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Performance improvement of evaporative cooling system by combine with heat recovery and desiccant

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Abstract— Evaporative cooling is a good alternative of refrigeration cooling systems. This system is environmentally friendly and consumes low electrical energy. However, this system has some disadvantages which is greatly affect on the performance of the system. One of these problems is the affected by external conditions (humidity) makes space uncomfortable and reduces the effectiveness of evaporative cooling. This paper will focus on overcome this problem and improving the performance of the system. An evaporative cooling system was combined with heat recovery and desiccant in order to improve the performance of the system in a humid condition. The unit was constructed and installed at University of Technology in Baghdad. The system includes ducting, desiccant bed, plate heat exchanger (heat recovery), centrifugal fans and heaters. This is accomplished through reducing the moisture imposed on the cooling unit, as a result of handling the latent load of air (by desiccant material). Three air flow rate of supply in desiccant were studied (0.48, 0.61, and 0.73 m³/s). Four regeneration air flow rate in desiccant were studied (0.15, 0.28, 0.49 and 0.59 m³/s). The results show adding the desiccant material and heat recovery system could improve the performance of the system by 106 % (in a humid condition W=20.86 g/kg).

Keywords— plate heat exchanger, heat recovery, evaporative cooling, desiccant.

English symbols

Symbol	Description	Unit
V_{air}	velocity of air	m/s
$\dot{V}_{air}$	Air flow rate	m^3/s
H_{HR}	High of heat recovery.	mm
W_{HR}	Width of heat recovery	mm
L_{HR}	Depth of heat recovery.	mm
X_{HR}	Center to center distance of plates	mm
NO_{Pass}	Number of pass of heat recovery	mm
H_{pad}	High of pad.	mm
W_{pad}	Width of pad	mm
L_{pad}	Depth of pad.	mm
$H_{of\ basin}$	High of basin	mm
$W_{of\ basin}$	Width of basin	mm
$L_{of\ basin}$	Depth of basin	mm
H_{pad}	High of pad.	mm
H_{des}	High of desiccant box	mm
L_{des}	Width of desiccant box	mm
W_{des}	Depth of desiccant box	mm
X	Center to center distance of plates	mm
X_{dash}	Distance between two plates	mm
d	Average diameter of silica gel	mm
t	Thickness of plate	mm
$Mass_{desiccant}$	Mass of silica gel in each desiccant	kg
T	Temperature	°C

$T_{regeneration}$	Regeneration temperature	°C
T_{in_hot}	Inlet temperature of hot air to heat exchanger	°C
T_{in_cold}	Inlet temperature of cold air to heat exchanger	°C
T_{out_hot}	Outlet temperature of hot air from heat exchanger	°C
T_{out_cold}	Outlet temperature of cold air from heat exchanger	°C

Abbreviations

Symbol	Description
HVAC	Heating, ventilation and air conditioning system
COPth	The thermal coefficient of performance
COPele	The electrec coefficient of performance
R/P	(reactivation air flow/process air flow)

1. Introduction

There are many cooling systems in the markets like vapor compression system, evaporative cooling system, absorption cooling system, etc. All these systems could achieve the thermal comfort in the space. Most of the residential buildings, in Iraq, are using vapor compression system. However, the evaporative cooling system has an advantage over vapor compression system, which is usually; require only a quarter of the electric power consumption [1]. Therefore, reduce energy consumption and participate to reducing greenhouse gas emissions could be done by this system. The wet bulb temperature of the process air is the minimum temperature that could supply to the space by using evaporative cooling system. The evaporative cooling system has been used as a low energy consuming system for different applications in manufacturing, agrarian and residential buildings. Adding desiccant materials with evaporative cooling help to use the system in a high-humidity conditions. Many papers have been published about using desiccant material with cooling systems. Therefore, an extensive survey, comparison and evaluation of published papers are required.

P. Mavroudaki et al. 2002 [2] the results of the energy analysis study of office space in various European locations have been presented. A solar desiccant cooling model has been used. The results showed that high latent gains lead to increasing the gas consumption. Because of the high regeneration temperatures required for the desiccant material. The authors conclude that electrical energy consumption is unchanged by the utilization of solar energy due to the operation of the fans and pump etc. for regeneration cycle of the desiccant materials.

K. Daou et al. 2004 [3] showed the basics underlying of desiccant cooling systems and their actual technological applications were discussed. Using free energy like solar or waste heat to reactivate the desiccant material represent an advantage of desiccant cooling systems. In addition, the desiccant material could improve the quality of the air by removing pollutants and contaminants. Therefore, this system represents an environmental friendly technology. A desiccant material that using low regeneration temperature is the key of augmenting even greater the contribution for saving energy. Finally, the authors have concluded that the desiccant cooling could improve the thermal comfort, energy and cost saving.

J. R. Camargo et al. 2005 [4] presented an air conditioning system that combined with the desiccant. Indirect and direct evaporative cooler have been used in this study. The analysis of R/P relationship (reactivation air flow/process air flow), regeneration temperature, and the thermodynamic conditions of the entering air flow have been studied. In addition, the possibility of using the system in different climate characteristics has been showed. The results showed that the system could supply a human thermal comfort in humid climates.

D. La et al. 2010 [5] an innovative thermally driven air conditioning system has been studied. The desiccant material has been combined with evaporative cooling. The thermal COP (COP_{th}) above 1.0 and an electric

COP (COP_{ele}) about 8.0 could be achieved at regeneration temperature of 80 ˚C, whereas COP_{th} of the system is the ratio between cooling capacity of the system to regeneration heat consumption and COP_{ele} of the system is the ratio between cooling capacities of the system to total electric power consumption.

L. Bellemo, 2018 [6] effect of implementing indirectly solid desiccant on the performance of cooling system has been investigated. The goals of the study were improving the performance of the system by changing the geometrical dimensions and operational parameters. The author has compared the results with chiller-based systems. Regeneration temperatures between 50 °C and 90 °C have been tested. The advantage of using this range is using low heat sources like solar energy or waste heat. The performance of the system has been improved significantly (COP_{th} above 1 and COP_{ele} above 20) with using indirect evaporative cooling. Because of using exhaust air from the air-conditioned space.

2. System description

This section is covering the important specifications of the main parts of the system. The unit consists of direct evaporative cooling, regenerative desiccant system and plate heat exchanger.

2.1 Direct Evaporative Cooling:

Specific dimensions and the parameters of evaporative cooling have been reached as shown in the figure (1) and table (1).

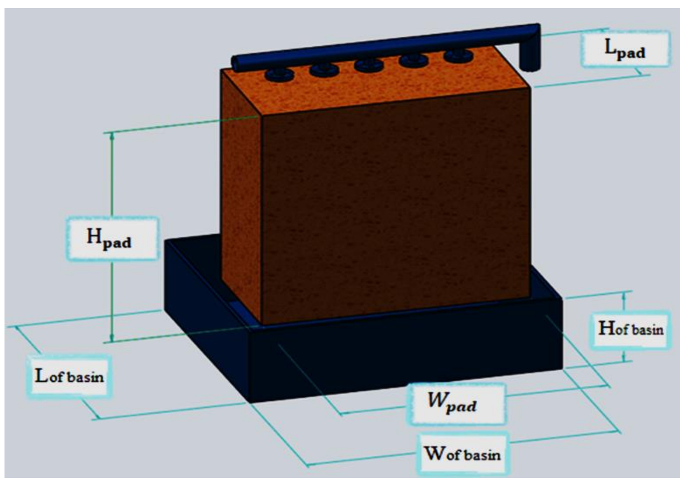


Figure (1) design of evaporative cooling.

Table (1): dimensions of direct evaporative cooling.

H_{pad}	**300 mm**	**High of pad.**
W_{pad}	300 mm	Width of pad
L_{pad}	150 mm	Depth of pad.
$H_{of\ basin}$	450 mm	High of basin
$W_{of\ basin}$	350 mm	Width of basin
$L_{of\ basin}$	300 mm	Depth of basin

The dimensions of the pad are (300 mm * 300 mm *150 mm) and dimensions of basin are (350 mm * 300 mm * 150 mm) as shown in the figure (2).

Figure (2) direct evaporative cooling after completed.

2.2 Desiccant:

The desiccant box consists of a set of plates inserted in a set of slots. The Silica gel grain coated the two sides of plates as shown in the figure (3).

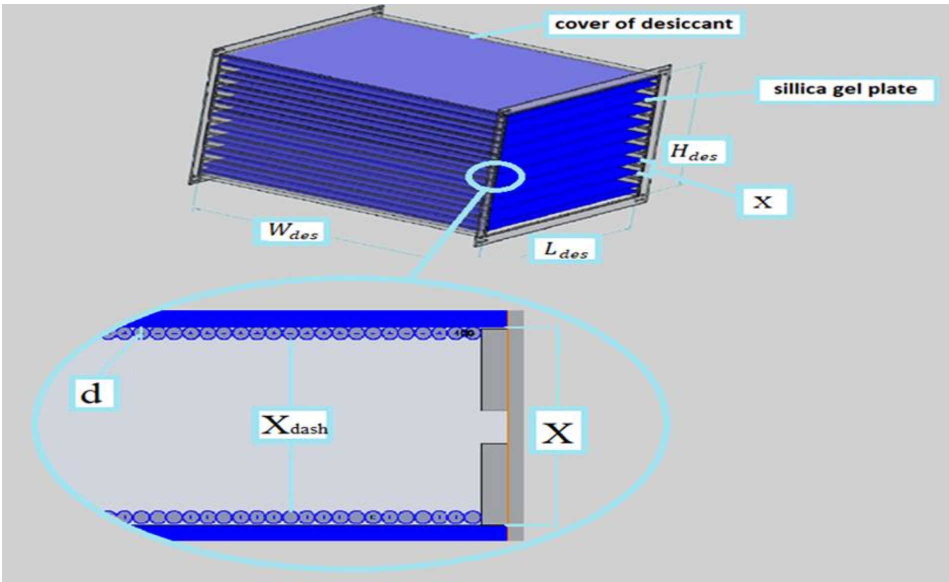


Figure (3) design of desiccant.

The dimensions of desiccant box shown in table (2).

Table (2): dimensions and parameter of desiccant box.

H_{des}	**550 mm**	**High of desiccant box**
L_{des}	600 mm	Width of desiccant box
W_{des}	800 mm	Depth of desiccant box
X	48 mm	Center to center distance of plates
X_{dash}	40 mm	Distance between two plates
d	3 mm	Average diameter of silica gel
t	1 mm	Thickness of plate

$Mass_{desiccant}$	22 kg	Mass of silica gel in each desiccant

2.2.1 Adsorption Rate Testing (estimation of absorption rates):

In order to estimation of absorption rates, test of samples silica gel was made. The test has made by dry the silica gel before use. This process has been done by passing a hot air to make sure it does not contain moisture. Dry silica gel has been placed inside highly humid space by using a water bath to estimate of absorption rates, a (90-95) % relatively humid environment. The absorption rate for sample (16.92%) from weight of silica gel.

2.2.2 Desiccant Material:

Silica gel has been used as a desiccant material in this work. Silica gel has been fixed on Plates from two sides. Each desiccant section contains many plates (as racks arranged). These plates were made from galvanized plate with width (600 mm), depth (800 mm) and thickness (1 mm). Silica gel is attached to the sheets by distributing Double-sided adhesive tape on the plate and then scattering silica gel granules on them regularly. Figure (4) shows the silica gel in the plate.

Figure (4**)** desiccant material coated on both sides of metal element.

The last step is insert the sheets of galvanized iron coated with silica gel inside the duct as shown in the Figure (5.a) and (5.b).

a b

Figure (5) final form of desiccant manufacturer.

2.3 Heat recovery (Plate heat exchanger):

Plate heat exchanger is made from aluminum sheets as shown in the figure (6). Table (3) shows the dimensions of plate heat exchanger.

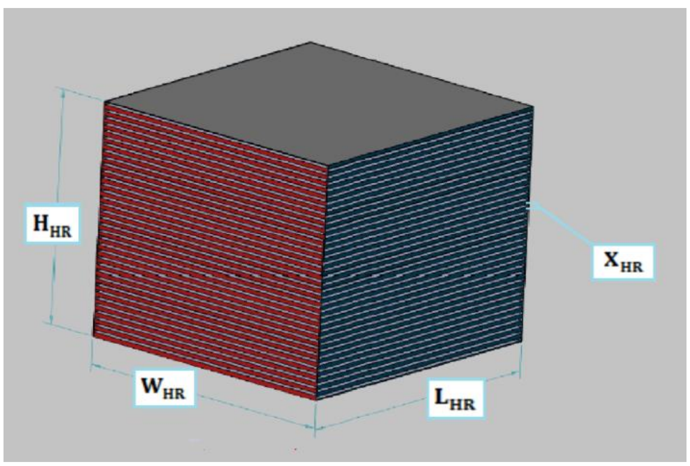


Figure (6) plat heat exchanger design.

Table (3): The dimensions of heat recovery.

H_{HR}	**440 mm**	**High of heat recovery.**
W_{HR}	550mm	Width of heat recovery
L_{HR}	600 mm	Depth of heat recovery.
X_{HR}	4 mm	Center to center distance of plates
NO_{Pass}	80	Number of pass of heat recovery

Figure (7) shows the manufactured heat exchanger after installed in the duct.

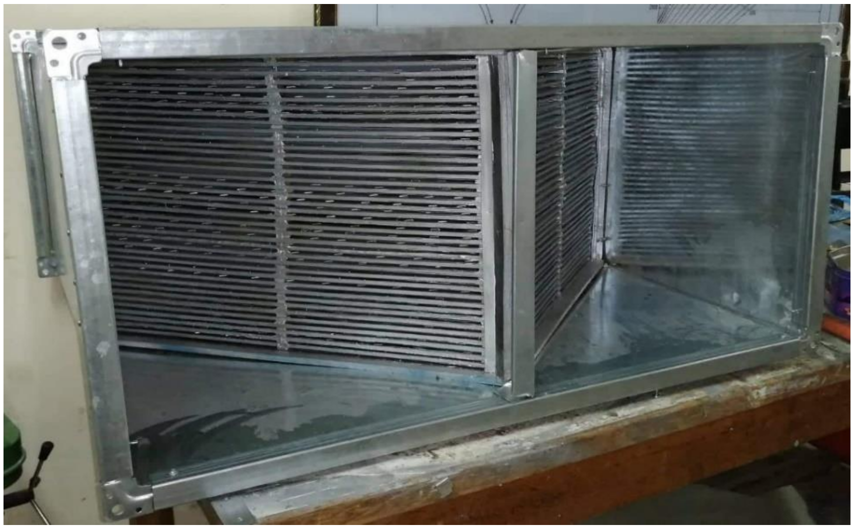


Figure (7) Manufactured heat exchanger after installed in the duct.

2.4 Supply fan Section:

The fan was chosen according to the cooling demand estimation. The system has been designed with (0.48 m^3/s). Different air flow rates have been tested in order to evaluate the effect of air flow rate on the performance of the system. Centrifugal fan has been installed, as shows in figure (8). The fan can be providing the variable air volume flow rate (0.48, 0.61 and 0.73 m^3/s). The specifications of centrifugal fan are shown in table (4)

Table (4): specification of centrifugal fan.

Rotating speed	voltage	frequency	Dimensions of case
1075 r.p.m	*230 v*	*60 Hz*	(550 mm × 550 mm × 500 mm)

Figure (8) supply fan.

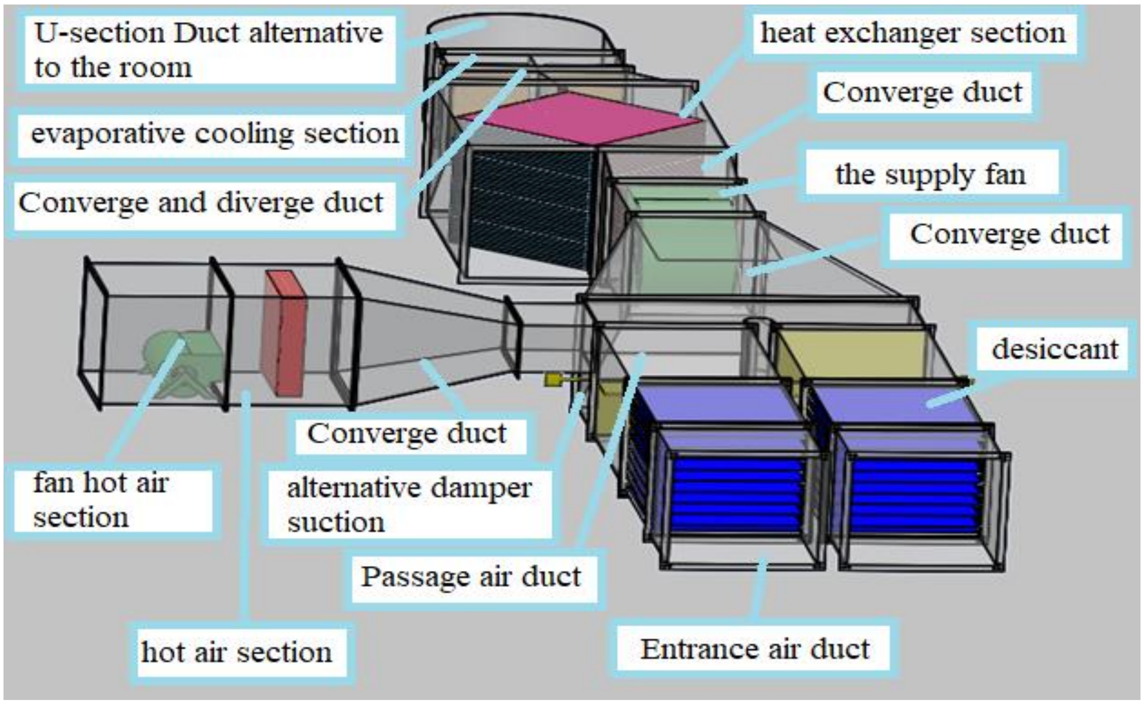
2.5 Regeneration fan Section:

In order to evaluate the effect of regeneration air flow rate on the performance of the system regeneration of flow rats have been used. Centrifugal fan providing the variable air volume flow rate (0.15, 0.28, 0.49 and 0.59 m^3/s) has been used for regeneration system. The specifications of centrifugal fan are shown in table (5)

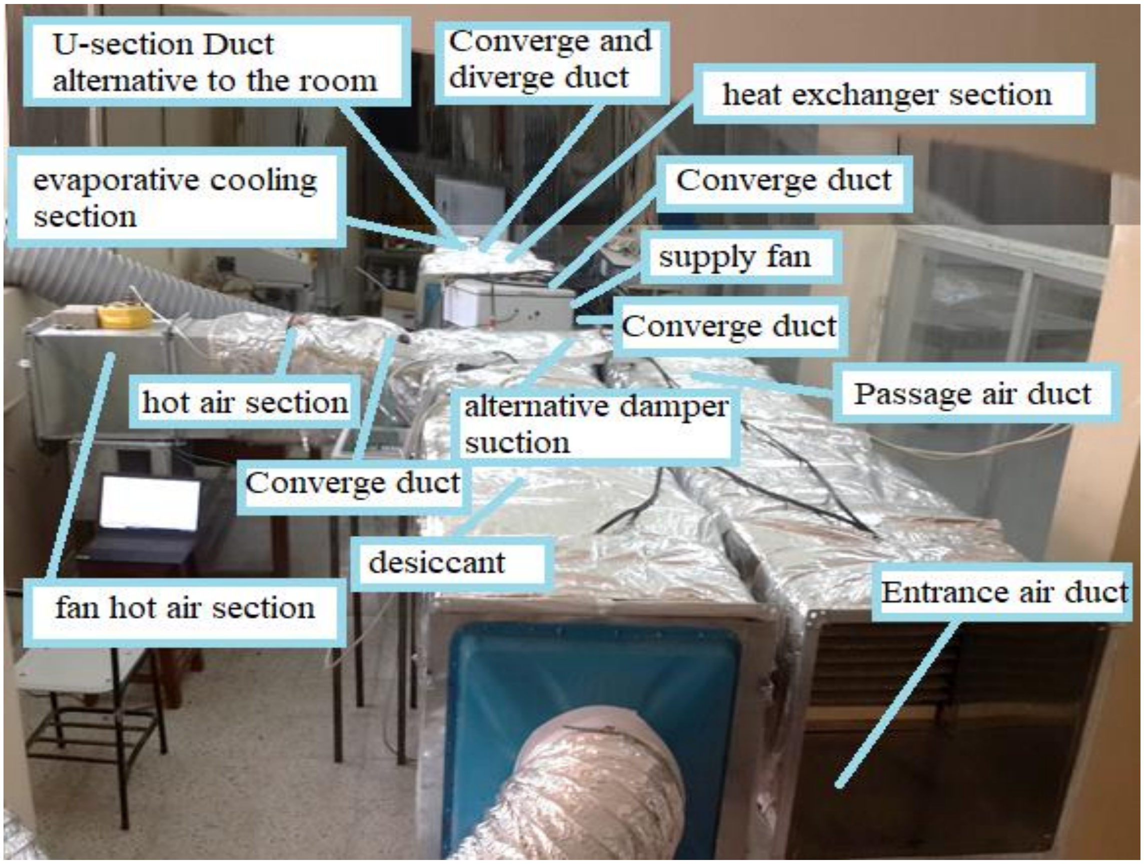
Table (5): specification of centrifugal fan.

Rotating speed	voltage	frequency	Dimensions of case
566 r.p.m	*220 v*	*60 Hz*	(450 mm × 450 mm × 500 mm)

Figure (9, a) and (9, b) show the system layout and the overall shape of the system.



(a)



(b)

Figure (9) system layout and the overall shape of the system.

3. Experimental setup

3.1 Summary of experiment steps

1) The heater and regeneration fan are switched on to regeneration the silica gel in first desiccant for different time periods.
2) Then the gates are replaced opened as the supply air flows into the first desiccant and the second desiccant is for regeneration, and so on.
3) Repeat the previous steps for various flow rates.
4) Repeat the previous steps for various flow time.
5) Repeat the previous steps for operate one evaporative cooling.
6) Repeat the previous steps without desiccant.
7) Repeat the previous steps in various external conditions.

4. Results and discussion

1- Sets of experiments, included study the main factors affecting on the performance of the double effect evaporator cooling system combine with desiccant and heat recovery, have been done in this study. The cooling load of the space for all tests is (500 watt). In this study, the effect of the outdoor condition, in terms of dry bulb and wet bulb, moisture content, air flow rate, best time of step and regeneration air properties on the performance of the system has been tested. The effect of inlet air flow rate and regeneration temperature of desiccant have been figured out as well.

4.1 Desiccant:

The air flow rate, in the regeneration section, has a significant effect on the performance of the system. The air flow rate effect on the ability of silica gel to remove the humidity. Four flow rates have been tested (0.15, 0.28, 0.49 and 0.59 m^3/s). Figure (10) shows that decreasing the air flow rate lead to increase the ability of desiccant to remove the humidity. The ability of hot air to remove humidity from the desiccant begin decline when the air flow rate exceeds 0.59 m^3/s due to decrease the temperature of regeneration air, a fixed heat source was used. The study concluded that the best flow rate for regeneration silica gel is 0.15 m^3/s, where the maximum amount of water vapor that can be removed from the silica gel is about (5.32g/kg).

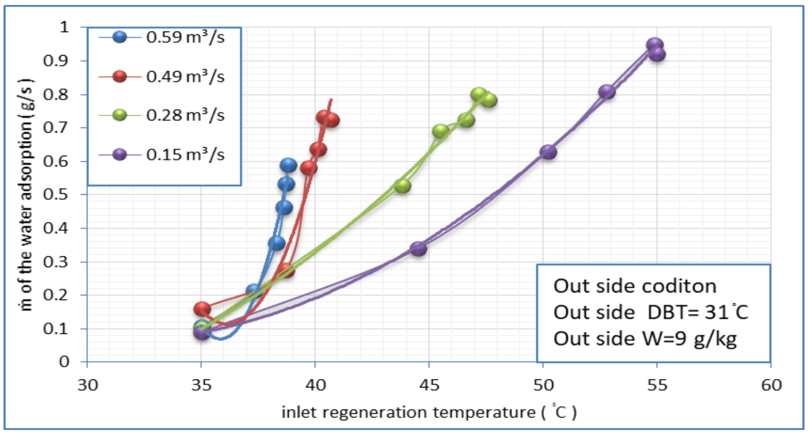


Figure (10) humidity removed from the silica gel with various regeneration temperature.

Different regeneration temperatures have been tested in this work (between 40 - 60 ̊C). The increase in regeneration temperature causes increase in the amount of moisture removed from the desiccant material to the air stream. The results show that, in this study, the best case in this study is at temperature (50-60 ̊C) and flow rate 0.15 m^3/s. Figure (11) shows the results of using difference regeneration temperature.

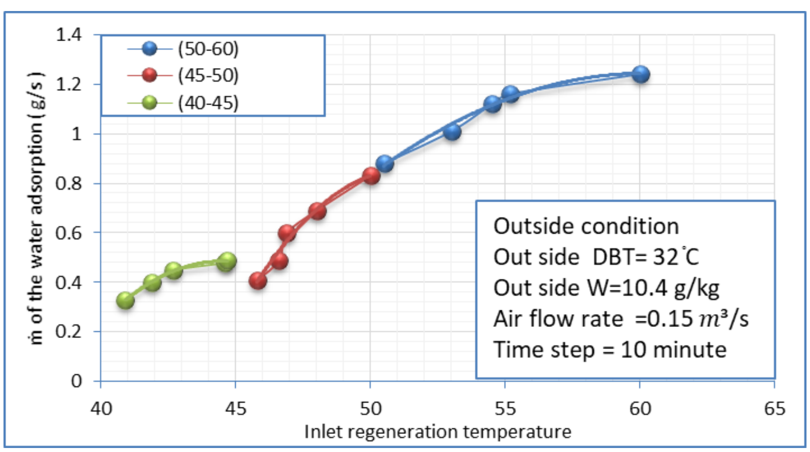


Figure (11) humidity removed from the silica gel with various regeneration temperature.

4.1.1 The optimum time to regeneration silica gel:

The suitable time to regeneration silica gel has been studied. Different periods for regenerating the desiccant material have been tested. An electric heater alternative to solar energy was used in this experiment. Figure (12) shows the decreasing in drawn moisture from desiccant with time, because with the passage of time, silica gel begins to approach drought relatively. The period for regenerating depend on the moisture in supplying air. If the moisture in supplying air is low (10.2 g/kg), the silica gel its dryness becomes reasonable in 15 minutes, however, when the processing air is very wet (20.3 g/kg), the silica gel its dryness becomes reasonable in 22 minutes. When the time exceed 30 min desiccant becomes completely dry. Therefore, it can be considered as the best time to regeneration the desiccant is 30 minutes.

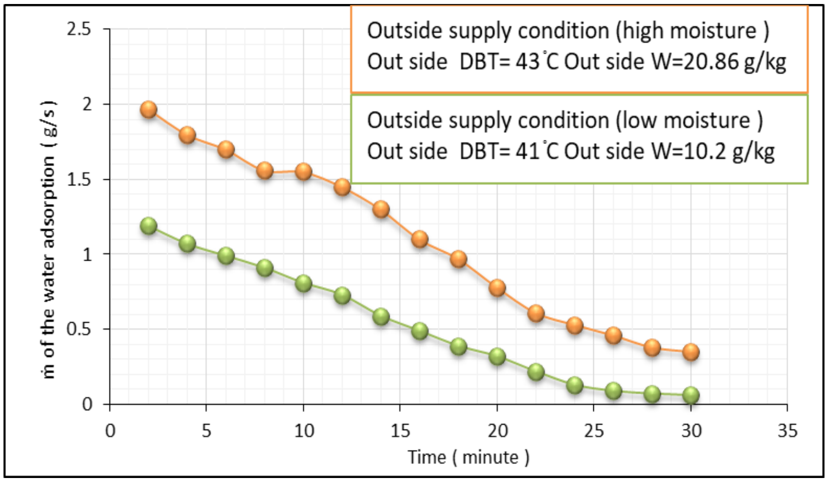


Figure (12) humidity removed from the silica gel with various time at regeneration air flow 0.15m^3/s.

4.1.2 The effect of time to remove humidity from the supplying air:

The ability of desiccant to remove the moisture from the supplied air decrease with the time. Because of the silica gel become saturated gradually with moisture. Figure (13) shows the effect of time on remove the moisture from air. When the time exceed 30 minute the silica gel become saturated with moisture, that is, the desiccant process becomes useless. However, if the processing air is very wet, the silica gel can absorb more moisture.

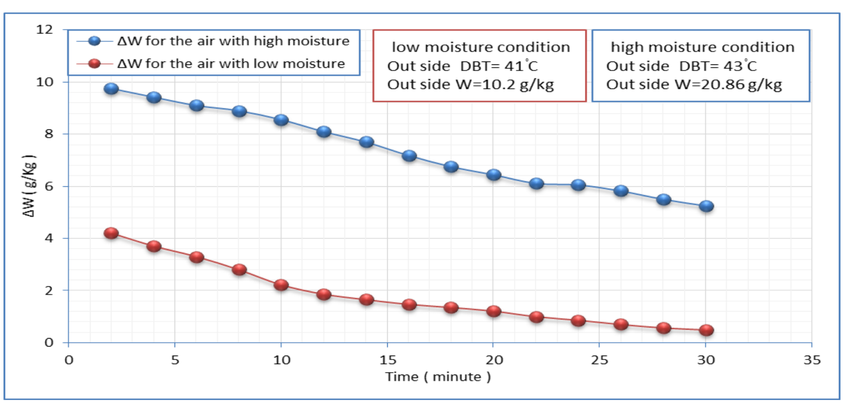


Figure (13) amount of moisture removed from the air flow with various time.

4.2 Evaporative cooling:

4.2.1 The best supplying air flow rate:

Figures (14) and (15) show that positive relationship between the supply temperature to the zone (outlet from evaporative cooling section) and flow rate. It was found that the best flow rate, in this study, for evaporative cooling to reduce the air temperature is 0.48 m^3/s. This is because low flow of air leads to a decrease in air velocity during the evaporative cooler section, and thus evaporative cooling works better.

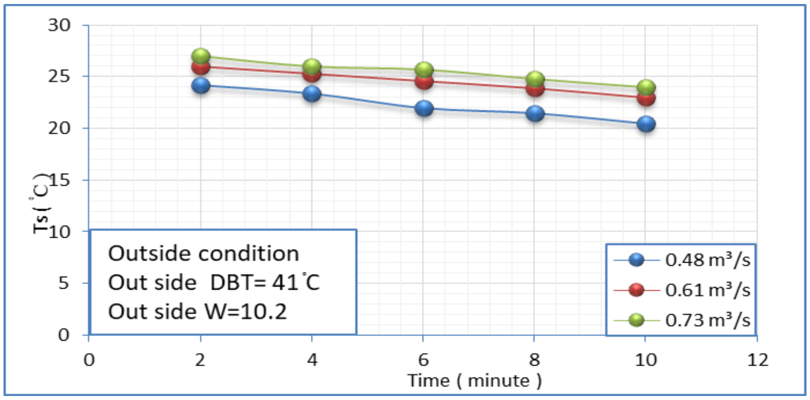


Figure (14) supply temperature with various air flow in the conditions of low moisture.

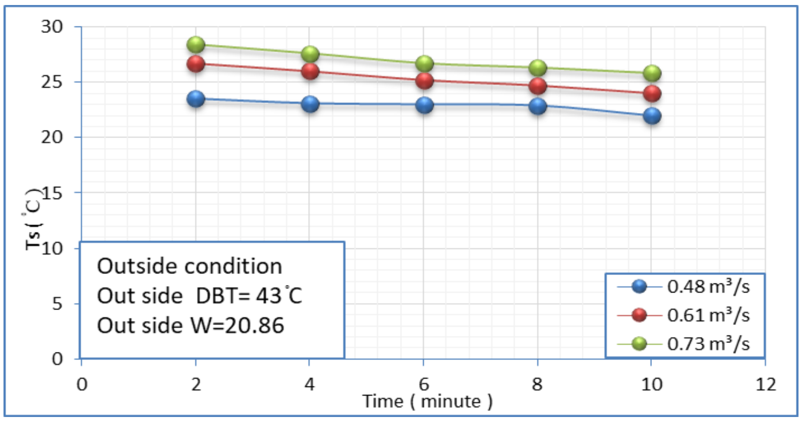


Figure (15) supply temperature with various air flow in the conditions of high moisture.

4.2.2 The effect of desiccant on evaporative cooling:

Desiccant materials affect significantly on the performance of evaporative cooling. The wet bulb temperature of the inlet air is the lowest temperature can be reached by the evaporative cooling. The temperature is increased when the inlet air moisture increased. Figures (16) and (17) show the performance of evaporative cooling with and without the desiccant. It is clear that the performance of evaporative cooling and supply temperature with desiccant are much better (especially in high humidity environment) due to the ability of desiccant material to reduce the moisture of the inlet air.

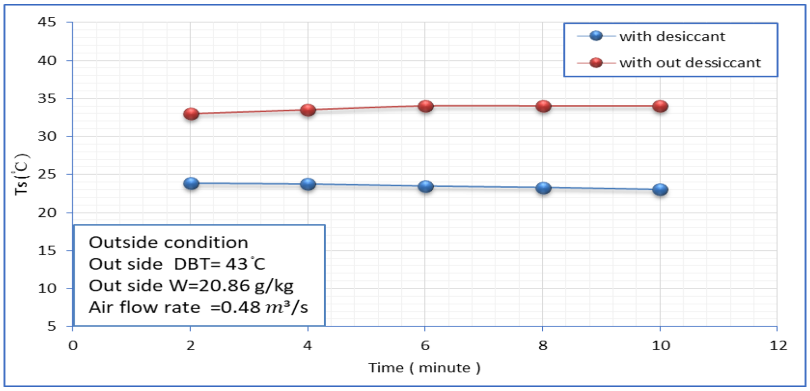


Figure (16) effect of using desiccant on the supply temperature.

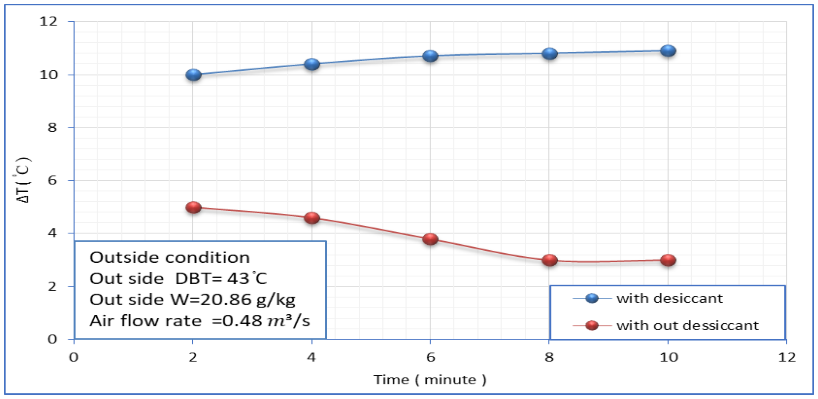


Figure (17) temperature change through the evaporative cooling with and without desiccant.

4.2.3 The effectiveness of evaporative cooling.

The effectiveness of the evaporative cooler change with the outside conditions. The lowest temperature, which can be reached by the evaporative cooling, is the wet bulb temperature of the inlet air. This temperature increase when the moisture of the inlet air is increases. Where in low-humidity conditions the effectiveness is high. In the high-humidity conditions with use desiccant is less than it. In a high-humidity conditions without use desiccant the effectiveness will be very low. Figure (18) shows the effectiveness of first evaporative cooler with various moisture content and figure (19) shows the effectiveness of second evaporative cooler with various moisture content.

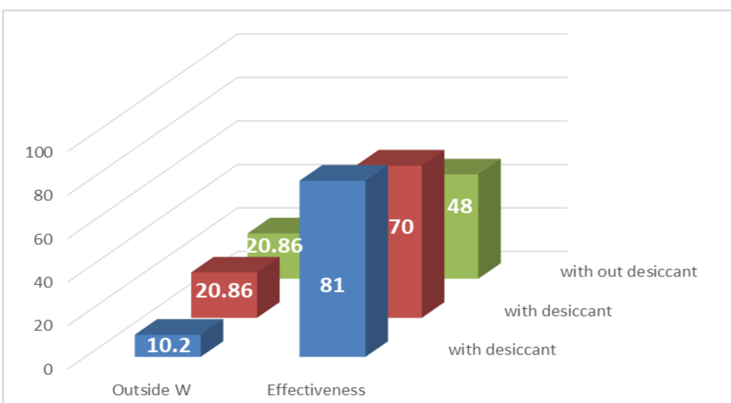


Figure (18) effectiveness of first evaporative cooler (supply) with various moisture content at same air flow rate 0.48 m^3/s.

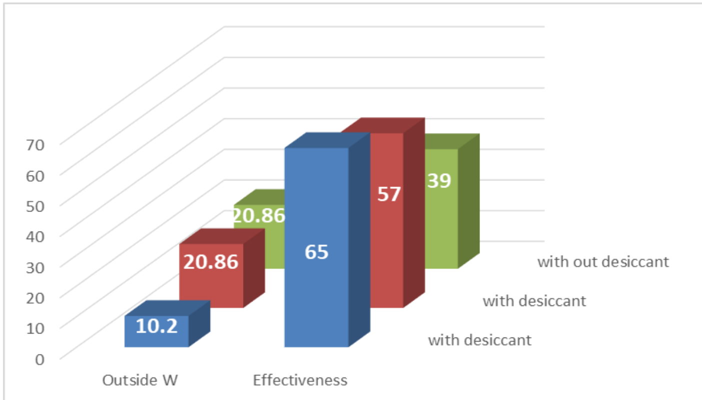


Figure (19) effectiveness of second evaporative cooler (return) with various moisture content at same air flow rate 0.48 m^3/s.

4.3 plate heat exchanger:

Figures (20) and (21) show the relationship between temperature changes during the heat exchanger with the time, and figure (22) shows the relationship between sensible heat transfer during the heat exchanger with the time, at various flow rates (0.48, 0.61 and 0.73 m³/s). It turns out that low flow rate is best to decrease the air temperature. Because that increase flow rate lead to reduce the ability of heat exchanger to decrease air temperature, due to increase the velocity of air. It was found that the best flow rate (in this study) for heat exchanger is 0.48 m³/s.

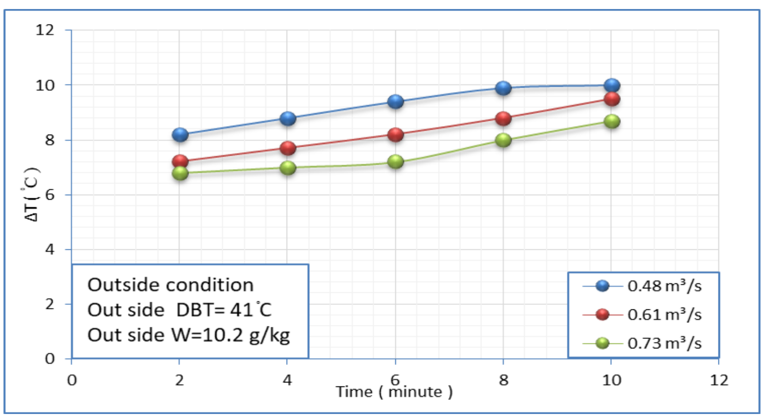


Figure (20) relationship between temperature changes during the heat exchanger with the time at various flow rates (w= 10.2 g/kg).

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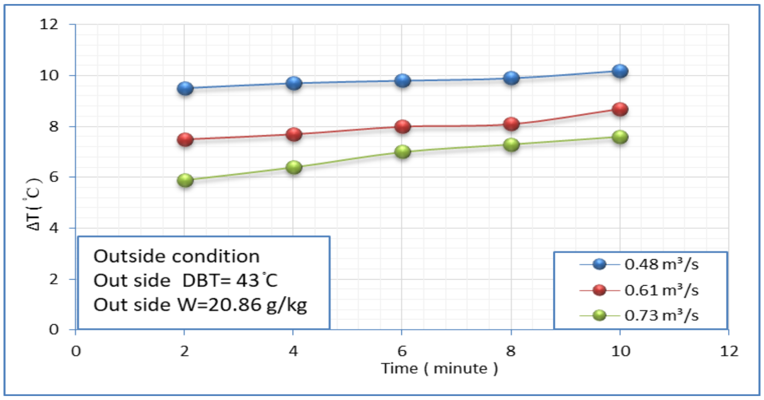

Figure (21) relationship between temperature changes during the heat exchanger with the time at various flow rates (w= 20.86 g/kg).

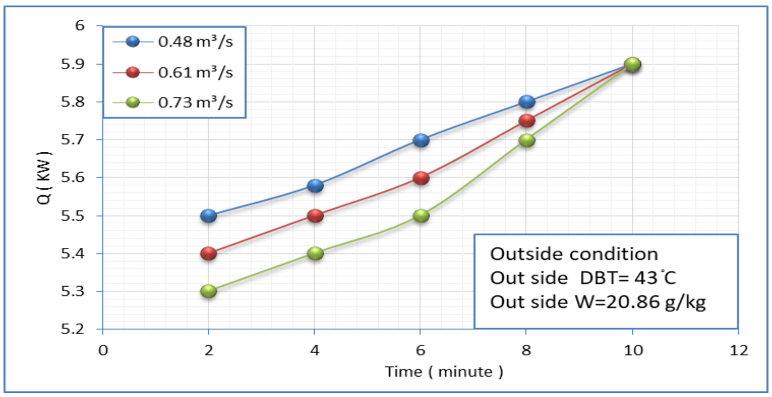

Figure (22) relationship between sensible heat transfers during the heat exchanger with the time at various flow rates.

The effectiveness of the heat exchanger depends significantly on the outside conditions. Where in low-moisture conditions the effectiveness is high. In case of high-moisture conditions with desiccant the effectiveness is good. In the case of high-moisture conditions without desiccant the effectiveness is very small. Figure (23) shows the effectiveness of heat exchanger with various moisture content in the outside. It can be seen that even in high moisture condition, the effectiveness of the system with desiccant (in high moisture condition) is almost the same as the effectiveness of the system with desiccant (in low moisture condition). It was found that the effectiveness of the heat exchanger manufactured is very good [7].

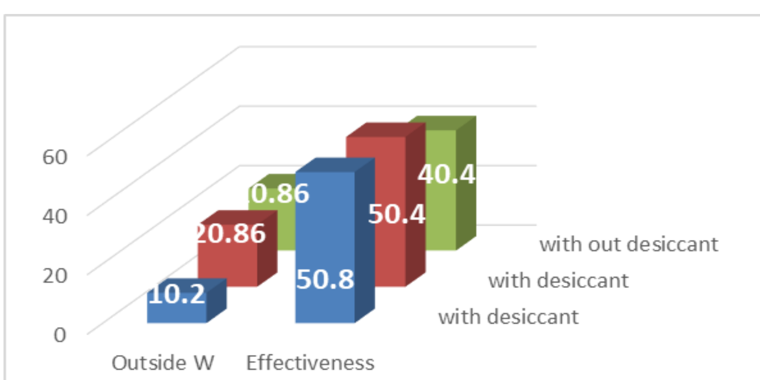

Figure (23) effectiveness of heat exchanger with various moisture content.

4.4 COP of the system:

4.4.1 COP_{ele} of the system:

The COP_{ele} of the system affected with the change in outside conditions. Where in low- moisture condition the COP_{ele} is 13.95. The COP equal 13.74 when the moisture of air is high and using desiccant. In the case of high-moisture condition without desiccant, the COP_{ele} is 6.67. Figure (24) shows the COP_{ele} of the system with various moisture content. In some studies, demonstrate that the COP_{ele} between 8-20 [5, 6].

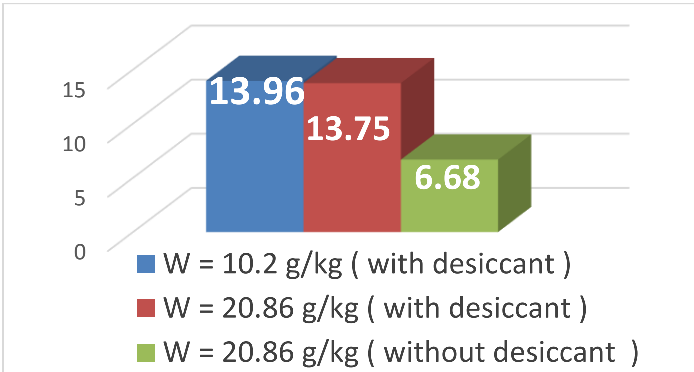

Figure (24) COP_{ele} of the system with various moisture content.

4.4.2 COP_{th} of the system:

As in the case of COP_{ele}, the COP_{th} depends significantly on the outside weather condition. In low- moisture condition the COP_{th} is 2.3. The COP_{th} decreased to 2.27 in case of high-moisture condition with desiccant. The COP_{th} decreased significantly to 1.04 in the case of high-moisture condition without desiccant. Figure (25) shows the COP_{th} of the system with various moisture content. In some studies, demonstrate that COP_{th} above 1 [5-6].

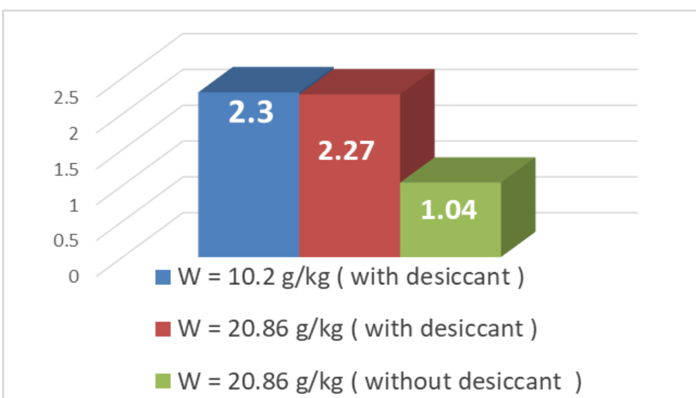

Figure (25) COP_{th} of the system with various moisture content.

We note from the above figure that the coefficient of performance is significantly affected by a change in external conditions and the addition of a desiccant. Figures (26) shows the processes of adsorption system on the psychrometric chart. It can be seen from these figures that the external conditions have a major impact on system performance and the adsorption system which is depicted by points (1, 2, 3, 4, 5, 6, 7 and 8).

- (1) - (2) the dehumidification process. The temperature of air is slightly increased and the moisture was decreased.
- (2) - (3) there is very little changes because the air passes through the ducting only.

- (3) - (4) sensible cooling by heat exchanger.
- (4) - (5) first stage evaporative cooling (cooling and humidification).
- (5) - (6) increase heat in room due to load.
- (6) - (7) second stage of evaporative cooling (cooling and humidification).
- (7) - (8) sensible heating by air heat exchanger.

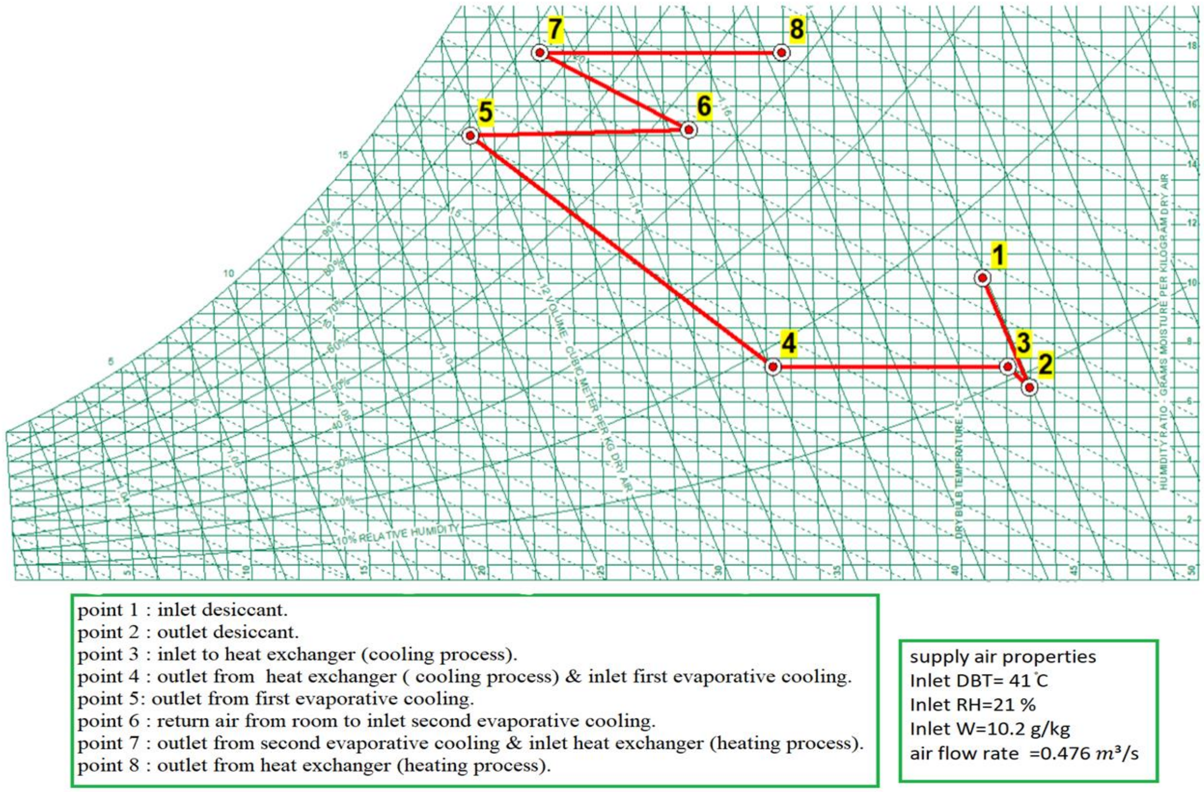

Figure (26) effect of the processes of system on the psychrometric chart the conditions of low moisture with desiccant.

5. Conclusion

In this study a system that consists of two stages evaporative cooling combine with heat recovery and desiccant has been evaluated. From the experimental study, the following points has been concluded:

1- The performance of the double effect evaporative cooling system with heat recovery and desiccant depends significantly on the weather conditions. In a high-humidity conditions, the performance of the double effect evaporative cooling with heat recovery and desiccant is much higher than the traditional evaporative cooling system (without heat recovery and desiccant). In low humidity conditions, the performance of the desiccant is less clear.

2- The supply temperature of the system depends significantly on the air flow rate. The supply temperature decrease when the air flow decrease.

3- The study showed that the double effect evaporative cooling with heat exchanger and desiccant system can cool the fresh air below its wet bulb temperature, which is overcoming the limitations of the traditional evaporative cooling system.

4- The environmental friendly proposed cooling system could be an alternative system to CFCs cooling systems that is affecting on Ozone layer.

5- The regeneration temperature effect significantly on the performance of the desiccant material. It is recommended to keep the regeneration temperature between (50 - 60 $^{\circ}$C) (for silica gel).

6- Using desiccant material led to increases the coefficient of performance of the system. The COP_{ele} of the system is 13.75 and the COP_{th} of the system is 2.27, compared to the system without use desiccant the COP_{ele} of the system is 6.68 and the COP_{th} of the system is 1.04 at same outside weather condition.

7- When use desiccant in low moisture condition, the maximum time to switch desiccant is 30 minutes.

8- The recommended time to regeneration the silica gel with high moisture condition is between (10-22) minutes.

6. References

[1] M. F. El-Refaie, S. Kaseb, Speculation in the feasibility of evaporative cooling, Building and Environment, Issue 44, 2008.

[2] P. Mavroudaki, C. B. Beggs, P. A. Sleigh, S. P. Halliday, the potential for solar powered single-stage desiccant cooling in southern Europe, Applied Thermal Engineering, Issue 22, 2002.

[3] K. Daou, R. Z. Wang, Z. Z. Xia, Desiccant cooling air conditioning: a review, Renewable and Sustainable Energy Reviews,Issue. 10, 2004.

[4] J. R. Camargo, E. Godoy and C. D. Ebinuma, An evaporative and desiccant cooling system for air conditioning in humid climates, Braz. Soc. of Mech. Sci. and Eng., 2005.

[5] D. La, Y. Dai, Y. Li, T. Ge, R. Wang, Study on a novel thermally driven air conditioning system with desiccant dehumidification and regenerative evaporative cooling, Building and Environment, Issue 45, 2010.

[6] B. Lorenzo, E. Brian, K. M. Ryhi, M. W. Brix, L. O. Reinholdt, Analysis of a solid desiccant cooling system with indirect evaporative cooling, PhD Thesis, Technical university of denmark, 2017.

[7] K.Anastasiia, Efficiency of heat recovery, Bachelor's Thesis, Building Services Engineering, 2012.

[8] ASHRAE HANDBOOK, 2005.

[9] A. A. Alyahya and Nawari, towards net-zero energy in hot-dry regions: building envelope design strategies for single-family homes, Journal of Sustainable Development, Issue 3, 2018.