stronger desiccant solution while the dehumidification COP should be improved at lower concentration ratio. Under the system steady operation condition, the conditioner COPth,c and the regenerator COPth,r are reached 0.4854 and 0.2861 respectively at concentration ratio of 37.2%, while the supply air temperature is provided at 25℃ and the inlet desiccant solution temperature entering conditioner is set for 30℃ as listed in table 1.

Hence, the simulated results reveal that the LDC system is feasible for applications, and the supply air condition could meet the comfortable indoor environment requirement allowing continuous operation of the system and ensuring mass balance.

Table 1. Simulated results revealed at mass balance point.

1..29	1 $T_{a,in,c}$ [°C]	2 $COP_{th,c}$	3 $Q_{Latent,C}$ [kJ/s]	4 $Q_{sensible,C}$ [kJ/s]	5 $T_{cw,in}$ [°C]	6 $\phi_{in,c}$	7 $\varepsilon_{deh,c}$	8 $T_{d,in,c}$ [°C]	9 $X_{in,c}$ [kgd/kgsol]	10 $X_{out,c}$ [kgd/kgsol]	11 $\dot{m}_{va,d}$	12 $X_{in,r}$ [kgd/kgsol]	13 $X_{out,r}$ [kgd/kgsol]	14 $\dot{m}_{vd,a}$	15 ε_{reg}	16 $T_{hw,in}$ [°C]	17 Q_{Rege} [kJ/s]	18 $Q_{Latent,R}$ [kJ/s]	19 $COP_{th,r}$
Run 4	25	0.4259	18.08	17.02	15	0.35	0.4	30	0.372	0.3575	0.0071	0.3575	0.3599	0.006689	0.3	50	-36.19	17.03	0.2058
Run 5	25	0.4474	20.7	17.33	15	0.4	0.4	30	0.372	0.3555	0.00813	0.3555	0.3583	0.007819	0.3	50	-38.87	19.91	0.2332
Run 6	25	0.4672	23.33	17.64	15	0.45	0.4	30	0.372	0.3535	0.009164	0.3535	0.3567	0.008996	0.3	50	-41.65	22.91	0.2599
Run 7	25	0.4854	25.98	17.95	15	0.5	0.4	30	0.372	0.3515	0.0102	0.3515	0.3551	0.01022	0.3	50	-44.54	26.03	0.2861
Run 8	25	0.502	28.63	18.26	15	0.55	0.4	30	0.372	0.3495	0.01124	0.3495	0.3536	0.01149	0.3	50	-47.55	29.27	0.3117
Run 9	25	0.5172	31.29	18.58	15	0.6	0.4	30	0.372	0.3476	0.01229	0.3476	0.3521	0.01282	0.3	50	-50.67	32.63	0.3366
Run 10	25	0.531	33.97	18.89	15	0.65	0.4	30	0.372	0.3457	0.01334	0.3457	0.3506	0.01419	0.3	50	-53.9	36.13	0.3609

V. CONCLUSION

This study represented the development of a simple model that describes the performance of each component of the liquid desiccant system conditioner and regenerator. A complete simulation was developed by EES for solving the mass and heat balance equations using previously experimental calculated effectiveness parameters to estimate their performance based on their fluid inlet and ambient conditions. It was found that the cooling water temperature has a dominant effect on the coefficient of performance for conditioner where Increasing the desiccant concentration entering the conditioner improved the water transfer performance in the humidifier, but inversely affected moisture desorption in the regenerator part. The mass balance between the dehumidifier and regenerator obtained for the system steady operation. Conditioner thermal $COP_{th,c}$ of 0.4854 and regenerator thermal $COP_{th,r}$ of 0.2861 obtained respectively under inlet conditions at LD concentration ratio of 37.2%, process air temperature of 25℃, 50% relative humidity and 30℃ solution temperature.

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