Analytical Study of a Heat Recovery/Desiccant Cooling System under Tunisian Climatic Conditions

S. Sabek, K. Ben Nasr, R. Chouikh, and A. Guizani

***Abstract*—The solar potential energy in Tunisia can be used like a principal factor for the operation of new technologies of air conditioning. Studies could be carried out like approaches of simulation, analyzes experimental or both unit. In this paper, we present an analytical solution of heat and mass transfer processes in regenerator and air conditioning system (ACS) cores of a heat recovery /desiccant cooling system (HRDCS) under Tunisia weather conditions. Simulations programs were carried out to test the principal components of the HRDC system. The results show that the coefficient of performance of system improves when we use the renewable energy for heating and cooling. This study is significant and effective to prove the efficiency of such HRDC systems in this country.**

***Index Terms*—Air conditioning, liquid desiccant cooling system, simulations, Tunisian climatic conditions.**

I. Introduction

Energy consumption in buildings has been increased in recent years with the development of the economy worldwide, recent studies have shown that buildings are responsible for the consumption of about 40% of the primary energy and the emission of nearly 33% of the greenhouse gases in the world [1]. Therefore, liquid desiccant cooling technologies has been researched and demonstrated in recent years, focusing on applications such as cooling of human houses, commercial buildings, hospitals. It can be an efficient way to provide cooling and to reduce building energy consumption.

Approximately 30 years ago, [2] accounted for the operation of a device of air-conditioning on a large scale using water- LiCl, where they presented the direct regeneration in collectors open and storage to the cold in the form of regenerated solution. Some investigators tested the use of the organic absorbents, such as tri ethylene glycol (TEG) to reduce the problem of corrosion involved in inorganic salts [3]. Researches [4], [5] have been carried on the liquid desiccant systems for cooling and dehumidification by using solar energy to regenerate the liquid desiccant during the regeneration process and to re-use it for the dehumidification of air. In several cases, the direct regeneration of the liquid desiccant to the sun was considered by using a special type of collector.

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Among people who make research and experiments of this type of system are, Mavroudaki [6] presented a review of desiccant dehumidification/cooling systems applications in north Europe and they concluded that there was a potential to use these technologies in the European countries.

Saman and Alizadeh [7] examined a solar system with liquid desiccant air conditioning (LDAC) in the tropical climate of Queensland, Australia (2002). The performance of a LDAC solar system for dehumidification/cooling was studied experimentally and theoretically. It noted that the system is an effective manner to dehumidify and to cool air in hot and wet climates and that the performance of LDAC could be increased by using the optimum flows of air and solution of 1000 L/s and 3 L/min, respectively. In 2006, Gommed and Grossman [8] regarded that the town of Haifa as an ideal place to examine a cooling system placed on the Mediterranean coast with the latitude 33 of north, it has the typical climate of the Mediterranean cities. They concluded that this system has a simple construction, simple capacity storage and an ordering of dirtiness and capacities by using an air-to-air heat exchanger to recovery the thermal heat.

In 2008, Shuli Liu [9] studied a novel heat recovery/cooling system to carry out low energy cooling with a low emission of CO_2. This system is very useful for a hot and wet climate with the abundance of solar energy. The economic analysis based on a case (office of 200 m^2 in London) indicated that the new system of cooling and recovery of heat could save energy 5134 kWh as prevent the emission of 3123 kg CO_2 annually compared with a traditional system. The capital and maintenance costs of this system of cooling are higher than the traditional system, but its cost of operation are the much lower last. It showed that the new system of cooling and heat recovery is profitable and friendly to environment.

In many places in India, the air-conditioning in the summer is used not only for the comfort of the occupants but to also improve their productivity. Jain [10] presented a cooling system composed by a regenerator and dehumidifier. Theoretical and experimental studies are presented to the principal components of a liquid desiccant cooling system and a comparison of the two results. By changing the air temperatures and the ratio of moisture and the solution flow rates, the operating conditions of dehumidifier and regenerator varied.

Grossman and Gommed noted that the desiccant systems of cooling liquids had good cooling the performance in the hot and wet climates as in the Mediterranean countries solving the problem of the lack to cool air. The system was worked since April 2003 [11] studied and examined a liquid desiccant system for cooling and dehumidification, it includes a novel heat/mass exchanger (HME) designed to reserve a liquid desiccant with the regenerator and the

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dehumidifier and to allow the mass transfer between them with a minimum thermal losses.

In this paper we present a research project, in progress, whose objective is to set up a desiccant cooling system.

It could to minimize fossil fuel-based energy use, reduce electricity demand and to achieve low energy cooling with low CO_2 emission. The system incorporates a solar thermal collector, a dehumidifier, a cooling tower, heat exchangers and a building. We present an analytical solution of heat and mass transfer processes in system cores and also results of the simulation computer code. The project aims at assessing the effectiveness of this kind of a desiccant cooling technology under Tunisian climatic conditions.

II. Climate and Energy Considerations in Tunis

Tunisia has a high level of solar power with an average direct irradiation which varies from 2 kWh/m²/day in the extreme north to 6 kWh/m2/day in the zones of the extreme south [12]. It receives an average of 4 kcal/ m2/day with a total insolation period of 3500 h/year and 350 sunny days per year [13]. As we can see in Fig. 1 there is an abundant solar energy in overall the country of Tunisia from the north (Tunis) to the south (Tatouin) which must be explored and especially to produce the cooling demand and to provide the occupants with healthy and productive environments [14].

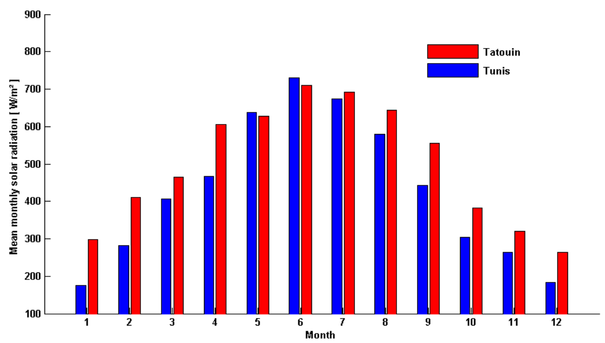

Fig. 1. Mean monthly solar radiation intensities in Tunis and Tatouin.

The indoor comfort conditions, as presented in Table I by setting the desired zone temperature and humidity ratio at 25 ℃ and 50% in summer and 20 ℃ and 60% in winter. We have exploited in this study climatic data collected from a two meteorological stations the first one is placed at the Sahara (southern zone) and the other is at the northern coast.

TABLE I: The Arrangement of Channels

	Summer	Winter
Temperature (℃)	25	20
Relative Humidity (%)	50	60

III. Description of the System

The liquid desiccant system is designed to serve as an open-cycle absorption system that can operate with low grade solar heat. The system consists of six components: an air dehumidifier, a solution regenerator, two water-to-solution heat exchangers, a solution-to-solution heat exchanger, and air-to-air heat exchanger, a schematic description of a system is given in Fig. 2.

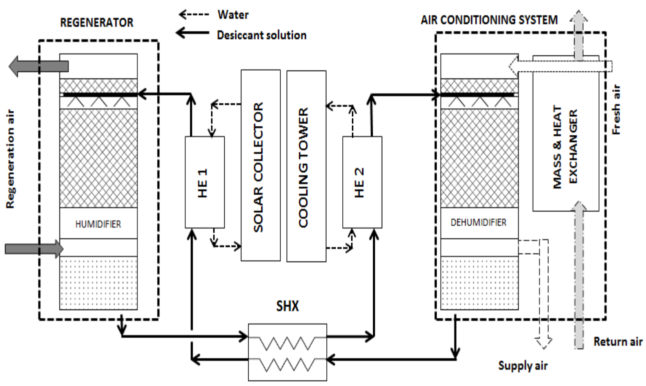

Fig. 2. Description of liquid desiccant system.

When the fresh air enters the system into the dehumidifier, it makes contact with the concentrated and cool liquid desiccant. The fresh air, preliminarily cooled in the heat exchanger recovery (air-to-air heat exchanger), is thus dehumidified and cooled. The liquid desiccant cycle begin by pumped the solution at the bottom of the dehumidifier, passes through the solution to solution heat exchanger to be preheated, then it's heated until regeneration temperature by solar energy, and finally it's sprayed in the regenerator to be concentrated.

IV. Choise of Liquid Desiccant Solution

From the researches in hydroscopic substances, it can be said that a large number of solution used in the cooling system (LiCl, LiBr, $CaCl_2$, KCOOH,etc), but the choice of the adequate liquid desiccant solution is based on four important parameters which are : vapor pressure, solution concentration and it is the crystallization limit, and the regeneration temperature and finally the price of desiccant solution.

A comparison study between LiCl and LiBr solutions frequently used HRDC system proves that the efficient one is the LiCl solution because it is more used owing to its higher absorption ability and relatively lower regenerator temperature (60-65 ℃) and high crystallization limit. Although it is corrosive but not a toxic material and does not pose any health hazards and its cost lower compared with LiBr [15].

An experimental analysis carried by Pietruschka [16], it deduced that the calcium chloride solution $CaCl_2$ provided lower dehumidification potential that the lithium chloride solution LiCl which had a cheaper price and no causticity with metal. The lithium chloride solution gave 40-50% higher dehumidification rates over a wide relative humidity range.

From the different types of liquid desiccants are available in the market, the lithium chloride LiCl selected as a desiccant solution to use in this study.

V. Mathematical Formulation

Many researchers has developed mathematical models of the coupled heat and mass transfer processes in the ACS or regenerator, and most of the models were solved numerically [17], [18]. In this part, we present a schematic model and an analytical solution of heat and mass transfer processes in the principal components of a liquid desiccant cooling system.

Fig. 3 shows a schematic model of the liquid desiccant system and the circle of desiccant solution, where, the different number (1, 2, 3, 4, 5, and 6) is the solution position in the operating circle.

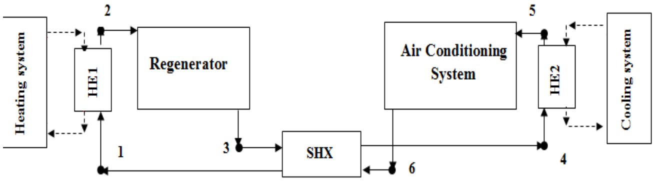

Fig. 3. Diagram of the desiccant cycle.

The following assumptions are made for the analysis:

1) The mathematical formulation was developed under steady state conditions.
2) The specific heat of the fluids with respect to the temperature is constant.
3) The heat loss through the regenerator and dehumidifier was negligible.
4) The desiccant inlet temperature is different from the inlet temperature of air.

A. Regeneration Process

The balance of heat and mass is written for a long of core regenerator *L*, where we consider that air and solution desiccant in the opposite direction. The desiccant outlet temperature is defined as:

$$\theta_{sol3} = \frac{H_{sol2} + m_{air} * \left[\left(H_{air,de,in} - H_{air,deh,out} \right) + \lambda_{des} * \left(W_{air,deh,out} - W_{air,deh,in} \right) \right]}{\left(m_{sol3} * C_{sol} \right)} \quad (1)$$

where m_{air} is the air mass flow rate (Kg/s), m_{sol} is the desiccant solution mass flow rate (Kg/s), Hair is the enthalpy of the air stream (J/kg), W_{air} is air humidity ratio (Kg/Kg) and C_{sol} is desiccant solution specific heat capacity (J/kg K).

The solution desiccant concentration at outlet of the regenerator is given by:

$$\zeta_3 = \frac{m_{sol\,2}}{m_{sol\,3}} * \zeta_2 \quad (2)$$

where, ζ is the solution concentration.

B. Dehumidification Process

In this part, the air stream is dehumidified and cooled by the strong/cold solution in the dehumidifier core, the desired air temperature and moisture content at the outlet of air conditioning system (ACS) is described as the following:

$$\theta_{air,deh,out} = \frac{m_{air} * \left(C_s + C_v * W_{air,deh,in} \right) - \eta_{deh} * \left(H_{sol6} - H_{sol5} \right)}{\left(C_s + C_v * W_{air,deh,in} \right)} \quad (3)$$

where, H_{sol} is the enthalpy of the desiccant solution (J/kg).

$$W_{air,deh,out} = W_{air,deh,in} - \eta_{deh} * \left(W_{air,exh} - W_{air,deh,in} \right) \quad (4)$$

The desiccant solution at the outlet of the ASC in terms of the known solution and air temperatures at the inlet, the solution desiccant outlet temperature is defined as:

$$\theta_{sol6} = \frac{H_{sol5} + m_{air} * \left[\left(H_{air,de,in} - H_{air,deh,out} \right) + \lambda_{abs} * \left(W_{air,deh,out} - W_{air,deh,in} \right) \right]}{\left(m_{sol6} * C_{sol} \right)} \quad (5)$$

where, λ_{abs} is the enthalpy of absorption (dilution) (J/kg), which is defined for the aqueous solution of lithium chloride as [19]:

$$\lambda_{abs} = \left(169.105 + 457.850 \times \left(273 + \theta_{sol} \right) \right) \times \left[1 + \left(\frac{\zeta}{0.845 \times \left(0.6 - \zeta \right)} \right)^{-1.965} \right]^{-2.265} \quad (6)$$

The desiccant concentration at outlet of the ACS is given by:

$$\zeta_6 = \frac{m_{sol5}}{m_{sol6}} \times \zeta_5 \quad (7)$$

C. Heating and Cooling Systems

The temperature of cooled water leaving the cooling system (cooling tower) is assumed to be lower than the solution temperature .entering in the heat exchanger (HE2) and the effectiveness of the cooling tower is assumed constant equal to 0.8. The heat transfer rate (Q_{cool}) transferred from the solution to the cold water is calculated:

$$Q_{cool} = m_{sol4} \times C_{sol} \times \left(\theta_{sol4} - \theta_{sol5} \right) \quad (8)$$

The energy consumption rate of the cooling system (E_{cool}) is calculated by the equation as follows:

$$E_{cool} = \frac{Q_{cool}}{0.8} \quad (9)$$

The temperature of heated water leaving is assumed to be higher than the solution temperature entering in the heat exchanger (HE1) and the effectiveness is assumed constant equal to 0.8. The heat transfer rate (Q_{heat}) transferred from the hot water to the solution is calculated:

$$Q_{heat} = m_{sol1} * C_{sol} * \left(\theta_{sol2} - \theta_{sol1} \right) \quad (10)$$

The energy consumption rate of the heating system (E_{heat}) is calculated by the equation as follows:

$$E_{heat} = \frac{Q_{heat}}{0.8} \quad (11)$$

Electrical energy (Eel) consumed in this system, we take the electrical consumption of the example of Shuli Liu system (Shuli Liu, 2008), which is like our system, which require a small amount of energy with the maximal value of about 500W (There are 6 pumps (30W) and 3 fans (100W)).

D. Performance of the Desiccant Cycle Process

In this part, we present the coefficient of performance (*COP*) to describe the working performance of the global system. As the definition of *COP*,

$$COP = \frac{producing\_energy}{input\_energy} \quad (12)$$

The output energy (cooling capacity) is energy reduction from the fresh air to supply air as shown in the following:

$$CC = m_{air} \times C_s \times \left(\theta_{freshair} - \theta_{\text{supplyair}}\right) \quad (13)$$

The *COP* is defined as the ratio between the cooling capacity and the total primary energy consumption in the whole liquid desiccant system, it should be considered in two conditions: when natural energy is unavailable, and natural energy is sufficient.

1) When no renewable energy is utilized, the *COP* of the whole system is:

$$COP1 = \frac{CC}{\left(E_{cool} + \left(E_{el}/0.3\right)\right) + E_{heat}} \quad (14)$$

2) When renewable heating and cooling energy are utilized, the *COP* of the whole system is:

$$COP2 = \frac{CC}{E_{el}/0.3} \quad (15)$$

where, 0.3 is the assumed equivalent conversion coefficient of electric power to thermal energy.

VI. Numerical Results

A. Air thermal Process and Desiccant Solution Cycle Thermal Process

In this part, Fig. 4 presents the air thermal process on psychometric chart in a typical summer day (at 13:00). The fresh air is pre-cooled and dehumidified from **point 1** to **point 2** by heat and mass transfer to the existing air in the heat/mass exchanger. Then into the desiccant dehumidifier core, the fresh air is cooled and dehumidified until **point 3** to supply into the building. The exhaust air humidity and temperature is varied from **point (i)** into psychometric chart to **point 4** through the air to air heat/mass exchanger and then exits.

The air Temperature and humidity ratio values of circle thermal process are presented in Table II.

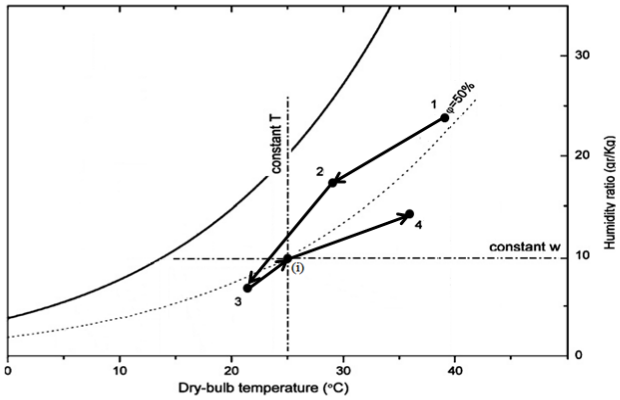

Fig. 4. Air thermal process on psychometric chart.

TABLE II: AIR THERMAL PROCESS

	T_{air} [℃]	W_{air} [g/Kg]
Point 1	39.22	23.9
Point 2	28.16	18.1
Point 3	21.34	7.3
Point (i)	25	9.8
Point 4	36.38	14.8

Fig. 5 shows the desiccant solution cycle process on Chart of equilibrium between the vapor pressure of aqueous solutions of lithium chloride and the partial pressure of water vapor in the air, at the normal sea level atmospheric pressure [18]. Before entering the regenerator, the weak desiccant solution (**point 1**) is heated by a hot water coming from the heating system (**point 2**), which the water vapor is removed from the weak desiccant solution to the regeneration air. Then, the strong desiccant solution from the regenerator (**point 3**) pre-cooled by passing in sensible heat exchanger (SHX), resulting in a lowered temperature state to **point 4**. However, on the way to the air conditioning system, the desiccant solution temperature decreases due to absorbing heat from the cool water coming from the cooling system to the desiccant solution in the heat exchanger (HE2) (**point 4** to **5**).In the dehumidifier core, the moisture and part of the heat moves from the passing air by a strong desiccant solution (**point 5** to **6**).

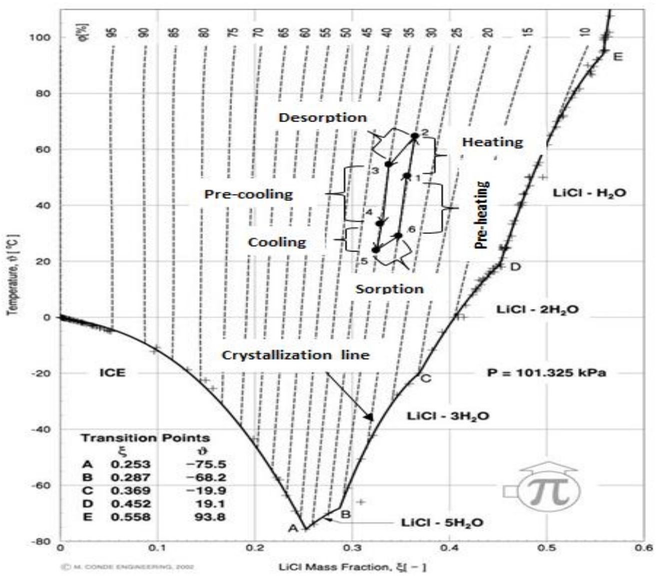

Fig. 5. Desiccant solution cycle thermal process.

Both desiccant solution temperature and concentration values are presented in Table III.

TABLE III: DESICCANT SOLUTION CYCLE THERMAL PROCESS

	T_{sol} [℃]	ζ_{sol} [%]
Point 1	49.61	30
Point 2	64.58	30
Point 3	55.17	35
Point 4	32.94	35
Point 5	23.01	35
Point 6	27.39	30

B. *Typical Summer Day Results*

Fig. 6 presents the climatic conditions (solar radiation, ambient temperature) for a sunny day representative of the month of August chosen from data file. The results of simulation related to one typical day of summer (02/08). In summer, it is expected that the temperature of the ambient humid air that enters the dehumidifier is higher than the solution inlet temperature. Hence, in addition to moisture transfer, heat transfer will also occur due to the temperature difference. The primary objective of the dehumidification process is to remove water vapor from the ambient humid air [20].

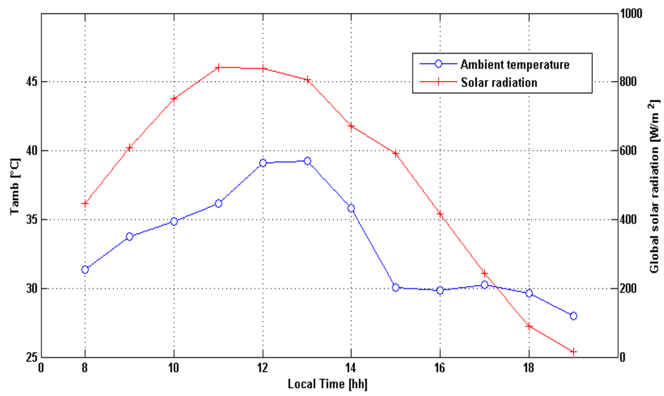

Fig. 6. Climatic conditions (solar radiation, ambient temperature).

Fig. 7 presents the air specific humidity (absolute) at the inlet and outlet of air conditioning system under the indicated climatic conditions. The inlet specific humidity decreased between 40-65 % in this typical day, this deference between inlet and outlet is proportional to moisture transfer during an air dehumidification process.

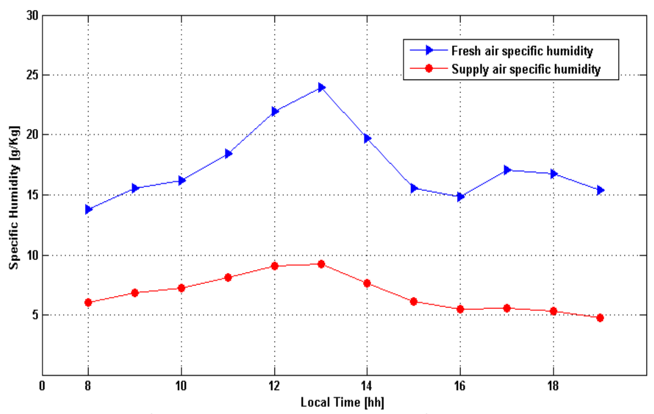

Fig. 7. Air specific humidity at inlet and outlet of air conditioning system.

Fig. 8 presents the air temperatures at the inlet and the outlet of the air conditioning system under the indicated climatic conditions. The supply air temperature is expected to be lower than that of the inlet air due to the contact of the air stream with the cool and strong desiccant solution. This is confirmed with the experimental data given by Chung [21].

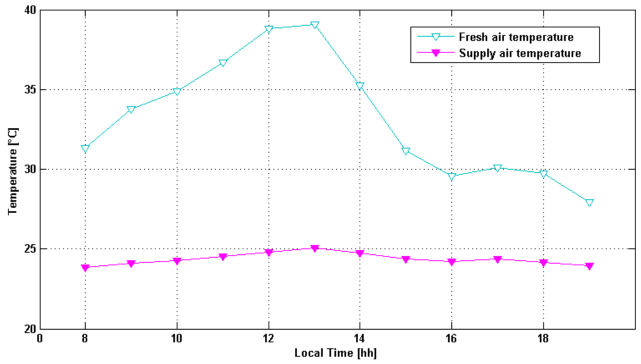

Fig. 8. Air temperature at inlet and outlet of air conditioning system.

Fig. 9 presents the coefficient of performance (COP) of the global system. By varying the climatic conditions, it can be seen that the climatic conditions greatly influenced the COP, the COP1 without renewable energy is as low as 1, when the renewable heating and cooling energy are both available, the COP2 of the system is 3.0. This is proving that the use of renewable energy sources is an efficient to improve the COP of the desiccant cooling system and minimize the electrical energetic consumption.

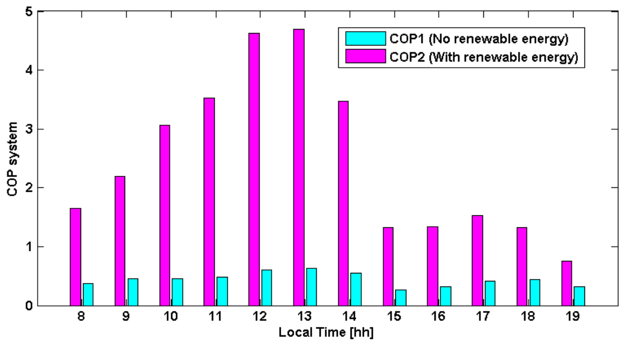

Fig. 9. Coefficient of performance of the heat recovery/cooling desiccant.

VII. CONCLUSION

The objective of this study is to present a research project which aims at assessing the effectiveness of this of a desiccant cooling technology under Tunisian climatic conditions. A simulation computer code is carried to test this kind of system. The simulation results show that the heat recovery/desiccant cooling system is effective and can be functional for Tunisian climatic conditions. There is efficient in the hot and humid places and in Tunisia. We can use this system only on the Mediterranean places, however the other places were very dry and hot, for example Tatouin was in the south of Tunisia, we can't use this system for many problem first the climatic conditions of this place in the summer and another problem it is the low water sources for heating and cooling the desiccant solution. This system of cooling is profitable and offers an alternative solution to minimize energy related emissions of CO_2 and reduce electricity demand. To validate these results we will test this system by an experimental work under the real weather conditions.

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