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Simulation of dynamical performance of solar desiccant cooling cycle

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Abstract

In this research, solar desiccant cooling cycles in ventilation and hybrid mode are simulated. To simulate cycles, at first a model for desiccant wheel simulation is presented and a computer code based on experimental correlations is used to solve equations. Then by TRNSYS software a model for solar hot water system is simulated, and eventually by representing a suitable algorithm, computer program for simulating solar desiccant cooling cycles by EES software is developed. For all components of desiccant cycle, the dynamic optimum were based on regeneration temperature and solar fraction, and after optimum, dynamic cycle performance in an office building with an area of 115 m^2 located in Bushehr city, capacity of cooling 3 ton refrigeration were analyzed. The results show that solar desiccant cooling cycles in comparison with compression refrigeration cycles with 40% saving in energy consumption and also during the day and in office buildings have a better performance.

Nomenclature:

W_{rotor}	Energy consumption in desiccant wheel rotor	[kw]
W_{comp}	Energy consumption in compressor	[kw]
Q_{qool}	Cooling capacity	[kw]
Q_{heater}	Amount of incoming heat in shell & pipe heat exchanger	[kw]
Q_{aux}	Amount of temperature necessary in auxiliary heater	[kw]
Q_{load}	Thermal capacity of solar hot water system	[kw]
T_{in}	Temperature of the fluid of solar hot water system entering the exchanger	[c]
T_{out}	Temperature of the fluid of solar hot water system exiting of the exchanger	[c]
T_{set}	Regulated temperature of auxiliary hot water system	[c]
ω_i	Humidity ratio in various part of cycle	[gr/kg dry air]
H_i	Humid air enthalpy in different points of the cycle	[kj/kg]
C_{pw}	Water special temperature	[kj/kg]
M_w	Mass flow of the fluid inside the solar hot water system	[kj/kg]
T_{wbi}	Wet bulb temperature in various part of cycle	[c]
M_i	Mass flow of the humid air in different points of desiccant cycle	[kg/s]
W_{fan}	Energy consumption in the fans of process and regeneration path	[kw]
φ_i	Relative humidity in various part of cycle	
DEC	Direct Evaporator Cooler	
ε	Efficiency	
deh	Dehumidification	
reg	Regeneration	
HWST	Hot Water Storage Tank	
HEX	Heat exchanger	
SHR	Rate of sensibel heat	
COP	Coefficient of performance	
SF	Solar fraction	

1. Introduction

The universal tendency to use renewable energies and its environmental consequences encouraged various organizations and research centers in Iran to conduct some projects in this context.
The outlook of energy and environment in the world until 2030 and the Earth's climate due to the human being activities, especially in energy sector, have much changed. The most part of climate and environmental changes in the world during recent years relate to the increase of 31% of CO2 emission 200 years ago and also a 2-fold increase of CH4 emission since 1800. In Iran, the existence of appropriate climate conditions and the sunshine in many regions in most seasons, and the presence of altitudes and heights along rivers, and the existence of regions with high wind potential and capacity of generation of Earth thermal energy have together created a good and appropriate situation to use and develop new energies [21].
Since the average of annual total radiation in Iran is higher than the average of the world, the implementing potential of solar cooling cycle is proper. In below figure the total radiation of some cities in Iran is shown. According to this figure (1) Noor and Sari have the smallest annual total radiation and Zahedan and Isfahan have highest total radiation. Also Bandar Abbas and Bushehr, two seashore ports in south of Iran have great sunny hours, but because of special weather condition in Persian Gulf region, at the results of great sunny hours, the annual total radiation is high.

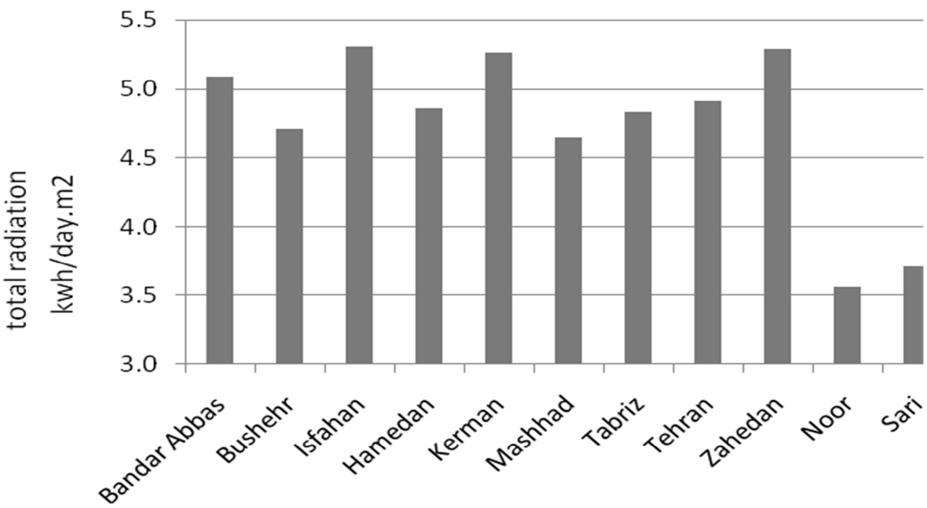

Fig 1 : Average of annual total radiation in Iran

2. A review of previous literature

The studies on desiccant cooling cycle and its components were conducted on a theoretical and empirical basis. They can be divided into following categories:

- Feasibility study on manufacturing and using desiccant cycle in different regions;
- Use of new energies to supply desiccant regeneration heat;
- Evaluation of its efficiency and improvement empirically and theoretically, and the effect of the parameters of cycle performance;
- Optimization of the structure and components of desiccant cooling cycle;
- Use of new absorbent materials to reduce regeneration heat and to improve the performance of cycle.

Most of the known scientific works performed at international levels in this context are shown in table 1.

Table 1: Review of survey literature

Ref.	Description of research	Author	Year
[2]	Mathematical model for simulating desiccant cycle by simultaneous heat and mass transfer	Geng and Vork	1993
[1]	Using cooling tower and cooling coil instead of air evaporative cooling systems	McLine – Cross	2001
[5]	Empirical review of desiccant wheel in two modes (rate of regeneration to dehydration 1 and 0.33)	Kodama et al.	2001
[4]	Using solar energy to provide regeneration heat in desiccant cooling systems particularly in hot and dry regions	Haning et al.	2001
[6]	Feasibility study on using solar energy on solid absorbent systems (desiccant cooling) in different cities of Europe	Marodaki et al.	2002
[12]	Simulation and optimization of desiccant cooling cycle based on rotation speed not to mention surface penetration effects	Mozaffari et Pahlevanzadeh	2002
[7]	Using desiccant cycle to control humidity in places where the latter is less needed	Sabramaniam et al.	2004
[8]	Simulation and modeling the desiccant cycle by MATLAB software	Esfandiari et al.	2006
[9]	Numerical and empirical analysis of integrated desiccant cooling cycle	Jia et al.	2006
[13]	Mathematical model for fixed desiccant bed using Ackerman correction factor	Pahlevanzadeh et Zamzamian	2006
[14]	Empirical studies on desiccant cycle in ventilation and return modes and review of desiccant material structure	Heidarnejad et al.	2006
[3]	effects of erosion and passage of time on the cycle performance	William	2006
[15]	Review of the effect of rotation angular velocity on desiccant cycle performance and solution of equations by Finite Element method considering temperature and humidity gradients in desiccant layer	Hosseinalipour et al.	2007
[10]	Review of desiccant cycle performance coefficient with the change in regeneration temperature	Ji et al.	2009
[11]	Simulation of solar hybrid desiccant cycle by TRNSYS software.	Dangla et al.	2011

In previous surveys conducted, optimization of the above components was performed statically, in all of them, parameters were fixed, while in this survey, to optimize each parameter, the performance of all components of the system were taken into account as variable or dynamic in a period of 9 months. This increased the accuracy in cycle optimization and, in fact, this is the distinction existing between our survey and others.

3. System description and Simulation

By desiccant cooling cycles, we mean the use of desiccant wheel and other components of heat transfer and cooling systems, given the space under consideration and also economic requirements. Among standard, traditional desiccant cycles, we can mention ventilation cycle, recirculation cycle, ventilation makeup cycle (full ventilation), and mix cycle and hybrid desiccant cycle.

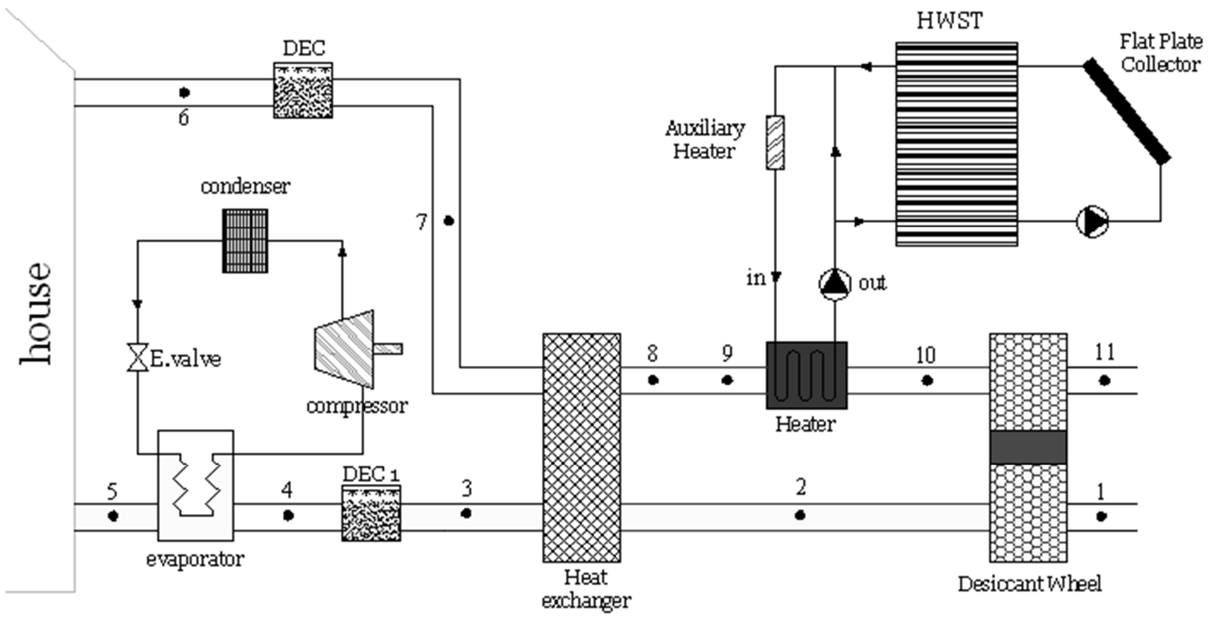

Fig 2-A: Diagram of solar hybrid solid desiccant cycle

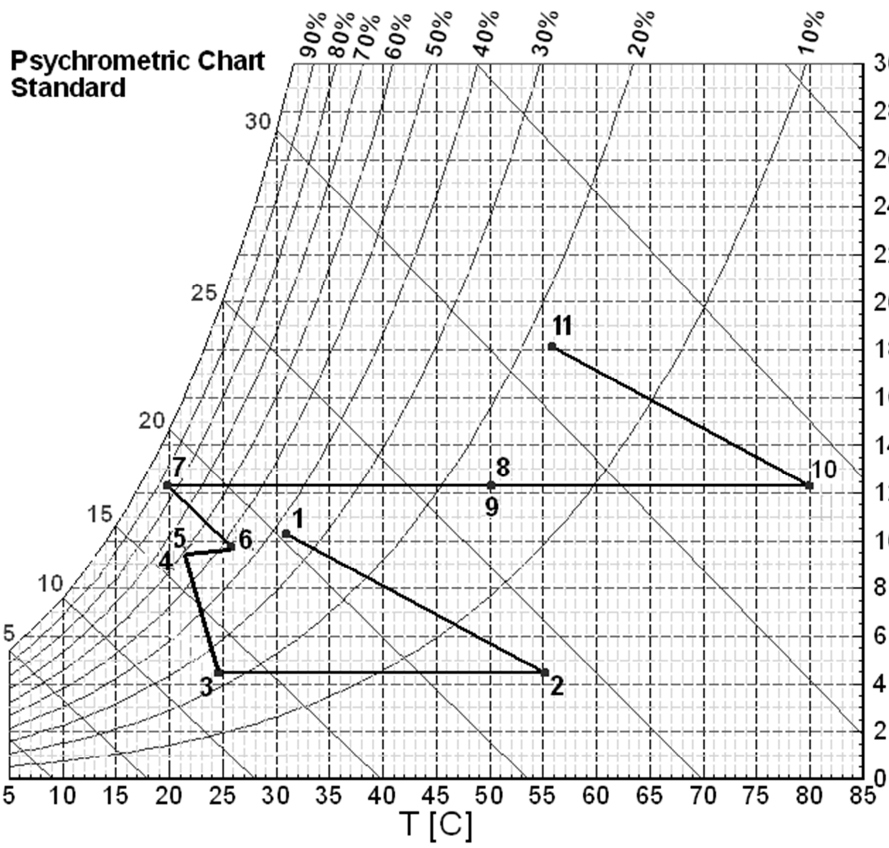

Fig 2-B: Psychrometric chart of solar hybrid solid desiccant cycle

According to the figures 2-A and 2-B, that show a diagram of equipment and psychrometric chart, humid air first enters desiccant wheel then, after dehumidification and temperature raise, the air enters to air heat exchanger and, after temperature reduction and humidity increase and stabilization of special humidity, enters the evaporator or evaporative cooler (for hot and desert cities and for humid cities respectively evaporative cooler and evaporator are recommended). The air enters finally into the ventilation space.

In the returning path, the air is re-cooled by direct evaporative coolers and air enters into the heat exchanger and in order to reduce exiting temperature from desiccant wheel, the air inters into heat

exchanger. After increasing the air temperature, we reach the temperature of the humid air to imagined temperature by using heater (solar collector) and it enters into the desiccant wheel and for dehumidification from the absorbent material.
According to the figure 3, there are two loops in this model: One between solar collector, pump, storage tank, and the other between storage tank, T-piece, auxiliary heater and tempering valve.
In the first loop, the temperature of the fluid (water) is increased after crossing the solar collector. Then it enters into the storage tank. After heat missing (to warm load water) by means of pump, the path is circulated. If the output temperature of the tank is more than that of the collector, controller turns off the pump to prevent the loss of hot water inside the tank and the energy waste in the pump.
In the second loop, hot water exits from the storage tank to enter T-piece then auxiliary heater. If the output temperature of the tank is less than that of the auxiliary heater, the latter will increase the designing temperature of the fluid close to T_{set}.
If the temperature of the output fluid of the tank is more than the setting temperature, the auxiliary heater turns off. Then it enters the shell and tube heat exchanger (to increase the temperature of the humid air in the desiccant cycle) and, after temperature reduction for rotation in the second loop, it enters the pump. After exiting from the pump, the fluid enters the tempering valve.
In this state, if the temperature of the fluid entering the valve is more than that exiting the tank, the fluid crosses the loop 2, otherwise, it enters into the storage tank.

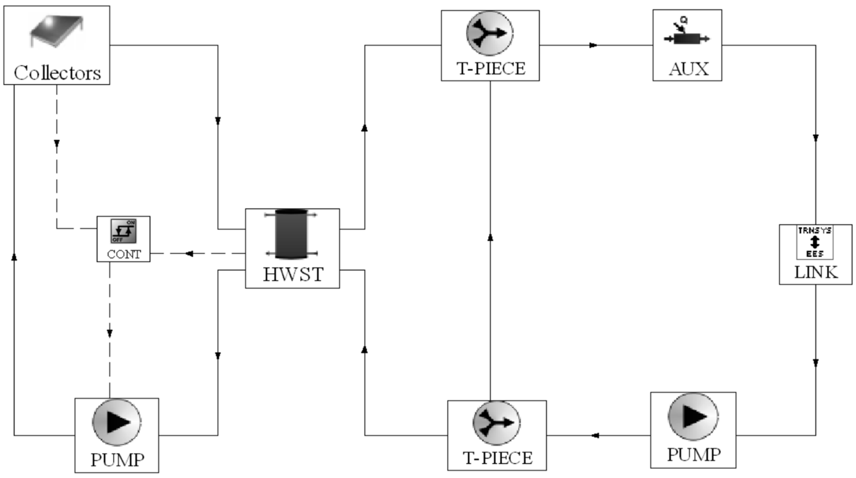

Fig 3: Diagram of solar hot water system

Cycle flowchart of the solar desiccant cycle is composed of three parts as shown in figure 4 , The first part presents thermodynamic conditions of the outside environment air when entering the desiccant cycle and includes the ventilation space (point 5) as process path and output humid air of the ventilation space until desiccant wheel outlet (point 11) as regeneration path, and the second part includes temperature and mass flow of the fluid inside the solar hot water system which is calculated by TRNSYS software. Finally, we have parameters in the third part that we consider as the first estimation in points 5 and 8 (given that the desiccant cycle contains two heat exchangers in process and regeneration paths, it is so necessary to estimate thermodynamic properties of the humid air including temperature and relative humidity (for outlet conditions calculation) when entering the heat exchanger.

4. Hypothesis

4.1- Coefficient of performance (COP)

Coefficient of performance is an index to determine the optimum coefficient of energy consumption level. In fact, cooling capacity of a machine determines the COP according to its consumption in one hour. It is defined in desiccant cycle as follows. [11]

$$COP = \frac{q_{cool}}{q_{in}} = \frac{q_{cool}}{q_{heater}} = \frac{m_5(h_6 - h_5)}{m_{10}(h_{10} - h_9)} \tag{1}$$

In solid desiccant cycle mixed into the vapor compression cooling cycle, it is defined as follows:

$$COP = \frac{q_{cool}}{q_{heater} + W_{system}} = \frac{m_5(h_1 - h_5)}{q_{heater} + W_{com} + W_{fan} + W_{rotor}} \tag{2}$$

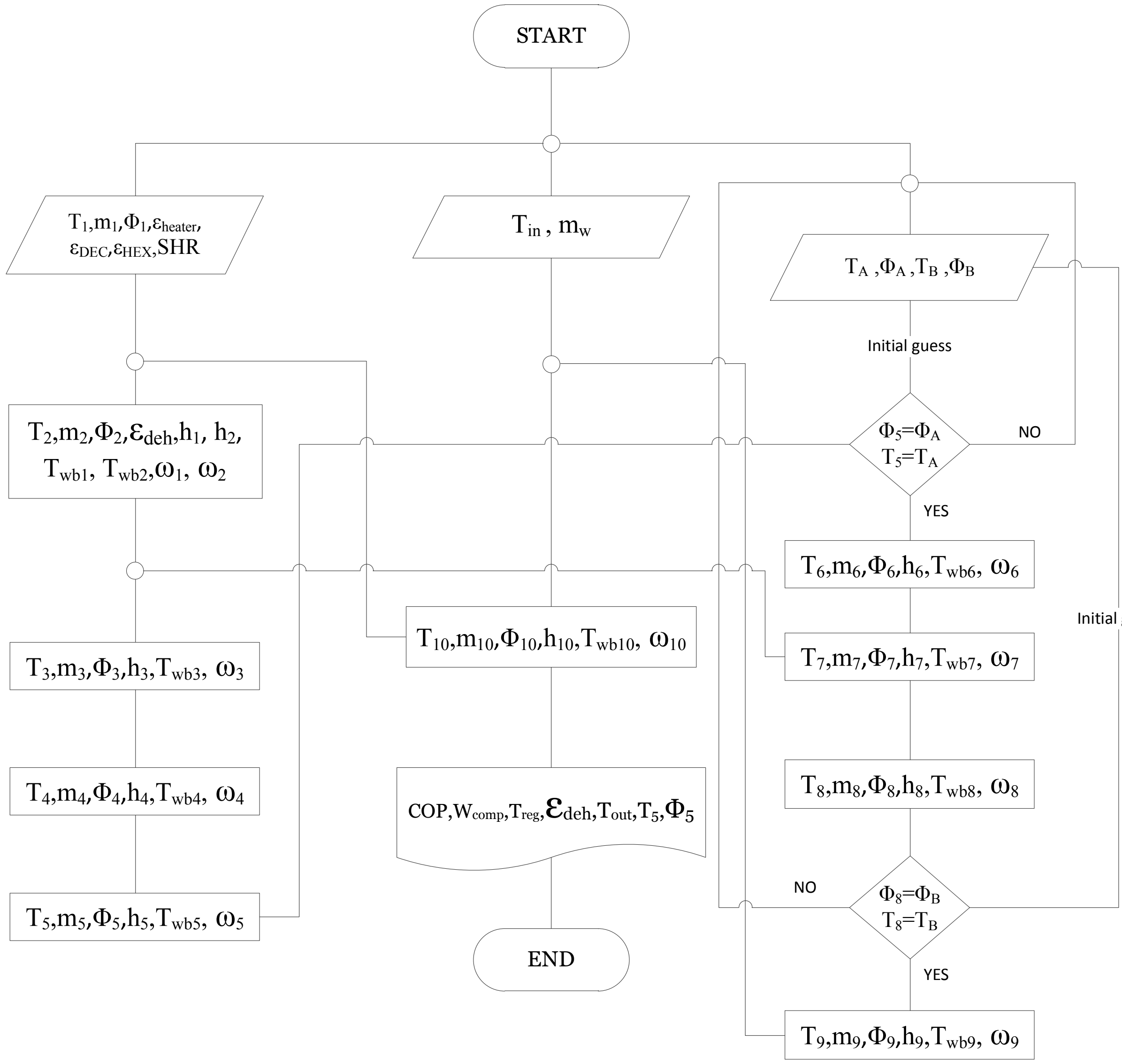

Fig 4: Flowchart of solar desiccant cycle

4.2- Solar fraction

As a share of energy, we define the cooling system by the energy which supplied by the collector and the thermal storage tank. In this system, we didn't take into consideration the power used by the pumps.

Usually, solar fraction in researches is defined as follows:

$$solarfraction = \frac{q_{load} - q_{aux}}{q_{load}} \tag{3}$$

$$q_{load} = \dot{m}_w C_{pw}(T_{in} - T_{out}) \tag{4}$$

5. Results and Discussions

First, we suppose that we use the desiccant cycle to cool a house in Bushehr city. The house has an area of 115 m^2 and cooling load of 3 Ton refrigeration; as a result, after necessary calculations, we need each time 0.85 (kg/s) ventilyzed air. In this section, we analyzed the behavior of different components of the desiccant cycle and the solar hot water system during operation for 48 hours since June 21. Conditions of the cycle performance after optimization is explained at table 2:

Table 2: Results of the dynamic analysis of solar desiccant cycle

Cycle description	Amount	Cycle description	Amount
Cooling capacity	3 ton ref	Storage tank volume	4 m^3
Collector area	86 m^2	Temperature of auxiliary heater	75 c
Collector angle	31 degree	Solar fraction	0.55
Hot fluid mass flow	0.2 kg/s	Wheel rotation velocity	20 rph
Collector water flow	0.25 kg/s	Desiccant absorbent material diameter	0.15 mm
Humid air flow	0.85 kg/s	Adsorbent desiccant wheel	Ethylene glycol

In most of the previous researches, the results of verification was performed according to the fixed (static) inputs like temperature and relative humidity; this issue caused that the performance of the cycle in all season conditions of each climate region was not analyzed and, in fact, it reduced the accuracy of analysis in system design. Therefore, we tried in this paper to study the dynamic behavior of the cycle in each determined time interval. As shown in table 3, the output of different points of the cycle which was subject to different researches (theoretical and experimental) was not much different from that in the research carried out. It is worth noting that in this part, we did not take into account compression cooling cycle to comply with other researches.
It means that in most done researches desiccant cycle didn't hybridize with vapor compression cycle and just solar desiccant cycle is analyzed, because of that the thermodynamic condition is determined without evaporator in table 3.
As shown in figure 5, auxiliary heater provides the heat necessary for the solar hot water system at night. As office buildings do not need ventilation at night, SF of solar desiccant cycle is, therefore, higher in such environments in comparison with residential buildings.

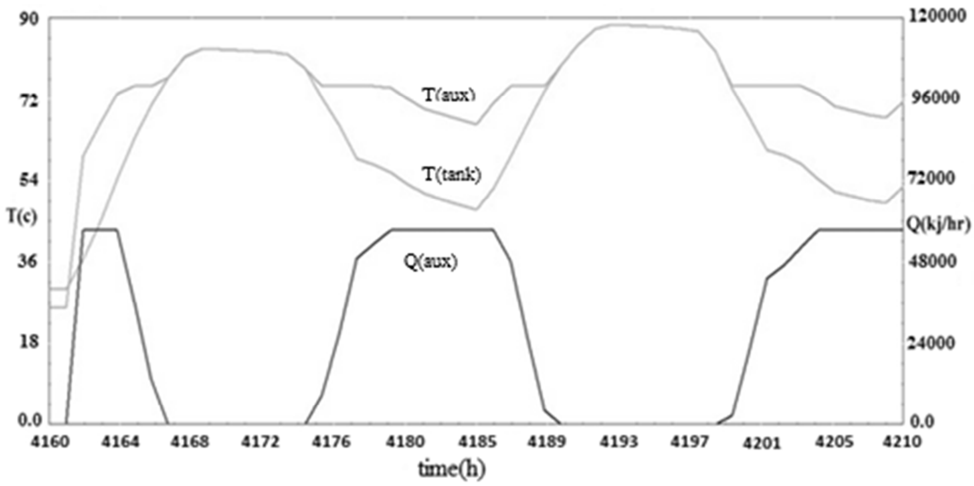

Fig 5: Comparison between the auxiliary heater temperature and the temperature exiting from the tank and Qaux

Since this case system is designed in warm season so we can use this system in cold season for providing consumed hot water and heating the buildings. More over according to energy consumption in vapor compression cycle we can use cycles like ejector cycle and absorption cycle for decreasing energy consumption in form of hybrid with desiccant cycle.

In desiccant cycles, with the increase of ambient temperature, efficiency or COP is reduced, because with increasing of ambient temperature, the efficiency of the desiccant wheel is reduced and, consequently, rate of dehumidification from air is reduced. But in the cycles with solar regenerators, with the increase of the ambient temperature (radiation intensity), the regeneration temperature is increases and, accordingly, in spite of reduction of the cycle efficiency, the rate of dehumidification from humid air is increased (fig 6-A); finally, the COP (fig 6-B) will improved.

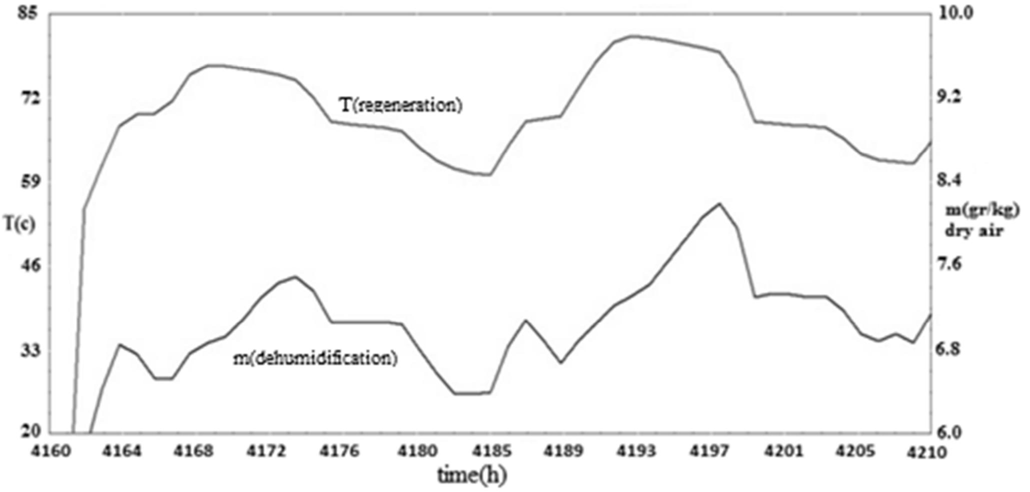

Fig 6-A: The effect of regeneration temperature on dehumidification of desiccant wheel

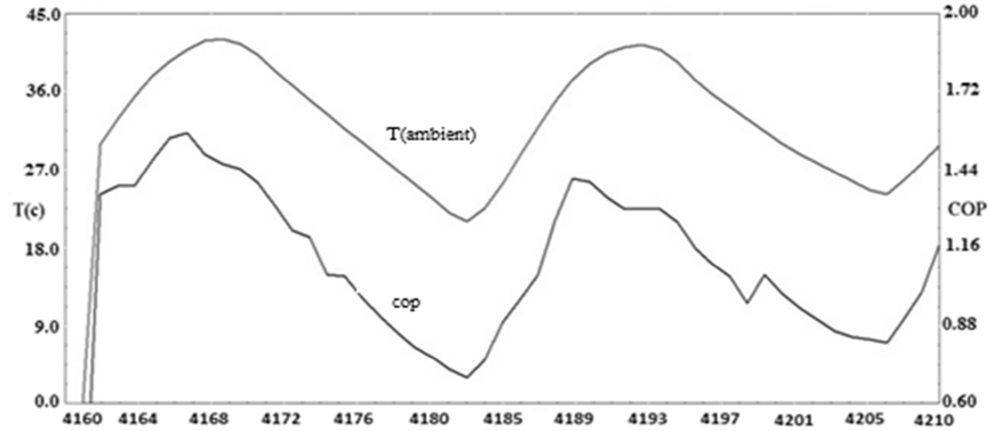

Fig 6-B: The effect of the ambient temperature on COP

According to figure 7, solid desiccant cycle is not in itself appropriate for each climate conditions, it means that where ever the air enthalpy is more than 55 kj/kg (very hot days), the desiccant cycle will not provide comfort conditions, but the compressor will do it by energy consumption.

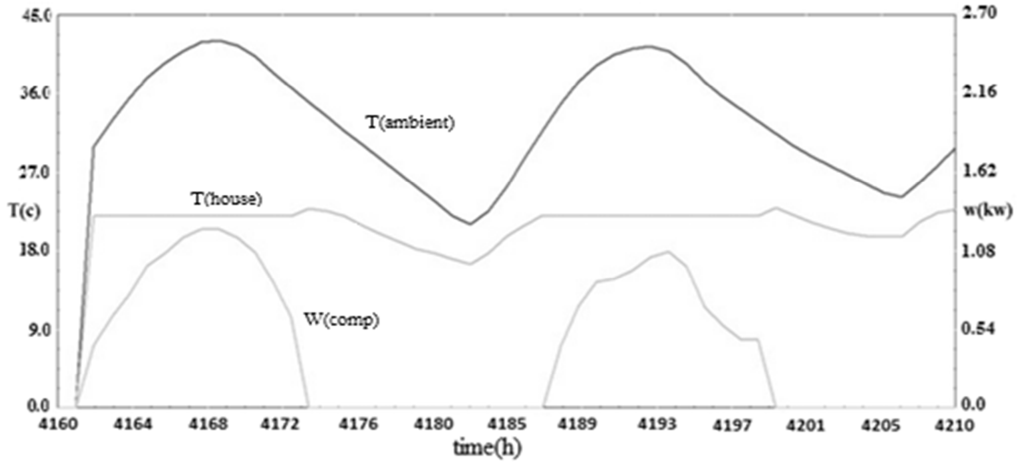

Fig 7: Comparison between ambient temperature and ventilation space temperature and the amount of the energy consumed by the compressor

Table 3: Comparison of results between simulated cycle and certain theoretical and empirical researches

paper	*properties*	*1*	*2*	*3*	*4*	*5*	*6*	*7,8*	*9*	*10*	*COP*	*ε (DW)*	*ε (HE)*	*ε (IEC)*	*ε (DEC)*
Case study	*T*	*35*	*52.2*	*25.4*	*20*	*26*	*18.8*	*45.3*	*75*	*52.4*	*1.2*	*0.56*	*0.8*	*0.8*	*0.9*
	Φ	*50%*	*12%*	*52%*	*73%*	*46%*	*93%*	*21%*	*9%*	*17%*					
paper	*properties*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*COP*	*ε (DW)*	*ε (HE)*	*ε (DEC)*	*ε (DEC)*
17	*T*	*31.5*	*43.5*	*30.2*	*17.3*	*26.7*	*20.4*	*33.7*	*60.8*	*49.8*	*0.345*	*0.409*	*0.575*	*0.953*	*0.918*
	Φ	*32.9%*	*11.5%*	*23.7%*	*94%*	*53.0%*	*95%*	*43.5%*	*11%*	*22.7%*					
paper	*properties*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*COP*	*ε (DW)*	*ε (HE)*	*ε (DEC)*	*ε (DEC)*
18	*T*	*32*	*52*	*19*	*11*	*24*	*17*	*49*	*71*	*53*	*0.85*	*0.43*	*0.85*	*0.95*	*0.95*
	Φ	*34%*	*4%*	*25%*	*95%*	*50%*	*94%*	*16%*	*5%*	*20%*					
paper	*properties*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*COP*	*ε (DW)*	*ε (HE)*	*ε (CC)*	*ε (DEC)*
19	*T*	*32.8*	*77*	*28*	*18*	*25.7*	*19.4*	*68.4*	*92.9*	*48.7*	*0.49*	*-*	*0.85*	*0.85*	*0.8*
	Φ	*64%*	*3%*	*36%*	*66%*	*50%*	*91%*	*7%*	*3%*	*33%*					
paper	*properties*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*COP*	*ε (DW)*	*ε (HE)*	*ε (DEC)*	*ε (DEC)*
20	*T*	*32*	*48*	*25*	*17*	*26*	*19*	*42*	*75*	*55*	*0.37*	*0.49*	*0.79*	*0.77*	*0.92*
	Φ	*40%*	*9%*	*31%*	*77%*	*48%*	*96%*	*26%*	*5%*	*20%*					

6. Conclusion

6.1- On the most important results obtained in this survey was the accuracy of optimizing the components of solar hot water system. In previous surveys conducted, optimization of the above components was performed statically: in all of them, parameters were fixed, while in this survey, to optimize each parameter, the performance of all components of the system were taken into account as variable or dynamic in a period of 9 months. This increased the accuracy in cycle optimization and, in fact, this is the distinction existing between our survey and others.

Finally after optimizing all components of desiccant cycle on the basis of regeneration temperature and solar fraction, the dynamical performance of cycle in an apartment located in Bushehr with area of 115 m^2 and cooling capacity of 3 ton refrigeration and solar fraction 0.55. the results indicate that for designing the cycle we need to 86 m^2 , flat plate collector, and heating storage tank capacity 4000 liter, mass flow in collector loop 0.25 kg/s, mass flow in heat exchanger loop 0.2 kg/s, angle of collector 31 degree. Solar desiccant cooling cycle comparing with vapor compression cycle with %40 saving energy consumption and also they have better performance during a day and in official buildings.

6.2- Considering that the desiccant cycle in humid climates has a high performance, it has to be noted that in desert, hot and dry cities of Iran, the use of solar regenerators, due to intense radiation, is more economic and, consequently, the SF will be higher. In fact, this diagram is the best justification for using solar desiccant cycle and vapor compression cycle simultaneously in humid climates like southern sea sides of Iran (because of having great sunny hours).

References

[1] Robert van Zyl. Brian Warwicker. Desiccant, the future. FCIBSE Conference. London 2001. http://www.cibse.org/pdfs/3dwarwicker.pdf

[2] W. Zheng, W.M. Worek, Numerical simulation of combined heat and mass transfer process in a rotary dehumidifier, Numerical. Heat Transfer Part A 23 (1993) 211–232.

[3] K.Daou, R.Z.Wang, Z.Z.Xia. Desiccant cooling air conditioning: a review. RENEWABLE & SUSTAINABLE ENERGY REVIEWS; 10 (2006) 55-77.

[4] H.M. Henning, T. Erpenbeck, C. Hindenberg, I.S. Santamiria. The potential of solar energy use in desiccant cooling cycles. International journal of Refrigeration; 24 (2001) 220-229.

[5] A. Kodama, T. Hirayama, M. Goto, T. Hirose, R.E. Critoph, The use of psychometric charts for the optimization of a thermal swing desiccant wheel. Applied Thermal. Engineering. 21 (2001) 1657–74.

[6] P. Mavroudaki, C.B. Beggs, P.A. Sleigh, S.P. Haliiday. The potential for Solar powered single-stage desiccant cooling in southern Euro. Applied Thermal Engineering; 22 (2002) 1129–40

[7] N. Subramanyam, M.P. Maiya, S. Srinivasa Murthy, Application of desiccant wheel to control humidity in air-conditioning systems. Applied thermal Engineering, 24 (2004) 2777-2788.

[8] F. Esfandiari Nia, D.v. Passen, M.H. Saidi, Modeling and simulation of desiccant wheel for air conditioning. Energy and Building; xxx (2006) xxx-xxx (Article In Press)

[9] C.X. Jia, Y.J. Dai, J.Y. Mu, R.Z. Wang, Analysis on a hybrid desiccant air-conditioning system. Applied Thermal Engineering; xxx (2006) xxx-xxx (Article In Press)

[10] Ge, T.S., Li, Y., Wang, R.Z., Dai, Y.J., 2009. Experimental study on a two-stage rotary desiccant cooling system. International Journal of Refrigeration 32, 498–508.

[11] Dong La, Y. Dai, Yong L, Tianshu Ge, Ruzhu W, Case study and theoretical analysis of a solar driven two-stage rotary desiccant cooling system assisted by vapor compression air-conditioning, Solar Energy, 85 (2011) 2997–3009

[12] H. Pahlavanzadeh, H. Mozafari, Optimization of Desiccant wheel performance available in air-conditioning systems, The first conference optimization of Fuel consumption in Iran, Tehran(2002)

[13] H. Pahlavanzadeh, A. Zamzamian, A mathematical model for a fixed desiccant bed dehumidifier concerning Ackermann correction factor. Iranian Journal of Science & Technology, Transaction B, Engineering, 30 (2006) 353-362

[14] G. Heidari nejad, S. Delfani, H. Pasdarshahri, Experimental study of desiccant cooling system for air conditioning in different climatic conditions. Iranian Journal of Construction Engineering & Housing Science, 8 (2007) 1-12

[15] S. M. Hosseinalipour, H. Mansouri, R. Ebrahimi,The numerical simulation of the effect of rotational speed on the performance of desiccant wheels using CVFEM in two dimensional simulation, 15th Annual Conference on Mechanical Engineering- ISME2007, May 15-17,2007, Tehran, Iran

[16] J.M.Abdulateef , K. Sopian, M.A. Alghoul,M.Y. Sulaiman. Review on solar driven ejector refrigeration technologies. Renewable and Sustainable Energy Reviews 13 (2009) 1338–1349

[17] Mehmet Kano , Melda Ozdin gglu, Murtaza Yildirim, Energy and exergy analyses of an experimental open-cycle desiccant cooling system, Applied Thermal Engineering 24 (2004) 919–932

[18] G. Panaras , E. Mathioulakis, V. Belessiotis, Solid des iccant air-condition ing systems e Design parameters, Energy 36 (2011) 2399 - 2406

[19] L.Z. Zhang, J.L. Niu, A pre-cooling Munters environmental control desiccant cooling cycle in combination with chilled-ceiling panels, Energy 28 (2003) 275–292

[20] Hans-Martin Henning, Thomas Erpenbeck, Integration of Solar Assisted Open Cooling Cycles into Building Climatisation Systems Fraunhofer Institute for Solar EnergySystems ISE, Oltmannsstr. 5, D-79100 Freiburg

[21] Renewable Energy Organization of Iran website