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Exergoeconomy of a desiccant enhanced evaporative cooling system using exergetic incremental function

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ABSTRACT

In this paper, exergoeconomic analysis of a rotary liquid desiccant dehumidifier (wheel) operating in conjunction with an evaporative cooler has been carried out to analyze the exergetic manufacturing cost of the system. The proposed system has advantage of simultaneous process of dehumidification and regeneration. After analyzing the energy and exergy performance of the system, an exergoeconomy model has been developed using exergy incremental functions to optimize exergetic cost of the system. The main objective of exergoeconomy model is to minimize the investment and operating costs by selecting the optimum values of operating parameters. The effect of two basic parameters which define the required input energy i.e. regeneration temperature and ratio of regeneration to process air flow rate, have been taken into account for exergoeconomy optimization of the system. The results showed that for the certain conditions, the operating costs may be reduced but will have high capital cost. Therefore, the optimal values for all parameters should be selected considering both operating as well as capital costs.

Keywords: Desiccant dehumidification; Thermo-economics; Exergy; Anergy; Exergoeconomy

1. Introduction

In hot and humid climates air-conditioning is an essential part for human comfort [1–3]. The conventional air conditioning systems can control the temperature efficiently but maintaining comfort humidity level is a big task for these systems [4]. The two components of the load are described by the sensible heat ratio which is the ratio between sensible load to the total load, that is, (sensible + latent). Smaller the value of sensible heat ratio means larger the value of latent cooling loads.

$$\text{Sensible heat ratio} = \frac{\text{Sensible heat}}{\text{Sensible heat} + \text{Latent heat}} \quad (1)$$

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Usually, the value of sensible heat ratio is kept about 0.75 for the conventional vapor compression air conditioning systems which means that 75% capacity of the system is used to control the sensible load and the remaining 25% for the latent load. So, the conventional systems can provide the comfort conditions only when sensible heat ratio is greater than 0.75 [5].

The relative humidity of outside air remains above or around 80–90% for most of the time in hot and humid conditions. Therefore, it is very important to dehumidify fresh air before supplying to buildings. In fact, control of humidity or latent load accounts for 40–60% of the cooling load in hot and humid regions. The dehumidification of air has an important role in current air conditioning industry because it separates the treatment of latent load from sensible load [6].

These problems of conventional air conditioning systems can be addressed using a technology called desiccant based evaporative cooling. This technology is a combination of a desiccant dehumidifier and an evaporative cooler. The only energy used in this system is to drive the fan, water pump and to regenerate the desiccant during the regeneration process. This energy can be provided from any low grade thermal energy source such as solar, waste heat, etc. The sensible and latent loads can be controlled separately in this system using a humidistat and thermostat for the control of wet and dry bulb temperatures respectively. This system can operate on wide range of sensible heat ratios because of the decoupling of sensible and latent cooling loads. A comparison between different cooling techniques is presented in Table 1 [7].

Desiccant dehumidification is a low grade thermal energy driven device and can be utilized in both air conditioning and dehumidification applications. The desiccant cooling system can either be solid or liquid depending upon the type of desiccant material used. Liquid desiccants have advantage over the solid desiccants that these only require low temperature heat source (60–80°C) to drive the system. This makes the use of some renewable energy resources like solar, biomass, etc. more feasible and efficient [8]. The main component of any desiccant system is desiccant dehumidifier. The rotary type desiccant dehumidifier commonly known as desiccant wheel is of particular interest for many researchers. These can work continuously for dehumidification of air instead of intermittently as is usually found in other configurations of desiccant systems [9,10]. Different techniques have been employed to lower both the installation and operating costs and to improve the performance of desiccant wheels. Various kind of efforts includes, identifying new desiccant materials, optimizing operating parameters, geometry, etc. The development of desiccant materials with improved dehumidification capacity and lower regeneration temperate has been the focus of recent researches.

Lithium and calcium chlorides have a higher hygroscopic capacity but the lyolysis phenomenon which leads to the loss of desiccant materials may reduce the performance due to the formation of solid crystalline hydrate [11]. So the weight or molar loading of lithium chloride or calcium chloride should be given prime importance while using these in a desiccant wheel. Different studies have used different compositions for composites of $CaCl_2$ and LiCl with other desiccant materials [12]. Room for further performance improvement still exists with regard to some low regeneration temperature and commercially available desiccant materials. Solid desiccant materials have higher regeneration temperatures as compared to liquid desiccant materials. Also, a quick decrease in adsorption capacity of solid desiccant materials such as silica gel occurs with the rise of temperature, especially at low partial pressure of water vapor. The hygroscopic capacity LiCl and $CaCl_2$ is higher but phenomenon of lyolysis often takes place after the formation of solid crystalline hydrate. This phenomenon may reduce the performance of the systems because of the loss of desiccant material. To make the good use of features of liquid desiccant materials and to avoid their drawbacks, a rotary type configuration is designed. This rotary liquid desiccant helps to overcome the above disadvantages liquid desiccants. These new liquid desiccant wheels can efficiently replace the present silica gel or haloids desiccant wheel.

It should be noted that the real performance of any desiccant material should be analyzed from the viewpoint of a system taking care of operating conditions and the heat and mass transfer properties in the desiccant wheel. Different materials having the same capabilities for moisture removal but may have different performances when operated under real working conditions. Therefore, it is important to compare the performance of desiccants under different conditions from the viewpoint of a system as whole.

In this paper exergoeconomic analysis has been carried out for a rotary type liquid desiccant cooling system proposed by Rafique et al. [13]. The purpose of this investigation is to analyze the exergy and economics performance of the system including the manufacturing and operating cost along with the required energy input. The proposed system has the advantage of conducting dehumidification and regeneration simultaneously. An exergoeconomic model is developed for the proposed system to investigate its performance under different parameters.

Table 1
Comparison between different cooling techniques [7]

Parameter	Mechanical vapor compression	Evaporative cooling	Desiccant based evaporative cooling
Cost of operation	High	Low	Low
Input energy resource	Electricity, Natural gas, Vapor	Low grade energy	Low grade energy e.g. solar energy, waste heat etc.
Latent load control	Average	Low	Accurate
Sensible load control	Accurate	Accurate	Accurate
Quality of indoor air	Average	Good	Very good
System instalment	Average	Average	Slightly complicate
Emission of greenhouse gases	High	Low	Low
Market potential	Dominate the air conditioning market	Limited application	Immature technology with limited application
Cooling medium	Refrigerants	Water	Water

2. Exergy and anergy analysis

Exergy analysis of any energy system is the key factor for optimization and evaluation of its performance. The basic purpose of this analysis is usually to maximize the system overall performance by identifying the reasons/sites for the destruction of exergy. Many researchers have discussed the methodology and basic principles of exergy analysis [14,15]. The exergy analysis can be carried out for the whole system or for a complex system or for each component separately [16,17]. Kanoglu et al. [18] carried an exergy analysis of HVAC system which included psychrometric processes. The relations for exergy efficiency, entropy generation and energy were developed for air conditioning systems which are commonly used including cooling, cooling with dehumidification, heating with dehumidification and evaporative cooling.

2.1. Concept of exergy and anergy

The potential of a system to do work with reference to its dead state is defined as the exergy of that system. The dead state occurs when equilibrium takes place between the system and the environment. The energy which has no work potential and is rejected to the environment is referred to as anergy or exergy lost. Some differences between exergy and energy efficiency are listed in Table 2.

In general,

$$\text{Energy} = \text{Exergy} + \text{Anergy} \tag{2}$$

A simple flow diagram for the system under study is shown in Fig. 1. The total exergy for humid air comprises of two parts that is thermomechanical (physical) exergy and chemical exergy. The physical exergy is the maximum amount of work released to the restricted dead state as an original fixed composition. Chemical exergy is expressed as the maximum amount of work done when the mixture reaches chemical equilibrium with the reference environment. The Specific exergy, energy and anergy for a flow stream disregard of potential and kinetic energies are given as:

$$\text{Exergy} = \psi' = \left[(H - H_o) - T_o(s - s_o)\right] \tag{3}$$

$$\text{Energy} = \left[(H - H_o)\right] \tag{4}$$

Table 2
Differences between exergy and energy efficiency

Energy efficiency	Exergy efficiency
Defined by thermodynamics first law	Defined by thermodynamics second law
Always greater than 0 but in some cases can be greater than 1 i.e. heat pumps etc.	Always between 0 and 1
Not always homogenous terms	Homogenous terms

$$\text{Anergy} = \left[T_o(s - s_o)\right] \tag{5}$$

The rate of exergy can be written as:

$$\dot{\psi}' = \dot{m}\psi' = \dot{m}\left[(H - H_o) - T_o(s - s_o)\right] \tag{6}$$

The anergy also called as exergy destruction and exergy efficiency for all components of the system are defined as under. The exergy destruction rate can be obtained from rate of entropy generation ($\dot{S}_{gen}$) as follows:

$$\psi'_{destruction} = T_o\dot{S}_{gen} \tag{7}$$

where T_o is the dead state temperature which in this case represents T_1. The rate of entropy generation for desiccant dehumidifier (DW), evaporative cooler (EC), and heater is given by Eq. (8)–(10), respectively:

$$\dot{S}_{gen,\,DW} = \dot{m}_p\left[s_2 - s_1\right] + \dot{m}_r\left[s_6 - s_5\right] \tag{8}$$

$$\dot{S}_{gen,\,EC} = \dot{m}_p\left[s_3 - s_2\right] + \dot{m}_{water}\left[s_w\right] \tag{9}$$

$$\dot{S}_{gen,\,heater} = \dot{m}_r\left[s_5 - s_4\right] - \frac{\dot{Q}_r}{T_5} \tag{10}$$

The relation for exergy efficiency for the system can be written as given below:

$$\phi = \frac{\psi'_{out}}{\psi'_{in}} = \frac{\dot{\psi}'_{cool}}{\dot{\psi}'_{heat}} \tag{11}$$

where

$$\dot{\psi}'_{cool} = \dot{m}_p\left[(H_1 - H_3) - T_1(s_1 - s_3)\right] \tag{12}$$

$$\dot{\psi}'_{heat} = \dot{m}_r\left[(H_5 - H_4) - T_1(s_5 - s_4)\right] \tag{13}$$

Similarly for the individual components the exergy efficiency:

$$\phi_{DW} = \frac{\left[(H_2 - H_1) - T_1(s_2 - s_1)\right]}{\left[(H_5 - H_6) - T_1(s_5 - s_6)\right]} \tag{14}$$

It can also be found as:

$$\phi = 1 - \frac{\dot{\psi}'_{destruction}}{\dot{\psi}'_{in}} \tag{15}$$

For the evaporative cooler:

$$\phi_{EC} = 1 - \frac{\dot{\psi}'_{destruction,\,EC}}{\dot{\psi}'_2} \tag{16}$$

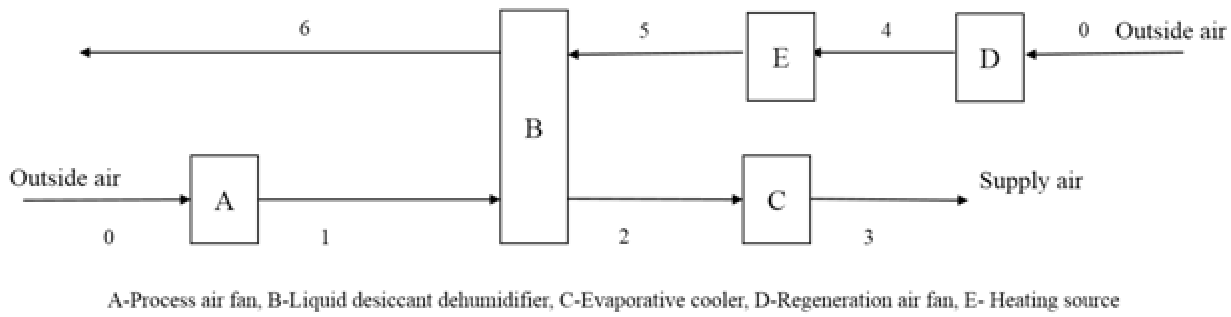

Fig. 1. Simplified flow diagram of liquid desiccant cooling system.

Where $\dot{\psi}'_2$ is the rate of exergy at state point 2. The exergy efficiency of the heater is defined as:

$$\phi_{heater} = 1 - \frac{\dot{\psi}'_{destruction,\,heater}}{\dot{\psi}'_4} \tag{17}$$

The developed exergy model is used to estimate the performance of the liquid desiccant system with the assistance of model developed in the previous sections.

3. Exergoeconomy

In order to provide the design information of the thermal system and to determine the related manufacturing costs, the exergy analysis can be combined with the economic principles. This information cannot be obtained from conventional economics and energetic analysis because exergoeconomy uses the exergy approach instead of energy [19]. The method used in this work combines the economics analysis with second law of thermodynamics and is developed by Silveira [20] for thermal systems. For exergoeconomy the following steps needs to be followed [21]:

- The identification of individual components and whole system.
- The determination of exergy flow for individual components and for whole system.
- The construction of functions for thermo economic
- The exergetic incremental function selection for individual components and for whole system.

3.1. Exergetic incremental function

The functional and physical diagrams and thermodynamic properties at inlet and exit of each component of the system are obtained from computer aided thermodynamics tables (CATT) [22]. The functional thermo economic diagram for the liquid desiccant cooling system is built using these diagrams and thermodynamic properties are presented in Fig. 2. Using Fig. 2, the exergetic incremental functions for each component can be defined as follows:

Process air fan (unit A):

$$\Delta\psi_{A.1} = \dot{m}_{out} \times \psi'_o \tag{18}$$

$$\Delta\psi_{A.2} = E_{fan} \tag{19}$$

$$\Delta\psi_{A.3} = \dot{m}_{out} \times \psi'_o - \dot{m}_p \times \psi'_1 \tag{20}$$

Liquid desiccant dehumidifier (unit B):

$$\Delta\psi_{B.1} = \Delta\psi_{A.1} \tag{21}$$

$$\Delta\psi_{B.2} = \dot{m}_r(\psi'_6 - \psi'_5) \tag{22}$$

$$\Delta\psi_{B.3} = \dot{m}_p(\psi'_1 - \psi'_2) \tag{23}$$

$$\Delta\psi_{B.4} = \Delta\psi_{E.2} \tag{24}$$

Evaporative cooler (unit C):

$$\Delta\psi_{C.1} = \Delta\psi_{B.3} \tag{25}$$

$$\Delta\psi_{C.2} = \dot{m}_{water} \times \psi'_{water} \tag{26}$$

$$\Delta\psi_{C.3} = \dot{m}_p(\psi'_3 - \psi'_2) \tag{27}$$

Regeneration air fan (unit D):

$$\Delta\psi_{D.1} = \dot{m}_{out} \times \psi'_o \tag{28}$$

$$\Delta\psi_{D.2} = E_{fan} \tag{29}$$

$$\Delta\psi_{D.3} = \dot{m}_{out} \times \psi'_o - \dot{m}_p \times \psi'_4 \tag{30}$$

Heating system (unit E):

$$\Delta\psi_{E.1} = \Delta\psi_{D.3} \tag{31}$$

$$\Delta\psi_{E.2} = \dot{m}_r(\psi'_5 - \psi'_4) \tag{32}$$

$$\Delta\psi_{E.3} = E_{regeneration} \tag{33}$$

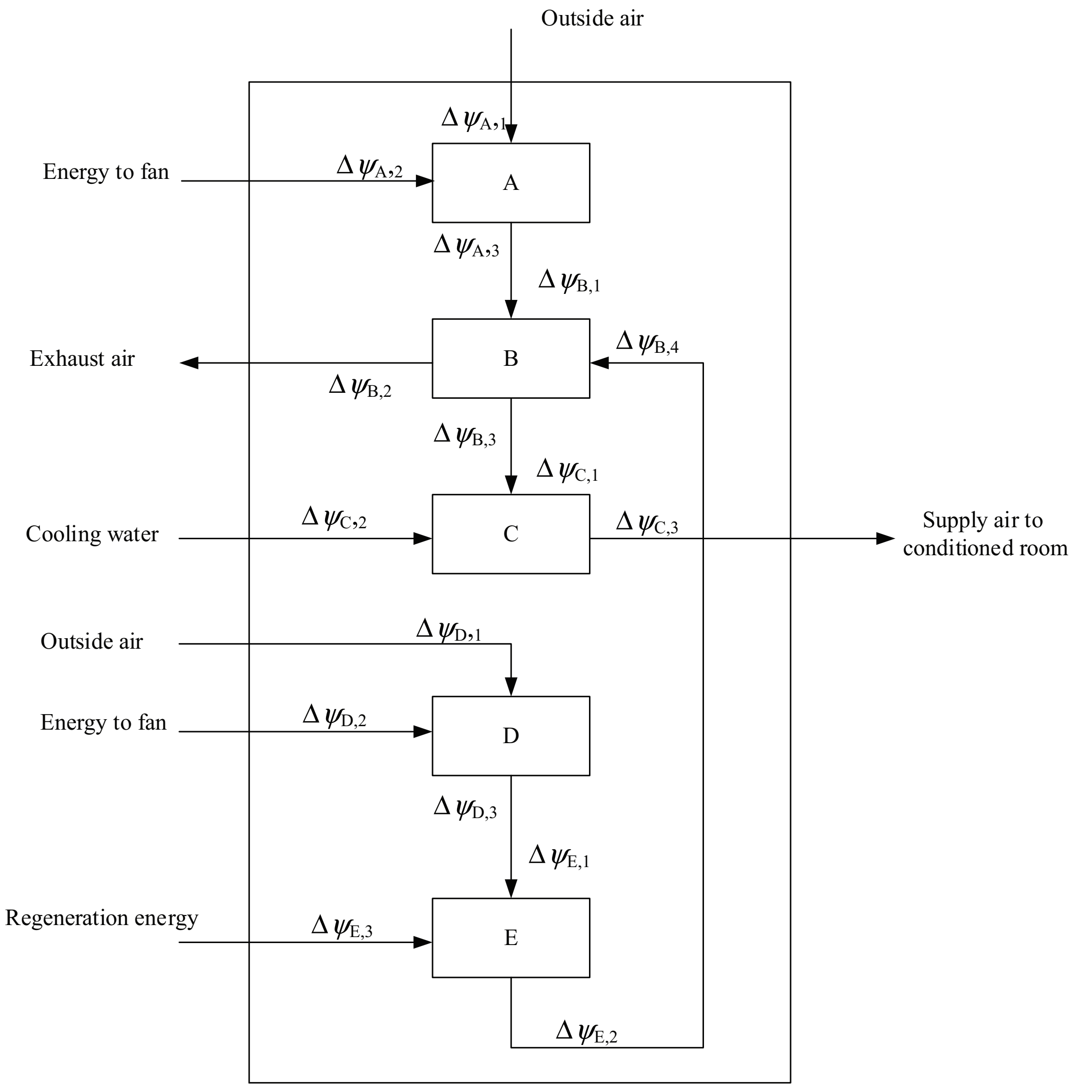

Fig. 2. Thermo-economic functional diagram of liquid desiccant cooling system.

3.2. Thermo economic analysis

The exergetic manufacturing cost $(MC)\psi$ in the case of liquid desiccant cooling system can be defined by the following relation:

$$(MC)_\psi = Cooled\,air\,produced\,(CA) \times Cost\,of\,\,production\,(\xi)_{pro} \quad (34)$$

$$(\xi)_{pro} = \frac{(\xi)_I \times f'}{H \times \Delta\psi_{C.3}} + \frac{\sum (\xi)_{energy}\left(\Delta\psi_{in} - \Delta\psi_{out}\right)}{\Delta\psi_{C.3}} \quad (35)$$

$$CA = \Delta\psi_{C.3} \quad (36)$$

Where, the value of annuity factor (f') is taken as 10%.

3.2.1. Investment cost $(\xi)_I$

The total investment cost includes the cost of liquid desiccant dehumidifier, fans, pump, heater, and evaporative cooler. The total investment cost for the system is described as follows:

$$(\xi)_I = (\xi)_{dehumidifier} + (\xi)_{fans} + (\xi)_{pump} + (\xi)_{evaporative\ cooler} \quad (37)$$

3.2.1.1. Cost of dehumidifier

The cost of desiccant dehumidifier can be estimated from the manufacturer of desiccant dehumidifiers such as Munters. For example the cost for model HCD-4500 is 35,946 US$.

3.2.1.2. Cost of fans $(\xi)_{fan}$

The investment costs for fan includes the cost of electric motor and can be expressed in US$ as follows [23]:

$$(\xi)_{fan} = [a + b(E_{fan})^{0.5}]^2 (USD) \quad (38)$$

Table 3
Values of coefficients

Coefficient	Value
a	16.9049
b	556.444
c	21.5644
d	20.1554

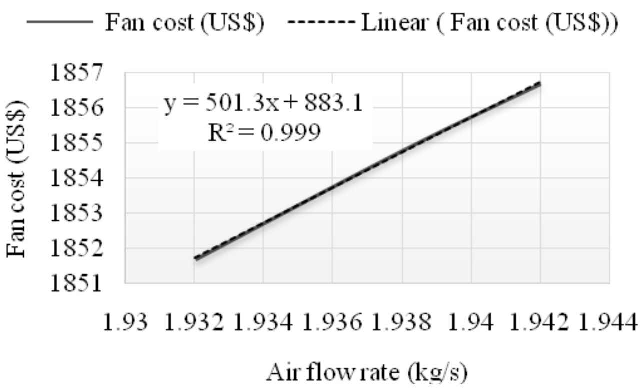

Fig. 3. Cost of fan.

The values of coefficients a and b are given in Table 3. The cost of fan for different mass flow rates of air can be obtained using Fig. 3.

3.2.1.3. Cost of pumps $(\xi)_{pump}$

The investment cost for the pump is given by Zalewski et al. [23] as:

$$(\xi)_{pump} = [c + d(\dot{m}_{water})^{0.5}(USD) \quad (39)$$

The values of coefficients *c* and *d* are given in Table 3. The investment cost of pump for different mass flow rates of water can be obtained from Fig. 4.

3.1.1.4. Cost of evaporative cooler $(\xi)_{pump}$

The evaporative coolers have higher efficiency, smaller size, less investment cost, and lower consumption of energy as compared to air exchangers. For example evaporative cooler require up to 50% less space, 30 to 50% saving of materials, and about 3 times less fan power compared to air heaters. Furthermore, the power consumption of water pump in evaporative cooler is 4 times less than the closed water cooling systems while it saves about 95% of water as compared to open water cooling system [23]. The cost of evaporative cooler includes cost of equipment and its installations. Bom et al. [24] presented the total installation cost of evaporative cooler as a function of area of conditioned space as shown in Fig. 5. In the present case the equipment cost can also be estimated using Boehm [25] technique:

$$(\xi)_{equipment} = (\xi)_{ref}\left(\frac{S}{S_{ref}}\right)^{m} \quad (40)$$

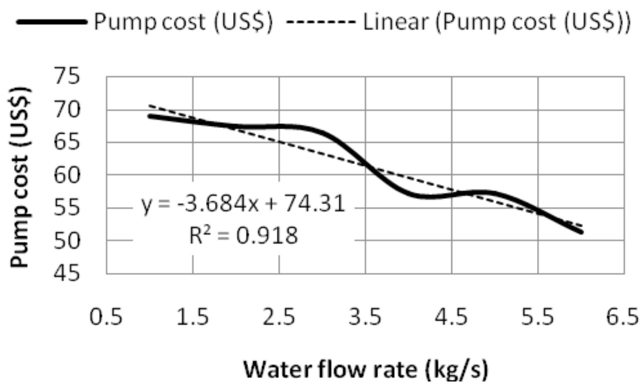

Fig. 4. Cost of pump.

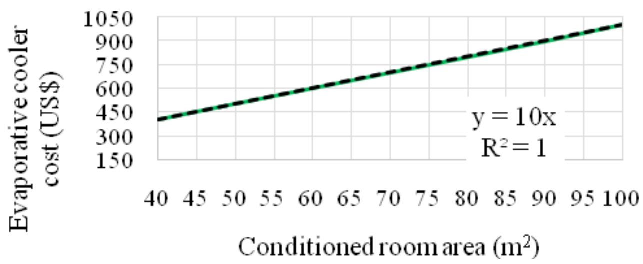

Fig. 5. Cost of evaporative cooler.

where $(\xi)_{equipment}$ is the investment cost for size S and $(\xi)_{ref}$ is the average cost for a reference size of S_{ref}. The factor *m* is called economy of scale and its value lies in the range of 0.5 – 1.0.

3.2.2. Energy costs

The total cost of water includes utilization and pumping cost. The cost of electricity is taken as 0.075 US$/kWh which makes the total cost of water about 0.853 US$/kWh.

$$\frac{\sum(\xi)_{energy}\left(\Delta\psi_{in} - \Delta\psi_{out}\right)}{\Delta\psi_{C.3}} = \frac{(\xi)_{electric}\left(\Delta\psi_{A.2} + \Delta\psi_{D.2} + \Delta\psi_{E.3}\right)}{\Delta\psi_{C.3}} \quad (41)$$

The developed exergoeconomic model assesses the system irreversibility and consumed resources costs.

5. Results and discussion

The effect of different key parameters on performance of the proposed rotary liquid desiccant cooling system has been discussed in this section. The base value and range for each parameter studied in this paper are presented in Table 4. Only one parameter is variedin each case, keeping all other parameters constant at the base value.

5.1. Exergy and anergy analysis

The values of exergy efficiency and anergy of the system and its components are presented in Table 5. Evaporative coolers (EC) have an exergy efficiency of 17%. The EC has

Table 4
The range and base value of different parameters

Parameter	Base value	Range
Regeneration temperature (T_5), °C	70	50–85
Ambient air temperature (T_1), °C	35	25–5
Ambient air humidity ratio (ω_1), kg/kg	0.02	0.015–0.030
Process air flow rate, kg/s	0.50	0.3–1
Regeneration air flow rate, kg/s	0.20	0.1–1

Table 5
Measured exergy and anergy data for the system and its individual components

Component	Exergy efficiency (%)	Anergy (kW)	Anergy (%)
Desiccant dehumidifier	74	0.130	33
Evaporative cooler	17	0.062	30
Heater	51	0.127	37
System overall	8	0.403	100

lower exergy efficiency because of higher irreversibility due to greater evaporation rate.

The heating source is considered to be operating at constant temperature. With this assumption of constant temperature the exergy efficiency of the heater is measured to be 51%. The exergy efficiency of the desiccant dehumidifier is found to be (74%) which is a good result as the maximum achieved exergy efficiency for this type of systems is about 85% as reported by Bulck et al. [26] . Smaller the exergy efficiency greater the value of anergy as it can be seen from the Table 5. Desiccant wheel and heater share the greater part of anergy with desiccant wheel having (33%) of the total anergy and heater (37%). The remaining 30% of anergy is accounted for evaporative cooler. These obtained results showed a good agreement with the experimental results of Kodama et al. [27].

The causes of irreversibilities for the dehumidifier are identified by Bulck et al. [26]. These causes include process and regeneration air mixing, difference of vapor pressure between regeneration air and matrix of desiccant, and heat transfer. The method adopted to provide the input heat determines the cause of irreversibility for heating system. Temperature difference (T8–T7) is a major factor for irreversibility for the heat source at constant temperature (ideal heat source). The system has lower overall exergy efficiency (8%). In order to approach the reversible COP, the entropy generation should be minimized for each component of the system. The process of entropy minimization should be started from the component having greater exergy destruction. The exergy efficiency and COP of the system can be increased remarkably by minimizing the exergy destruction in desiccant dehumidifier, heater, and evaporative cooler. Maclaine-cross [28] attempted to minimize the entropy generation by using wet surface heat exchanger instead of evaporative cooler.

Table 6
Details of two cases under investigation

Parameter	Case I	Case II
Regeneration temperature (°C)	70	60
Ratio of regeneration to process air flow rate	0.75	0.33
Ambient temperature (°C)	35	35
Ambient humidity ratio (g/kg)	17	17

5.2. Thermo economic analysis

The exergoeconomy method is a powerful tool for the optimization of thermal systems. For the present analysis,a thermal load of about 40 kW has been considered for conditioned space of about 205 m^2. Two different operational conditions have been considered for the system under investigated and a comparison is made for thermo-economic performance. Note that the climatic conditions remain the same for both cases. The details of two cases are given in Table 6.

The values of specific enthalpy, specific entropy and specific exergy at each state point of the system are presented in Table 7. A comparison has been made between two cases for power consumption, investment cost, and exergetic manufacturing cost in Tables 8–10, respectively. The electric power consumed by the fans and heater used in the liquid desiccant cooling system are presented in Table 8. It is observed that the waste of energy is less for the second case. The total power consumed for the Case I and II were found to be 64,095 and 52,060 W, respectively. Table 9 presents the investment cost for dehumidifier, evaporative cooler, fans, and pumps which are almost similar for the both cases. Furthermore, the results show that the second case lead to the least value of exergetic manufacturing cost which is 3,533.34 US$ for case I and 2,260.534 US$ for case II, as shown in Table 10. There exist some studies in the literature in which the desiccant cooling systems have shown better energy and cost efficiencies as compared to conventional air conditioning systems [29–31].

5.3. Sensitivity analysis

Although the results have been presented for two different cases by varying important parameters, but sensitivity analysis was carried out for total exergetic manufacturing cost of the system. Given the states of outdoor environmental conditions and the process air, the regeneration temperature and ratio of air flow rates become the important factors to influence the overall performance of the system [13]. The effect of regeneration temperature and ratio of regeneration to process air have been observed on exergetic manufacturing cost as shown in Fig. 6. The results clearly showed that the economic results are particularly sensitive to the regeneration temperature and flow rates ratio. The exergetic manufacturing cost increases with increase in temperature and ratio of air flow rates. This increase in cost is mainly because of the increase in energy cost of the system. With the increase in regeneration temperature or regeneration air flow rate, required input energy increases and so does the cost of energy. The effect of these parameters on required

Table 7
Thermodynamics properties at each state points of the system

State point	Case I			Case II		
	H (kJ/kg)	s (kJ/kg K)	ψ' (kJ/kg)	H (kJ/kg)	s (kJ/kg K)	ψ' (kJ/kg)
0	89.70	6.17	14.30	89.9	6.88	15.37
1	82.61	6.77	9.01	83.70	6.86	9.14
2	90.17	6.84	–2.90	87.60	6.93	–3.24
3	74.01	6.64	6.37	70.79	6.84	5.54
4	81.80	6.75	9.91	83.79	6.85	15.61
5	143.61	7.03	22.19	133.2	7.00	20.23
6	135.91	6.94	32.57	128.9	6.99	33.22

Table 8
Electric power consumed by the system

Case	Fan power (W)		Reactivation power (W)	Total power (W)
	Process	Reactivation		
I	1372.8	1812.2	60,910.00	64,095.00
II	1375.3	1535.5	49,150.00	52,060.80

Table 9
Investment costs of the system (US$)

Case	I	II
Cost of dehumidifier	35,945	35,945
Cost of evaporative cooler	5,730	5,730
Cost of fans	1,850	1,850
Cost of pump	125	118
Total investment cost	43,654	43,647

Table 10
Exergetic manufacturing cost of the system (US$)

Case	I	II
Total investment cost	43,654	43,647
Energy cost (US$/kWh)	256.17	233.37
Cost for cooled air (US$/kWh)	256.97	234.27
Cooled air produced (kW)	3.667	2.573
Exergetic manufacturing cost (US$/h)	3,533.34	2,260.70

input energy and performance of the system have also been discussed in detail in ref [13].

6. Conclusion

In this paper, the performance of a liquid desiccant cooling system using rotary dehumidifier has been investigated under various operating and climatic conditions. After analyzing the energy and exergy performance of the system, an exergoeconomy model was developed to determine the exergetic manufacturing cost of the system. The results showed that the system is well suitable and energy efficient alternative

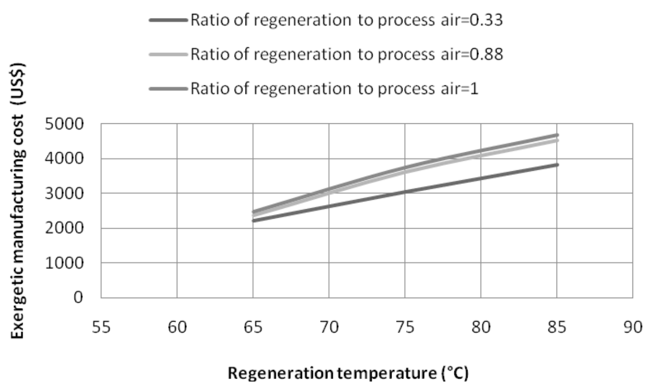

Fig. 6. Variations of exergetic manufacturing cost with regeneration temperature and ratio of mass flow rates.

to conventional air conditioning systems in hot and humid climatic conditions. The use of low grade energy sources such as solar and waste energy makes the proposed liquid desiccant cooling system more energy efficient and environmental friendly. Exergy analysis of the system showed that, the exergy efficiency of the evaporative cooler, heating unit, and dehumidifier was 17, 51, and 74%, respectively.

An exergoeconomy model was developed to minimize the investment and operating costs by selecting the optimum value of operating parameters. Two different cases were studied with different regeneration temperature and ratio of mass flow rates. The results showed that the exergy manufacturing cost is lower for case II (for regeneration temperature of 60°C and ratio of regeneration to process air flow rate of 0.33) as compared to case I (with regeneration temperature of 70°C and ratio of regeneration to process air flow rate of 0.75). The study found that for the certain operating conditions, the operating costs may reduce significantly but this can be accompanied by the high capital cost. Therefore, the optimal values for all parameters should be selected considering both operating as well as capital costs. Also, based on operating conditions and application of the system, payback period should be evaluated.

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Symbols

C_p	—	Specific heat (kJ/kg.K)
CA	—	Cooled air produced (kW)
DW	—	Desiccant wheel
EC	—	Evaporative cooler
E	—	Rate of energy consumption (kW)
E_{fan}	–	Electric power of fan (kW)
H	—	Specific enthalpy (kJ/kg)
H^*	—	Operating condition factor
h_{fg}	–	Latent heat of vaporization (kJ/kg)
H	—	Equivalent utilization period (h/year)
P	—	Pressure (kPa)
Q	—	Rate of heat transfer (kW)
$\dot{Q}_r$	—	Rate of regeneration heat (kW)
S	—	Specific entropy (kJ/Kg.K)
SHR	—	Sensible heat ratio (–)
SAR	—	Saudi riyal
T	—	Temperature (°C)
τ	—	Time (s)
$(MC)\psi$	–	Exergetic manufacturing cost
f'	—	Annuity factor (1/year)
$\Delta\ \psi$	—	Exergetic incremental function (kW)
ψ'	—	Specific exergy (kJ/kg)
$\dot{\psi}'$	—	Exergy flow rate (kW)
ξ	—	Cost (US$)

Greek

β	—	Equivalent conversion coefficient (–)
γ	—	Currency exchange rate

Subscripts

A	—	Air
amb	—	Ambient
o	—	Reference state
p	—	Process
pro	—	Production
r	—	Regeneration

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