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Investigating the impact of flow rate and moisture content for different concentration of liquid desiccant solution

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Abstract

The desiccant air conditioning system consists of two processes, namely cooling and dehumidification, in which the air temperature and humidity are controlled in order to provide comfortable thermal conditions. A typical system includes a dehumidifier, indirect evaporative cooler, and regenerator. The desiccant is selected depending on its ability to absorb water vapor present in the air. In this study, calcium chloride solution was used as a desiccant for the desiccant solution regeneration process, and a flat plate solar collector was employed. Different variables, such as the primary air flow rate, desiccant flow rate, and the concentration of the desiccant solution, were changed during the experiments. The impact of these variables on the performance parameters of the desiccant system such as moisture removal rate, moisture efficiency, enthalpy efficiency, sensible heat ratio, and the mass transfer coefficient was studied. The obtained results revealed that as the solution concentration and the flow rate of primary air increase, the moisture removal rate, sensible heat ratio, and mass transfer coefficient increase. A particular value of inlet primary air flow rate (0.18Kg/s), an increase in the inlet concentration of calcium chloride solution from 0.85 to 0.95 leads to a rise in moisture removal rate, sensible heat ratio, and mass transfer coefficient of (1.1 _1.65) g/s, (0.18-0.25), and (0.01075-0.0123) m/s respectively. While at a certain inlet concentration of a desiccant solution (0.95), increasing the inlet primary air flow rate from 0.1Kg/s to 0.18Kg/s leads to an increase in the moisture removal rate, sensible heat ratio, and mass transfer coefficient o (0.94-1.26) g/s, (0.24-0.26), and(0.0038 -0.011) m/s respectively.

Keywords: Desiccant column, dehumidification, regeneration process, calcium chloride solution.

الخلاصة:يتكون نظام تكييف الهواء الجاف من عمليتين، وهما التبريد وإزالة الرطوبة، حيث يتم التحكم في درجة حرارة الهواء والرطوبة من أجل توفير ظروف حرارية مريحة. يشتمل النظام النموذجي على مزيل للرطوبة ومبرد تبخيري غير مباشر وأيضًا مُجدد. يتم اختيار مادة التجفيف اعتمادًا على قدرتها على امتصاص بخار الماء الموجود في الهواء. في هذه الدراسة تم استخدام محلول كلوريد الكالسيوم كمجفف لـ عملية تجديد محلول المجفف، تم استخدام مجمع الألواح الشمسية المسطحة. تم تغيير متغير مختلف، مثل معدل تدفق الهواء الأولي، ومعدل تدفق المجفف وتركيز محلول المجفف، أثناء التجارب. تمت دراسة تأثير هذه المتغيرات على معاملات أداء نظام المجففة مثل معدل إزالة الرطوبة، وكفاءة الرطوبة، وكفاءة المحتوى الحراري، ونسبة الحرارة المعقولة، ومعامل نقل الكتلة. أوضحت النتائج المتحصل عليها أنه كلما زاد تركيز المحلول ومعدل تدفق الهواء الأولي، زاد معدل إزالة الرطوبة ونسبة الحرارة المعقولة ومعامل انتقال الكتلة. عند الحصول على القيمة الحالية لمعدل تدفق الهواء الأولي الداخل (٠,١٨ كغم / ثانية) ، تؤدي الزيادة في تركيب مدخل محلول كلوريد الكالسيوم من ٠,٨٥ إلى ٠,٩٥ إلى زيادة معدل إزالة الرطوبة ، ونسبة الحرارة المعقولة ، ومعامل نقل الكتلة بمقدار (١,١ _ ١,٦٥) غم / ثانية ، (٠,١٨-٠,٢٥) ، و (٠,٠١٠٧٥) -(٠,٠١٢٣) م / ث على التوالي، بينما عند تركيز مدخل معين لمحلول المجفف (٠,٩٥) ، تؤدي زيادة معدل تدفق الهواء الأولي الداخل من ٠,١ كغم / ثانية إلى ٠,١٨ كغم / ثانية إلى زيادة معدل إزالة الرطوبة ، ونسبة الحرارة المحسوسة ، ومعامل نقل الكتلة o (٠,٩٤-١,٢٦) غم / ثانية ، (٠,٢٤-٠,٢٦) ، (٠,٠٠٣٨ - ٠,٠١١) م / ث على التوالي.

1. INTRODUCTION

Indoor or settings are greatly influenced by humidity. High indoor humidity creates an unsettling and harmful atmosphere [1]. Desiccant dehumidification is an old technology that has been used for both industrial and agricultural uses, such as humidity management in textile mills and post-harvest vegetable drying in supermarkets

[2]. Desiccant technology has been discovered to be a viable replacement for traditional cooling systems. Under hot and humid climatic circumstances, it might provide more thermal comfort [3]. There has been a resurgence of interest in solar-powered air conditioning in recent years. The use of liquid-desiccant cooling systems is one possibility that has been researched [4]. As the push for energy saving continues to develop, Use of such liquid desiccants for dehumidification of HVAC (heating, ventilation, and air conditioning) process air is playing an increasingly important role [5] W.Z. Gao. et al. [6] experientially investigated an integrated liquid desiccant and M- cycle indirect evaporative cooler. The removing capacity of moisture in dehumidifier and sensible heat in M-cycle indirect evaporative cooler can be greatly improved while increasing the liquid desiccant flow rate or inlet concentration. Xianhua Ou et al. [7] experiential investigated the heat and mass transfer performance of a liquid desiccant cooling and dehumidification system form the result, with increased chilled water flow rate, desiccant solution flow rate, and concentration, thermal efficiency and moisture efficiency improve. Min Tu. et al. [8] simulated and analyses a novel liquid desiccant air conditioning system. The simulation of this system is formulated with two packed columns, one for regenerating the weak desiccant solution and the other for the dehumidification of the ambient air. first and second law of thermodynamics hour been used to analyse the effect of five key variables on the performance of the system. High efficiency could be reached if proper values of these variables are selected. M.M Bassuoni [9] analytically studied the modelling and performance of a crossflow air dehumidifier using liquid desiccant. the results show that hot humid air and desiccant concentration have the large impact on the performance of the dehumidifier. X. Cui et al. [10] analysed theoretically a liquid desiccant based indirect evaporative cooling system. The influence of several parameters on the performance of the system were investigated including the working –to-intake air flow ratio, the liquid desiccant film length, dimensionless channel length, and the inlet air conditions. Ali Sohani et al. [11] presented a novel approach based on descriptive methods compared the performance of desiccant enhanced evaporative cooling systems; examination of characteristics that may have an impact on desiccant improved evaporative air cooling performance. The measurement findings show that the temperature and concentration of the intake desiccant, working air and desiccant to air mass ratios, as well as the channel length, had a significant impact on the DEH's performance.

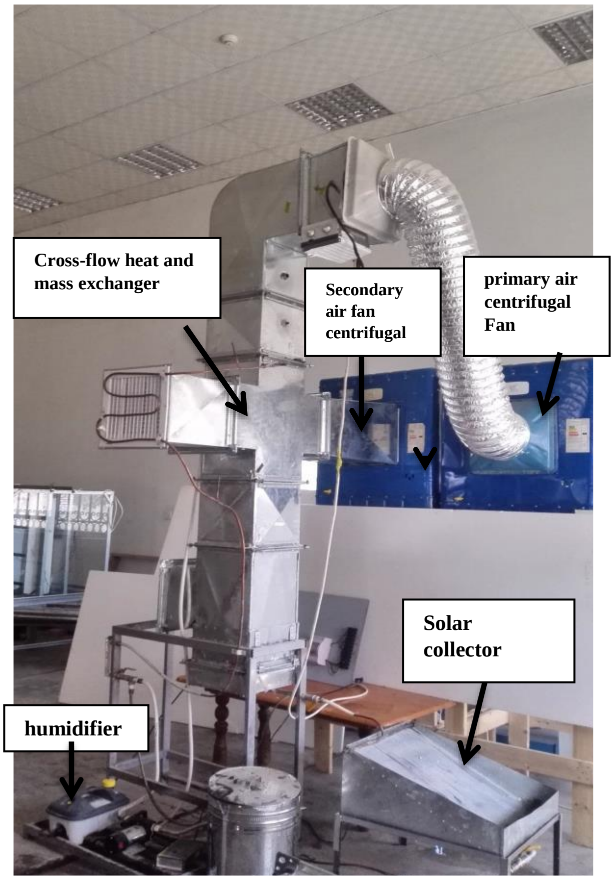
The aim of this study is to investigate the effect of changing the primary air flow rate and moisture content at different concentrations (95%, 90%, 85%) on desiccant system parameters such as: moisture removal rate, moisture efficiency, enthalpy efficiency, sensible heat ratio and mass transfer coefficient. To achieve this goal, the practical tests were carried out using the apparatus shown in Figure 1.

2. DESCRIPTION OF EXPERIMENTAL APPARATUS

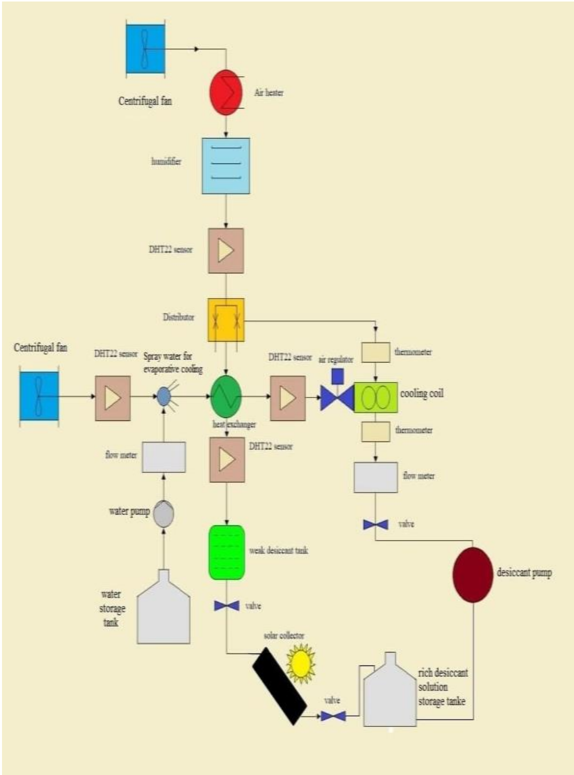
The apparatus that was used in the experiments of this study is shown in Figure 1. It consists of the following parts:

- Cross-flow plate heat and mass exchanger (HME).
- Air cirulation and treatment system includes: primary and secondary air streams centrifugal fans, Air heater, steam generator (humidifier), water jets in secondary air streams and air flow regulators.
- Liquid desiccant system includes: desiccant jets in primary air stream, liquid desiccant storage tank, and desiccant pump.
- Solar collector for regeneration the weak solution desiccant.
- Measuring devices includes: temperature and relative humidity measuring devices, arduino device, water and desiccant solution flow meters, digital thermometer, and velocity measuring device (thermo anemometer).

The heat and mass exchanger are essentially made up of thin aluminium sheets that are organized in a precise way to allow two perpendicular air streams (primary and secondary) to flow between parallel plates in alternate passage ways. The heat and mass exchanger construction are made up of fifty-two aluminium plates with a thickness of 0.5mm and a 5mm gap between them. Each air stream can flow through 26 channels to the heat exchanger's aluminium plate layout. Steel wire mesh of 0.5 mm square corrugations is placed between the plates to provide turbulence and enhance heat and mass transfer. Figure 2 shows the cross flow plate heat and mass exchanger.



(a) Snapshot of experimental test rig.



(b) Schematic diagram of experimental test rig.

Figure 1: The experimental rig.

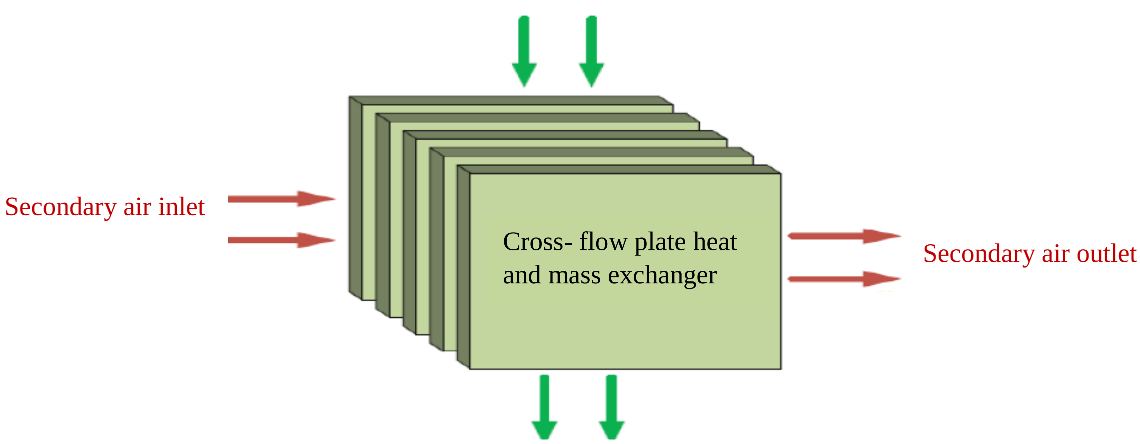


Figure 2: Cross flow plate heat and mass exchanger.

3. PERFORMANCE PARAMETER OF THE HEAT AND MASS EXCHANGER

Two processes take place simultaneously through the heat and mass exchanger (HME) that used in this study. The first process is to remove moisture from the primary air stream passing through the vertical passages of the plates of this heat exchanger by spraying a calcium chloride solution on the surfaces of these passages while the second process that occurs is the cooling of the primary air stream by means of a secondary air stream that is evaporatively cooled and pass in the horizontal passages of the exchanger.

A number of parameters have been used to determine the performance of this heat and mass exchanger, including:

The rate of Moisture Removal (MR) rate (Kg/s) from the primary air stream, which can be obtained from the following equation [12]:

$$MR = \dot{m}_a (W_{i-} W_o) \qquad (1)$$

Where $\dot{m}_a$the mass flow is rate of air with unit of Kg/s and $(W_{i-} W_o)$is the difference between the moisture content at inlet and outlet with units of Kg_v/Kg_{dryair}, respectively. According to the concept of efficiency, the performance of process of removing moisture and heat from the primary air stream in the heat exchanger can be expressed in term of both the moisture efficiency (η_m) and the enthalpy efficiency (η_h), which can be expressed by the equations 2 and 3 respectively [13].

$$\eta_m = \frac{(W_{i-} W_o)}{(W_{i-} W_e)} \qquad (2)$$

$$\eta_h = \frac{(h_{i-} h_o)}{(h_{i-} h_e)} \qquad (3)$$

The Sensible Heat Ratio (SHR) represents the required handling capability of the various sections of the air conditioner. It is defined as the ratio between the sensible heat load and the overall heat load of the air. As a result, calculating the SHR according to the inlet and outlet of air supply characteristics can be used to assess the effectiveness of cooling and dehumidifying procedures in lowering humidity and temperature. It can be calculated by using equation 4 [6]:

$$SHR = \frac{C_a (t_{i-} t_o)}{(h_{i-} h_o)} \qquad (4)$$

Where t is the temperature at ℃ and h is the enthalpy at Kj/Kg.

The Antoine equation is one of the most widely used formulas for determining the vapor pressure of desiccant solution. It can commonly written as follows [14]:

$$p_{sol} = a\, exp(A - \frac{B}{T+C}) \qquad (5)$$

Where p_{sol} is the desiccant solution's pressure at Pa, while A, B, and C are constants depending on the liquid desiccant temperature and concentration; and a can be expressed as:

$$a = a_0 + a_1 x_m + a_2 x_m^2 + a_3 x_m^3 + a_4 x_m^4 \qquad (6)$$

In which x_m represents the concentration of the solution; for calcium chloride solution used as a liquid desiccant in this study the coefficient in the Antoine equation take the following values which illustrated in table 1.

Table 1: Antoine s equation constant for calcium chloride solution [15].

	a_0	a_1	a_2	a_3	a_4	**A**	**B**	**C**
$cacl_2$	0.9899	-8.67E-3	-3.68E-2	4.624E-3	-1.67E-4	18.3036	3816.44	46.13

The equilibrium humidity ratio (W_e) of the moisture air in contact with calcium chloride solution can be written for an ideal gas as follows (in terms of atmospheric pressure p_{atm} and desiccant solution p_{sol}; see equation 7) [14].

$$W_e = 0.626185\left(\frac{p_{sol}}{p_{atm}+p_{sol}}\right) \tag{7}$$

In term of equilibrium humiidity ratio the following equation can be used to calculate the mass transfer coefficient (K_d) between the process air and calcium chloride solution:

$$K_d = \frac{m_a(w_{i-}w_o\ )}{A\rho(w_{i-}w_e\ )} \tag{8}$$

Where A is the area (m^2) and ρ is the fluid density (kg/m^3).

4. RESULTS AND DISCUSSION

Practical experiments were carried out under constant conditions at the entry section of the heat and mass exchanger (HME), including primary initial air temperature of 40 ℃ , and the flow rate of calcium chloride solution is 3 L/min.

Figure 3 depicts the effect of the primary air inlet humidity ratio on moisture removal rate at three different values of calcium chloride solution concentrations (0.85, 0.9, and 0.95). The moisture removal rate increases as the air inlet humidity ratio increase. In fact, increasing the air inlet humidity ratio will lead to an increase in the driving force, which in turn increased the mass transfer potential inside the crossflow plate heat and exchanger. As a result, there will be an increase in the moisture removal rate at all concentrations.

Figures 4 and 5 present the impact of a moisture content variation on the moisture efficiency and enthalpy efficiency, respectively. The change in the moisture content leads, as is illustrated in the figures, to slight changes in the values of these efficiencies. At a specific value of the moisture content, it is noted that the values of these efficiencies increase with the increase in the concentration of the solution.

The effect of air humidity ratio on the SHR is illustrated in Figure 6. The desiccant's humidification capability can be modified by increasing the air humidity ratio due to the higher surface vapor pressure differential between air and desiccant. Therefore, the inlet primary air entering the crossflow plate heat and mass exchanger had a negative effect on the cooling capacity, because of a higher temperature of the supplied air. Thus, the SHR decreases quickly due to the increase of the latent heat fraction in the whole air handling process. Increased moisture content from 0.026 Kg/Kg to 0.035 Kg/Kg led to a decrease in the SHR from 0.26 to 0.20 for 0.95 desiccant solution concentration.

Figure 7 shows the mass transfer coefficient under various air moisture contents. The heat exchanger mass transfer coefficient will decrease as the moisture content of the air rises. This behaviour is predicted since a rise in the air humidity ratio raises the water vapor pressure in the air, resulting in a reduction in the mass transfer coefficient.

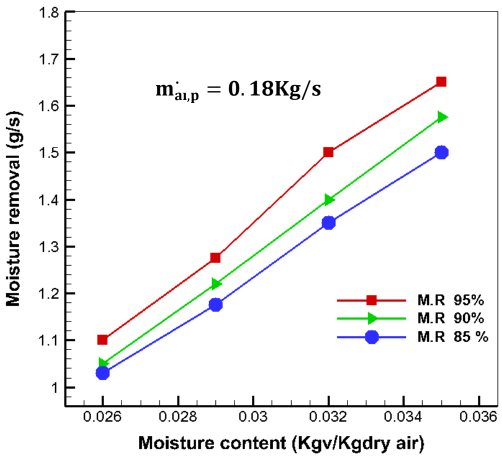


Figure 3: Effect of air moisture content on moisture removal.

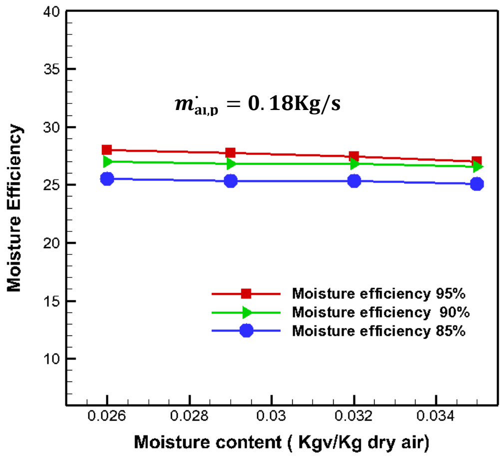


Figure 4: Effect of air moisture content on moisture efficiency.

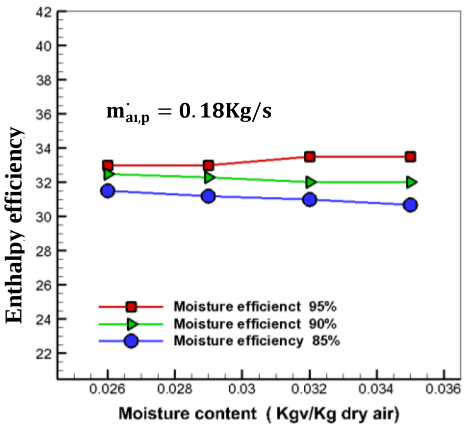


Figure 5: Effect of air moisture content on enthalpy efficiency.

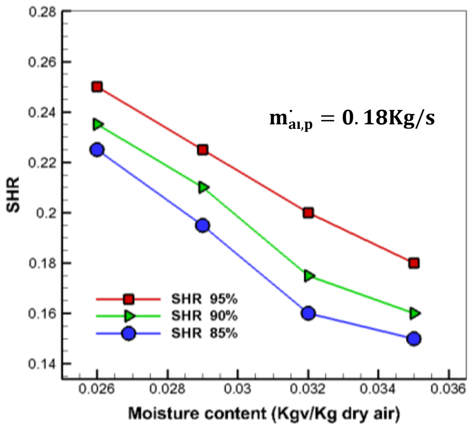


Figure 6: Effect of air moisture content on SHR.

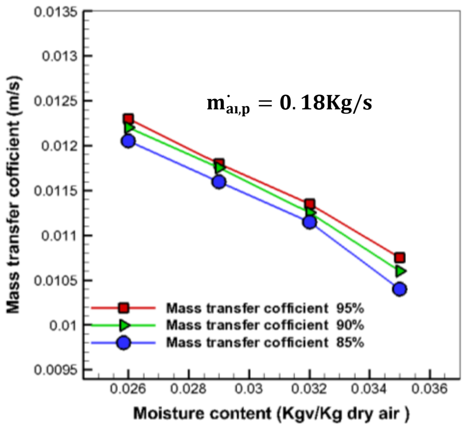


Figure 7: Effect of moisture content on the mass transfer coefficient.

Figure 8 illustrates the variations in moisture removal rate as a function of the primary air flow rate. The moisture removal rate increases with increasing air flow rate at the three different concentrations. Referring to the equation 1, as the value of the air mass flow rate rises, the value of the moisture removal rate (M R) rises as well. The difference in the moisture content $(W_i - W_o)$ in the same equation can be falls when the air flow velocity increases. Higher velocity of process air means a shorter contact time between process air and liquid desiccant.

The influence of the airflow rate on enthalpy efficiency and moisture efficiency are shown respectively in Figures 9 and 10. An increase in the rate of air mass flow results in decrease in the humidity ratio and enthalpy differences between inlet air and outlet air. So, both efficiencies are decreased because of the moisture reduction and enthalpy reduction decrease with the increase in air flow rate.

Figure 11 reveals the effect of the airflow rate on sensible heat ratio (SHR) for three desiccant solution concentrations (0.85, 0.9 and 0.95). From this figure, it can be notice the sensible heat ratio (SHR) increases with increasing air flow rate for all concentrations. The latent heat change was significantly less than that of the sensible heat. The higher airflow rate leads to the decrease of enthalpy reduction and therefore increases the SHR. A raised airflow rate from 0.1 Kg/s to 0.18 Kg/s leading to increase SHR from 0.24 to 0.26 for concentration 0.95. The effect of air velocity on temperature can decrease or increase depending on the contact time but at the same time, the temperature difference increases due to turbulence and therefore increased SHR.

Mass transfer coefficient under various air flow rates during dehumidification process and at three different values of the desiccant solution concentrations (0.85, 0.9 and 0.95) is shown in Figure 12. When the air flow rate changes from 0.1 Kg/s to 0.18 Kg/s the mass transfer coefficients increase almost linearly from 0.0037 m/s to 0.0115 m/s at a solution concentration of 0.95. The decrease in heat and mass transfer resistances with increasing air velocity can be considered as the explanation for this case. It is also seen from the figure that at a specific value of the air flow rate, the increase in the solution concentration values leads to an increase in the values of the mass transfer coefficient.

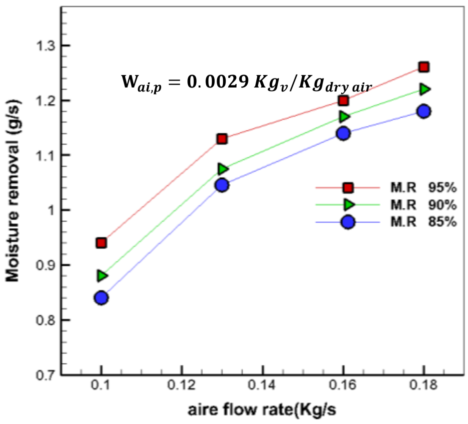


Figure 8: Effect of air mass flow rate on moisture removal.

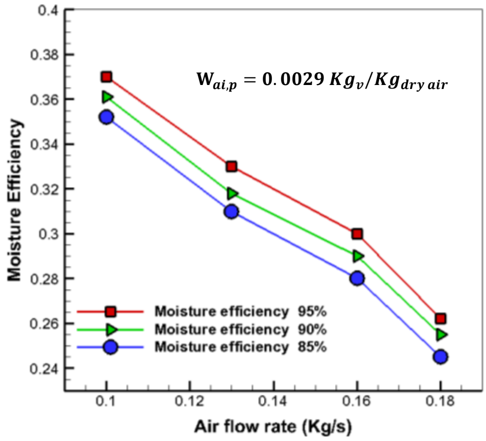


Figure 9: Effect of air mass flow rate on moisture efficiency.

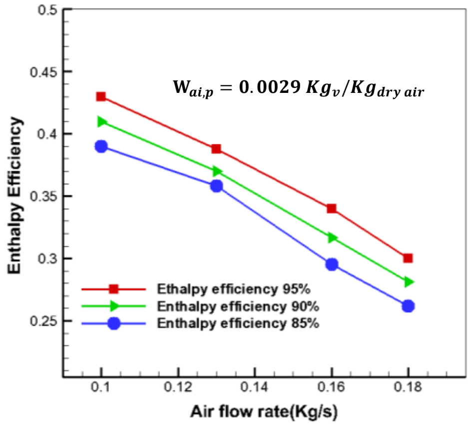


Figure 10: Effect of air mass flow rate on enthalpy efficiency.

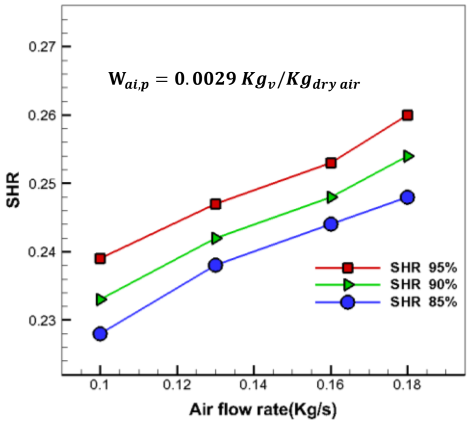


Figure 11: Effect of air mass flow rate on SHR.

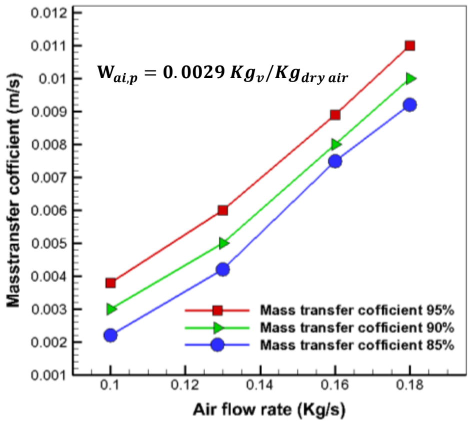


Figure 12: Effect of air mass flow rate on the mass transfer coefficient.

5. CONCLUSION

- The rate of moisture removal (M.R) increases with an increase in both the moisture contact of the primary air stream and its mass flow rates
- Both the moisture efficiency and the enthalpy efficiency change slightly with the change in the moisture content of the primary air stream; as the mass flow rate of this air stream increases, their efficiencies drop.
- The sensible heat ratio (SHR) decreases with the increase in the moisture content of the primary air stream, while it rises in synchrony with the mass flow rate of this stream.
- The same behaviour in the above point applies to the mass transfer coefficient; that is, it decreases with the increase in moisture content and increase with the increase in the rate of air flow.
- At specific values of moisture content and air flow rate, the values of all the above mentions performance perimeters increase with the increase in the concentration of the used calcium chloride solution.

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