International Journal of u- and e- Service, Science and Technology
Vol.7, No.2 (2014), pp.167-178
http://dx.doi.org/10.14257/ijunesst.2014.7.2.16

Performance assessment of a Solid Desiccant Based on Dehumidifier System Coupled with Air Conditioning System in a Tropical Climate

Alireza Zendehboudi *[1], Ramin Hashemi [2] and Abbas zendehboudi[1]

[1]Department Mechanical Engineering, Islamic Azad university, Science and Research Branch, Bushehr, IRAN (zendehboudi@ymail.com)
[2]School of Mechanical Engineering, Iran University of Science and Technology, Tehran, IRAN

Abstract

A comprehensive ventilation approach requires not only air exchange but also in many cases indoor humidity control. High humidity levels decrease occupant comfort and increase the likelihood of problems, such as mold growth. Occupants presently use air-conditioning systems or dehumidifiers in order to reduce the indoor moisture levels. These systems use large amounts of electricity and are expensive. Desiccant systems have shown several advantages, compared to conventional cooling and dehumidification systems. Therefore, their use is also spreading for restaurant and supermarket buildings, especially when the regeneration of the desiccant can be obtained by using available waste heat. When these systems are combined with vapor compression air conditioning systems, air -dry before entering the environment. In this paper Performance assessment of a Solid Desiccant Based on Dehumidifier System Coupled with Air Conditioning in a tropical climate Zone of IRAN have been evaluated. Results indicate that when the hybrid system is used, the efficiency increases 0.76 and energy consumption reduce 3.034kw.

Keywords: *desiccant system, silica gel, COP, energy consumption*

1. Introduction

Industrial cooling, ventilation, and air conditioning in recent decades have been faced with numerous challenges. Reducing energy sources, increased energy demand due to population growth and new regulatory policies are including the challenges. To respond to these challenges, greater efficiency heating systems, cooling systems, ventilation and moisture removing technology is required. The basic idea of desiccant air conditioning is to integrate the technologies of desiccant dehumidification and evaporative cooling together. While the former adopts water as refrigerant and can be driven by low grade thermal energy as solar energy, district heating, waste heat and bioenergy. The later is near-zero cost technology [21]. These indicate that desiccant air conditioning would be not only energy efficient and environment-friendly but also cost-competitive, especially for hot, dry and hot, humid areas.

Modeling this type of system and obtain the optimal conditions to achieve lower power consumption in different terms by different researchers have examined. Daou *et al.*, [1] in 2006 have been investigated desiccant systems in different climatic conditions and have emphasized the benefits of energy savings. Some commented examples are presented to show how the desiccant cooling can be a perfective supplement to other cooling systems such as traditional vapor compression air conditioning system, the evaporative cooling, and the chilled-ceiling radiant cooling. Dai yj *et al.*, [2] in 2001 have been investigated comparing between the cooling vapor compression systems, vapor compression with complementary

ISSN: 2005-4246 IJUNESST

desiccant and vapor compression evaporative cooler supplemented with desiccant. Thus this research they have obtained increasing productivity refrigeration between 38/8 % - 76% and increasing the coefficient of performance 20%-30%. Mazzei *et al.*, [3] in 2002, optimized the operating cost of desiccant cooling system by three software POWER DOE, DesiCal and DTPE. The operating cost of the desiccant system in summer Italian conditions, interesting saving up to 35% are obtained and reduced thermal cooling power up to 52% and payback period of about 5-7 years. Aly *et al.*, [4] in 1988 have been reviewed the vapor compression system and dehumidifier systems based on waste heat energy in weather conditions, in Saudi Arabia. Total Cop earned equal 1.73, which is 25% higher than the vapor compression system alone. A desiccant -based hybrid system by jai cx *et al.*, [5] in 2006 has been discussed on an integration of a rotary solid desiccant dehumidification and a vapor air conditioning unit. They found that the hybrid system compared to conventional vapor compression system when air humidity and air temperature are 30^{o}c and 55 %, electrical energy reduces 37.5 %.

However, in several articles have been studied on optimization parameters of industrial systems and lesser have been focused on different variations of the wheels that are most important part of the systems. Also, some research activities have examined the calculating COP of factory systems, but these works have not satisfactorily clarified effect of different variations of the wheels on COP in a tropical Climate Zone of IRAN or similar climate. The primary purpose of this research is design desiccant system by focusing on wheel and Performance assessment of a Solid Desiccant Based on Dehumidifier System Coupled with Air Conditioning system in a tropical climate.

2. Test Facility

The test facility is located in a tropical climate in Bushehr, the southern of Iran. Figure 1 shows a view from performance of the desiccant wheel.

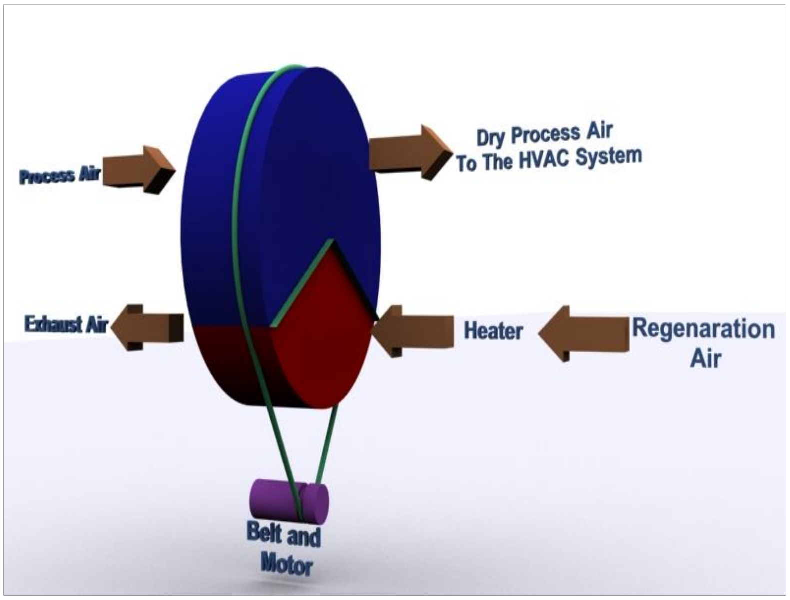

Figure 1. Performance of Desiccant Wheel

Figure 2 shows a view from the wheel of desiccant system which has been built.

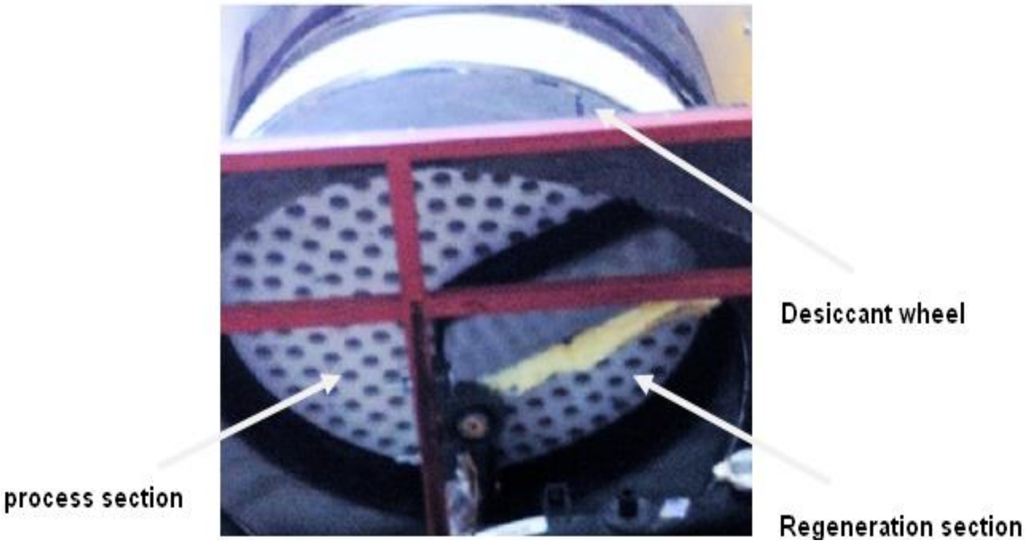

Figure 2. View of Wheel has Built

Wheel of desiccant system is as the heart of system that its design has the most important role in the functioning of the system. Many studies have been done on optimizing the parameters of industrial wheels, and less has focused on the different changes wheel design. This section is the main part of the system that requires calculation of the exact design, accuracy and precision in construction. For this study, the wheel is designed with a diameter of 55 cm and a thickness of 18 cm. This wheel must make from materials that have the ability to withstand temperatures prediction. Afterwards, survey and calculation have been used PVC. For the control of silica gel to the wheel, two sheets of Teflon and touring tires on both side of the wheel have been used that are attached to the wheel by using screws. The priority of this work is for replacement of silica gel. As is seen in Figure 2, Absorbent material (silica gel) is in a honeycomb that air passes over them. The wheel spins and airflow in two separate ducts passes over it. On wheel 205, holes were embedded with a diameter of 2 cm. after exact calculations was designed by using the SOLIDWORK software, and then was used the CNC machine and the mesh silica gel place has been created on the wheel. The wheel is attached by using of the center Shaft. The ratio between the supply air section area and regeneration air section area not only determines the quantity of supply air that can be handled by the wheel, but also influences the dehumidification and regeneration performance. As the value of this ratio increases the dehumidification section area increases and regeneration area decreases. Keeping the supply air and regeneration air velocities constant, enlarging the dehumidification part will result in the ability of the wheel to handle a higher rate of supply air, but may result in partial regeneration of the desiccant. If this ratio is small, this will result in a reduction in the quantity of supply air, complete removal of water vapor during the regeneration and better dehumidification performance. A smaller dehumidification part also contributes to the increased effect of the carry-over heat from the regeneration process [8, 11]. It is generally accepted that, as the regeneration temperature decreases, the regeneration part becomes a larger fraction of the wheel. According to the manufacturer’s catalog, the 1:3 split between regeneration and dehumidification is usually used for high regeneration temperatures and a 1:1 split for low regeneration temperatures. However, it is doubtful that each area ratio effectively covers such wide temperature ranges [13]. This wheel has made in such a way that is affected 120-degree of that by the air passing through the heating coil and the air of room passes through the other angle of the wheel. The desiccant system coupled with a vapor compression system. To move the wheel of containing silica gel has been used a motor of 90 watts as have been shown in Figure 3.

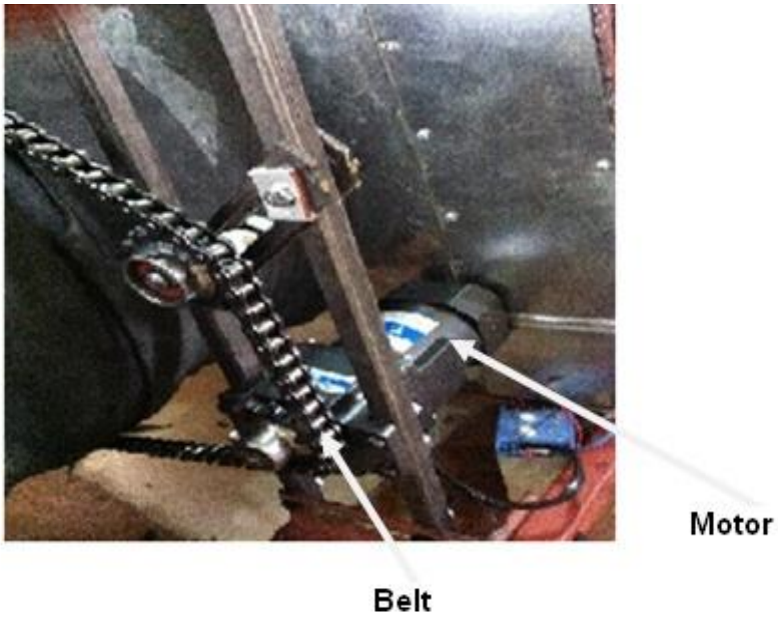

Figure 3. View of the Engine and Its Mechanism

Temperature around 70-100°C is needed for the desiccant wheel regeneration that for reduce of the annual heating cost should supply from renewable energy such as waste heat from conventional fossil fuel systems, solar energy and geothermal. In This system has been used 4 fans, the fan include warm air and the room air; 2 fans have been installed to blow air into system and 2 units Exhaust fan for better control of the air and prevent back-flow.

3. Conventional Cooling Systems

This study is done for a room that has located in the last floor of the building. Latitude, longitude and distance from the sea surface in order for Bushehr is intended 28.58deg, 50.49deg and 9m. temperature 47°c as dry bulb air temperature outside has been assumed for design the cooling system, and the temperature is average of maximum temperature in the warmest month of the year. Daily temperature difference between summer 15°k intended that represents the difference between the maximum and minimum dry temperature in the warmest month of the year in a day [10].This room area is $81m^2$, 2.7m height and weight approximately $341.8\ kg/m^2$, which is designed for 35 people with an average level of medium work. Three windows of size 2 * 1.5 m are in it. The outer surface of the walls and ceiling are white and black with total absorption coefficient $U=.907w/m^2.k$ and $U=1.45w/m^2.k$, windows with absorption coefficient $U=3.339w/m^2.k$, and the floor level is considered above the ambient air condition. Analysis of energy and load required for the building is calculated by using commercial software Carrier HAP4.5. The total amount of latent load and sensible load is equal 6710 W and 17242 W. in the place were installed two Standing Split Air condition.

The total refrigeration produced and energy consumed by the two coolers is equal 24.598kw and 9.8kw. Coefficient of performance for these systems is defined as follow:

$$\mathrm{Cop}_1=\frac{\dot{Q}_{\mathrm{cooling}}}{\dot{w}_{\mathrm{cool}}}=\frac{24.598}{9.8}=2.51 \qquad (1)$$

4. Hybrid Systems

Systems based on absorbent material (desiccant) as an alternative or complementary traditional vapor compression air conditioning system for cooling and ventilation emerged in commercial and industrial buildings. When these systems are combined with vapor compression air conditioning systems, air dry before entering the environment. Solid desiccant in dehumidifier systems usually use in the form of a wheel that rotate slowly. The desiccant wheel is a wheel which the solid desiccant covered. For continuous operation, it must be absorbed and regenerated periodically so that part of the wheel into the direction of the input air and moisture rejected and another part of the wheel is part of being a hot weather and will replace the two parts together. Wheel likes a honeycomb which looks open in both direction and adsorbents is silica gel. Absorbent material (silica gel) has been in the honeycomb that passes air over them. The wheel spins and airflow in two separate ducts passes over it. The first air flow is called the process which is dried by absorbent material. The second air flow is called reactivation which is hot air to dry the silica gel. Temperature around 70-100 ℃ is needed for the desiccant wheel regeneration that for reduce of the annual cost heating could supply from renewable energy such as waste heat from conventional fossil fuel systems , solar energy and geothermal. Air for dehumidifier was logged and placed in contact with the adsorbent wheel. The wheel rotates continuously and Process air is placed in contact of rotating the disc and the greater part of the water in the air stream is adsorbed by the disc is rotating. The air flow that has removed moisture can enter the central air or directly into the room. Several design parameters such as rotation speed desiccant wheel, regenerative temperature, volumetric flow rate of air, wheel thickness, angle of the sector and outlet temperature there are affected on performance of desiccant system. Equations 2-5 concerning water content balance and energy conservation are used to describe the complicated heat and mass transfer occurring in moisture adsorption and regeneration.

In this study, the unsteady one-dimensional model (t, z) is chosen for the coupled heat and mass transfer process in the rotary desiccant wheel. The numerical analysis is based on the following assumptions:

(1) The air flow is one-dimensional.
(2) The axial heat conduction and mass diffusion in the fluid are neglected.
3) There is no leakage of fluid in the desiccant wheel.
(4) All ducts are impermeable and adiabatic.
(5) The thermodynamic properties are constant and uniform.
(6) The heat and mass transfer coefficient between the air flow and the desiccant wall is constant along the channel.

Based on the above assumptions, the energy and mass conservation equations can be obtained as follows [22, 23]

Mass conservation for the process air

$$\frac{\partial Y_a}{\partial z}=\frac{h_m P_p}{u_a \rho_a A_p}(\mathrm{Y_w}-\mathrm{Y_a}) \qquad (2)$$

Where left-hand and right-hand sides mean sorbate influx by fluid flow and sorbate transfer rate to felt, respectively.

Energy conservation for the process air

$$(C_{pa}+ Y_a C_{pv}) \frac{\partial T_a}{\partial z} = \frac{h_c P_p}{u_a \rho_a A_p} (T_w-T_a) \qquad (3)$$

Where left-hand side means sum of energy transferred by fluid flow and decreased by sorbate transfer to felt and right-hand side means conduction heat transfer to felt.

Conservation of water content for the absorbent

$$\frac{\partial W}{\partial t} = \frac{h_m P_w}{\rho_w f_m A_w} (Y_a-Y_w) \qquad (4)$$

Conservation of energy for the absorbent

$$(C_{pw}+ f_m W C_{pl}) \frac{\partial T_a}{\partial t} = \frac{h_c P_w}{\rho_w A_w} (T_a-T_w)+ \frac{h_m H_{sor} P_w}{\rho_w A_w} (Y_a-Y_w) \qquad (5)$$

Where the first term of the left-hand side is the energy transfer by heat conduction and the second term is the energy transfer by mass transfer.

Remove moisture from the desiccant system is the most important parameter is defined as follows [8]:

$$D= Y_{in,p} – Y_{out,p} \qquad (6)$$

In Figure 4, the process moisture removed is reported as a function of the rotation speed of the desiccant wheel at various regeneration temperatures. It is shown that an increase in regeneration temperature helps to remove more moisture [6, 12, 16, 18]. It should be noted that if the regenerative temperature is too high, wheel will be dried before process period that this increases the cost and waste. This study has been discussed in inlet humidity 55%; inlet temperature 24.6^{o}c outdoor temperature and humidity 38^{o}c and 70%. In rotating desiccant wheel, the removal of moisture is better at low speeds rather than high speeds [8, 15-17]. Increase in speed of wheel rotation due to lesser contact surface of the air entering with the desiccant wheel will lead to decrease removing moisture. For example is seen when the wheel at regeneration temperature T =90^{o}c with speed 4rph rotates moisture removal is 3.74g/kg but when with speed 10rph rotates this value is reduced to 2.76g/kg.

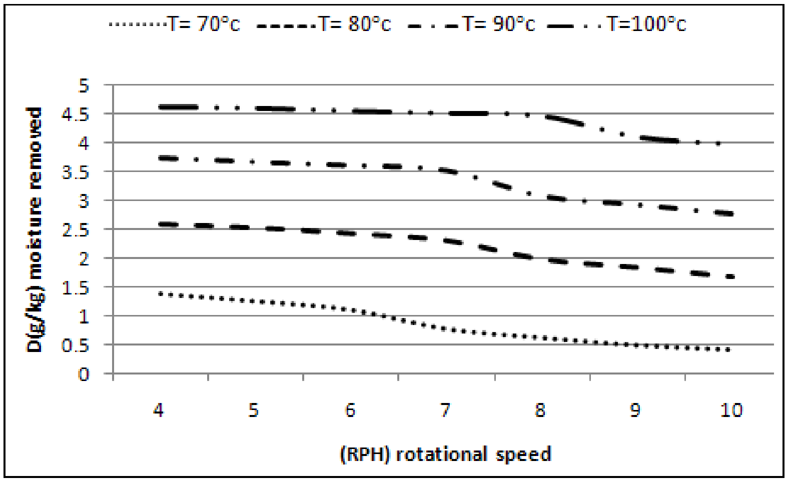

Figure 4. The Process Moisture Removed As a Function of the Rotation Speed

If the desiccant wheel rotates too slowly, the adsorption phase becomes too long the desiccant material reaches its maximum water vapor content, and it is not able to dry process air completely. On the other side, if the wheel rotates too fast, the adsorption period becomes too short, and it finishes when the desiccant material is still able to absorb the vapor. As a consequence, an optimal revolution speed which minimizes outlet process air humidity ratio exists [16, 18, 19].

Moisture removal efficiency is defined as follows [8]:

$$\eta = \frac{D}{Y_{in}} \qquad (7)$$

η shows the ratio of moisture removal to inlet humidity ratio of process air. Its value is between 0 and 1. For constant inlet humidity ratio of process air, η increases with increasing the moisture removal D [8]. The amount removes moisture from the air has a direct relationship with that how much air can pass through desiccant. One way increase the amount of desiccant in the desiccant wheel that this increases the cost and waste. Another way is increase regeneration temperature till the optimal size and placement of the wheel rotation speed in an ideal mode if cheap thermal energy be available, perhaps is the best way. In Figure 5, Moisture removal efficiency is reported as a function of the rotation speed of the desiccant wheel at various regeneration temperatures.

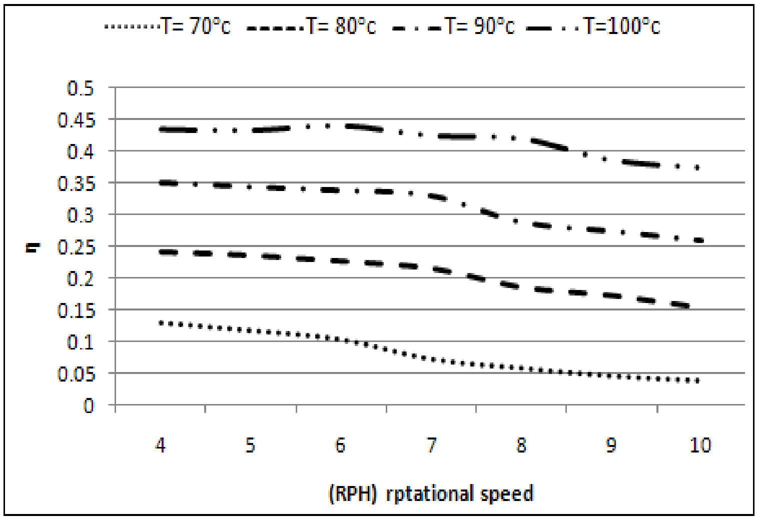

Figure 5. Moisture Removal Efficiency as a Function of the Rotation Speed

As seen for Figure 5, by increasing the rotational speed of the wheel, decreases moisture removal efficiency. For example, when regeneration temperature is T=90^{o}c and wheel rotates at speed 7rph, amount of efficiency is η = .33. When the wheel speed varies 10rph amount of efficiency decreases until η=.26. System in varied temperature of the regenerative, at low speeds the desiccant wheel has better performance rather than high speeds, so is preferred lesser rotation speed. It is clear that the regenerative temperature has a good influence on the performance and moisture removal efficiency. In order to with increases regeneration temperature, the moisture removal efficiency increase dramatically that has been confirmed by [15, 20]. For example, at a constant speed 7rph and regeneration temperature T=80^{o}c amount of moisture removal efficiency is η=.22. When regeneration temperature increase until T=90^{o}c amount of moisture removal efficiency increases to η=.33. With higher

regeneration temperatures, the moisture adsorbed in the desiccant is much easier to be desorbed; Therefore, the rotational speed should be increased to make the well desorbed desiccant rotate out of the regeneration section in time. This result is also confirmed in [17].
The coefficient of performance for the hybrid system is defined as follows:

$$\mathrm{Cop}_2 = \frac{\dot{\mathrm{Q}}_{\mathrm{cooling}} + (\mathrm{H}_{\mathrm{in}} - \mathrm{H}_{\mathrm{out}})_{\mathrm{desiccant}}}{\dot{\mathrm{w}}_{\mathrm{cool}} + \dot{\mathrm{w}}_{\mathrm{m}} + \dot{\mathrm{w}}_{\mathrm{f}}} \qquad (8)$$

From The denominator of equation (8) have to reduce equally to the electrical energy require of air conditioners for removed moisture that the desiccant wheel remove from the air.
B= Thermal energy needed for removed moisture in the evaporator Air conditioners: mass flow rate*(Enthalpy of water vapour in the air - the enthalpy of liquid water condenses on the evaporator of Air conditioners)
C= Air conditioners electrical energy required for removed moisture= B/COP_1
If desiccant do in rotation speed and regenerative temperature of 4rph and 80^{o}c:
$\dot{m}_{\mathrm{a}}$= 400cfm*4.72*10^{-4}*1.167 kg/m^3= .2203 (kg s^{-1})
$H_{in}=\dot{m}\ h_{in,a}$
$H_{out}=\dot{m}\ h_{out,a}$
$h_{in,a}$= 72 (kj/kg)
$h_{out,a}$= 76 (kj/kg)
Δh= -4 (kj/kg)
$\dot{m}_{\mathrm{a}}$ Δh= -0.8812 (kw)
D=2.58 (g/kg)
$\dot{m}_{\mathrm{cooling}}$= 2118cfm*4.72*$10^{-4}$*1.169*2.58= 3.015*$10^{-3}$ (kg s^{-1})
$h_{f,\ water,5^{o}c}$= 20.98 (kj/kg)
p_v= .55*3.169= 1.743 (kj/kg) & T= 25^{o}c $\longrightarrow$ h= 2547.23 (kj/kg)
B= $\dot{m}_{\mathrm{cooling}}$ Δh= 3.015*10^{-3}*2526.25= 7.616 (kw)
C= 7.616/2.51= 3.034
denominator of equation (8) =(9.8-3.034)+.09+.4= 7.256 (kw)

$$\mathrm{Cop} = \frac{\dot{\mathrm{Q}}_{\mathrm{cooling}} + (\mathrm{H}_{\mathrm{in}} - \mathrm{H}_{\mathrm{out}})_{\mathrm{desiccant}}}{\dot{\mathrm{w}}_{\mathrm{cool}} + \dot{\mathrm{w}}_{\mathrm{m}} + \dot{\mathrm{w}}_{\mathrm{f}}} = \frac{24.598 - .8812}{7.256} = 3.27$$

5. Conclusions

Performance assessment of a Solid Desiccant Based on Dehumidifier System Coupled with Air Conditioning System have been investigated in a Tropical Climate in Bushehr, the southern of Iran.

Dehumidifier system based on Desiccant systems and Conventional cooling systems when they are used together are the most cost effective. These are other complementary technologies. Strengths of Desiccant systems, cover weaknesses conventional cooling systems. Herein for reduce costs in dry wheel is used from waste heat of fossil fuel conventional systems. Difference in the cost of electricity and thermal energy allows us to bring the optimal combination of desiccant and the ordinary cooling systems. in total If the energy electricity cost is higher than energy thermal, it is economical that is used a desiccant system for moisture removal. When the hybrid system is used, the efficiency increases 0.76 and energy consumption reduce 3.034kw

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Nomenclature

COP	Relative moisture removal efficiency
$\dot{w}$	Power input (k w)
h	specific enthalpy (kJ/kg)
RPH	revolution per hour (h^{-1})
$\dot{m}$	Mass flow rate of air stream (kg s^{-1})
D	dehumidification capability (g/kg)
$\dot{Q}$	Refrigeration produced (k w)
P	pressure (k pa)

Z	axial coordinate (m)
h_m	mass transfer coefficient (kg m^{-2} s^{-1})
P	perimeter of flow channel (m)
u	velocity (m s^{-1})
ρ	density (kg m^{-3})
A	area (m^{2})
Cp	specific heat (J kg^{-1} K^{-1})
T	temperature (K)
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
W	water content of the desiccant material (kg kg^{-1})
t	time (s)
f_m	mass fraction of desiccant in the wheel
H_{sor}	heat of adsorption (J kg^{-1})

Greek symbols

η	coefficient of performance
Y	air humidity ratio (g/kg)

Subscripts

Cool	cooling coil
In	inlet
Out	outlet
P	process
M	motor
F	fan
a	dry air
V	vapor
w	desiccant
l	liquid

Authors

Alireza Zendehboudi was born in 30th June 1990. He received the Bachelor degree in 2012, and he is pursuing Master degree both in Mechanical engineering. His research interest includes are engineering calculations of HVAC, solar thermal systems, air-to-air energy exchangers, Design and Test of HVAC systems, CFD, Environment-Friendly Technologies.

Ramin Hashemi was born in 21th March 1982. He is an Assistant Professor in Mechanical Engineering Department at the Iran University of Science and Technology, Tehran, Iran. He received his PhD degree in Mechanical Engineering, in 2013 from University of Tehran. His research interests are manufacturing systems and technologies.

Abbas Zendehboudi was born in 4th February 1986. He received the Bachelor degree in 2008. he is pursuing Master degree in Department Chemical Engineering, Islamic azad university, Science and Research Branch, Bushehr, IRAN and works in South Pars Gas Company (SPGC). His current research interest include are engineering calculations of HVAC, solar thermal systems.