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Simulation of Hybrid Desiccant Cooling System with Utilization of Solar Energy

[1]Behnoosh Bakhtiari Heleyleh, [1]Abdolrazzagh Kaabi Nejadian, [1]Ali Mohammadi and [2]Mashhood Mashhoodi
[1]Department of Environmental and Energy Engineering,
[2]Young Researchers and Elites Club, Science and Research Branch, Islamic Azad University, Tehran, Iran

Corresponding Author: Behnoosh Bakhtiari Heleyleh, Department of Environmental and Energy Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ABSTRACT

Solar desiccant cooling cycle in combined mode with vapor compression refrigeration cycle in hot and humid weather of bushehr city was simulated. The main purpose of introducing the cycle was to reduce energy consumption, especially fossil fuel consumption, in vapor compression systems which are commonly used in buildings. To simulate the cooling cycle, a proper thermodynamic models and physical properties for each components of the system must adopted. A model for liquid desiccant system simulation was selected and coding was done in ESS based on experimental relations was used. The effects of regeneration temperature, thermal comfort condition and outdoor weather conditions such as air humidity were examined. In addition, in order to reduce further fossil fuel consumption in vapor compression cycle, the organic Rankine cycle was combined with vapor compression cycle so that required inlet work for compressor was supplied. Solar energy was adopted as the main required heat source for operation of organic Rankine cycle given the geographic potential of the area. A model of the solar system was simulated in TRNSYS and optimum values for all elements of the solar system were obtained based on Solar Fraction. Dynamic performance of the cycle in Bushehr city was analyzed in an area of 1000 m^2 and with cooling capacity 50TR. The effects of significant parameters on the COP of the cycles, air outlet temperature and rate of energy consumption in the compressor were investigated along with the effect of outdoor condition on reaching thermal comfort. Results indicated that using solar energy with combined cooling system (vapor compression and liquid desiccant) cuts fossil fuel consumption about 50%. In addition, outcomes demonstrated that removing moisture from supply air by using a dehumidifier section in desiccant section of proposed cycle leads to 13% reduction in building cooling load in summer.

Key words: Solar energy, hybrid desiccant cooling system, fossil feuls

INTRODUCTION

Growing demand for energy and limited human resources along with increase in world energy prices in recent years leads us to the fact that taking steps towards optimizing energy consumption is inevitable. Nowadays, solar energy has greater potential for replacing fossil fuels. Solar energy is an environmentally friendly source and can be useful to improve and decontaminate the environment.

Desiccant dehumidifier system is a method of cooling that answers maximization of efficiency, economy and environment friendly concerns; it also meets the standards of indoor air quality.

Combination of conventional air conditioning systems and absorbent systems results in less sensible and latent heat in hybrid systems which could be an answer for controlling temperature and humidity within thermal comfort limit. The air conditioning system with a hybrid desiccant system has the potential to reduce energy consumption thanks to its less latent cooling load is.

In summary, the use of these systems has the following benefits:

- Reducing energy consumption
- Reducing bacteria and fungi
- Improving indoor air quality
- Providing comfort
- No greenhouse gases by dehumidifier

Liquid desiccant cooling cycle studies are followed in theory and practice. Here some of the earlier studies and the obtained results obtained are reviewed.

The hybrid liquid desiccant cooling systems were made by Mago and Goswami, University of Florida. Comparison between vapor compression refrigeration system and liquid desiccant hybrid system showed that the rate of condensation increases in the former with air flow rate and temperature (Mago and Goswami, 2003).

An experimental study on dehumidifier and regenerator of liquid desiccant cooling air condition was performed by Yin *et al.* (2007a). They showed the relationships of regenerator mass transfer coefficient as a function of heating temperature and desiccant concentration (Yin *et al.*, 2007a).

An ideal liquid desiccant dehumidification system was featured by Wang *et al.* (2010) with idealization of practical liquid desiccant dehumidification system, regarding its exergy performance and thermodynamic properties.

A solar energy input for regenerating the lithium chloride liquid desiccant was modeled and created in TRNSYS for Toronto, Chicago and Miami; and results indicated that solar input could provide half of the required thermal input (Andrusiak *et al.*, 2010).

Artificial neural network analysis with a reasonable degree of accuracy was used for modeling liquid desiccant dehumidification system (Gandhidasan and Mohandes, 2010).

The open cycle solar collectors/regenerators was used to regenerate the desiccant solution. The effect of ambient condition variables and operating condition were also experimentally investigated (Yutong and Yang, 2010).

A simplified theoretical model was used by Chebbah (2002) to investigate the complex phenomena of simultaneous heat and mass transfer and the results showed that the cooling of air dehumidification process enhanced the mass transfer and reduced the strong desiccant solution requirement.

Mechanism of proposed cooling cycle: The following overview shows design of the cooling needs of the building under consideration. In Fig.1, ambient hot and humid air in point1 enters to the dehumidifier tower and the humidity of the air is reduced by passing through the liquid desiccant solution and then enters compression cooling system; consequently thermal comfort is provided.

In order to regenerate the sorbent in the desiccant cycle, regenerator liquid was used. By crossing in the regenerator the hot oil output of the collector provides the thermal energy needed

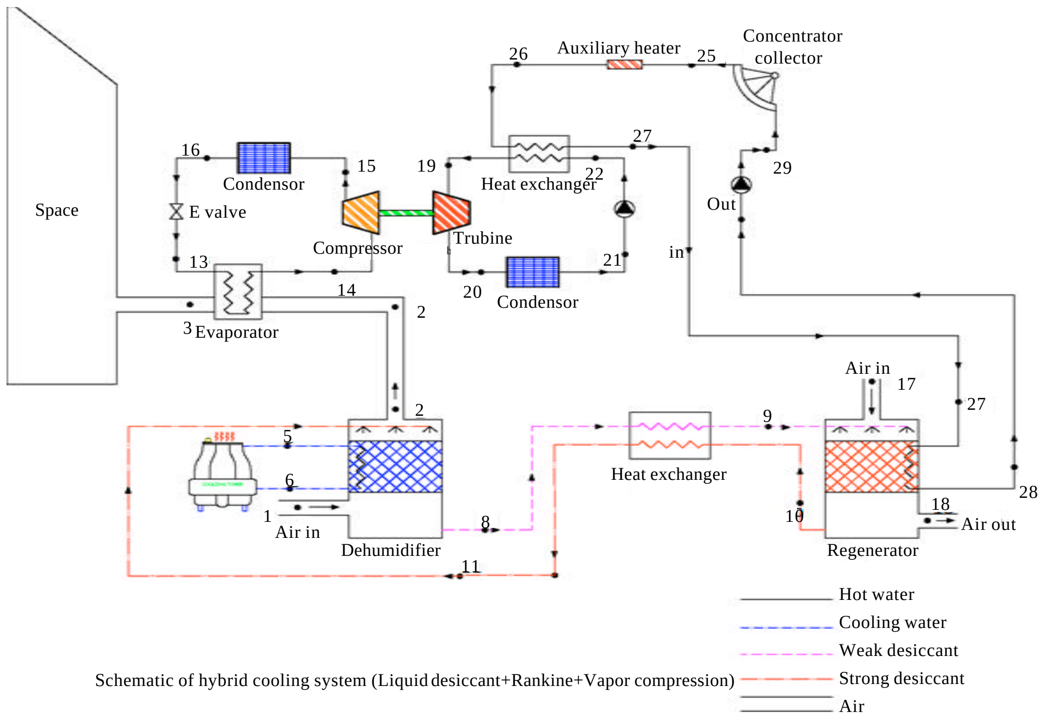

Fig. 1: Schematic diagram of the buildings cooling cycle

for regenerating desiccant liquid solution. Absorbing air moisture by absorbing the solution can be considered as a mass transfer from gas-phase into liquid. In the dehumidifier, humid air and liquid desiccant solution enter from the bottom and the top of the tower, respectively; thus heat and mass transfer between the gas and liquid phases occur simultaneously. This process produces a steady and continuous stream.

At a specific height of the tower, due to transferring of the solute (water vapor) from the gas phase into the liquid there must be a gradient density in mass transfer direction. In a liquid system, the liquid absorbent separates moist in direct contact with in the air. In this study, lithium bromide was utilized for dehumidifying of air. The most important parts of any desiccant system are absorbent and dehumidifier as described in the following sections.

Regenerator and dehumidifier: Desiccant solution absorbs air moist based on partial pressure difference between the desiccant surface and partial pressure of the vapor. The moist air loses humidity by passing over liquid desiccant which result to fine absorbent. After saturation desiccant solutions loses its efficiency and cannot absorb more moisture from the air. Thus, to continue the process of dehumidification it should be regenerated. Regeneration of this material usually is done by utilizing the hot air with lower vapor partial pressure than that is used in desiccant. This difference causes transferring moisture from saturated absorbent to hot air and finally provoked regenerated desiccant.

In the regenerator, the absorbent is reheated and revived. Therefore, a heat source is needed which here it is solar energy. It is notable that the capacity of regenerator is affected by the heat source and concentration of dryer.

As mentioned; mass and heat transfer are significant factors affecting performance of the system. Therefore, there is a particular interest in this area in all researches conducted. In what follows, the thermodynamic equations of each component of desiccant and regenerator are given (Yin *et al*., 2007b), (Yin and Zhang, 2010). In the Table 1 summary of results is indicated:

$$dh_a = (cp_a+cp_v\times\omega_a)\times dT_a+(q_v+cp_v\times T_a)\times d\omega_a \tag{1}$$

$$Le = \frac{hc}{h_D \times CP_a} \tag{2}$$

$$NTU = \frac{h_D \times WH\beta}{\left(\frac{M_a}{2}\right)} \tag{3}$$

$$h_D = \frac{D \times Sh}{d} \tag{4}$$

$$dT_{solution} = \left(-\frac{1}{CP_{solution}}\right)\times\left[\left(\left(\frac{M_a}{M_{solution}}\right)\times dh_a\right)+\left(\left(\frac{M_a}{M_{solution}}\right)\times CP_{solution}\times T_{solution}\times d\omega_a\right)\right] \tag{5}$$

$$dX_{solution} = \left(\frac{-M_s \times d\omega_a}{M_{solution}+\left(M_s \times d\omega_a\right)}\right)\times X_{solution} \tag{6}$$

$$\frac{dT_{oil}}{dZ} = \frac{h_{oil}\times\left(T_{solution}-T_{oil}\right)\times w}{\left(M_{oil}\times CP_{oil}\right)} \tag{7}$$

Compression refrigeration cycle: The purpose of hybridize desiccant cycle with compression refrigeration cycle is to reduce temperature of the air entering the designed space. Liquid desiccant cycle is not capable of providing comfort conditions, so compression refrigeration cycle is used. In this investigation, solar energy is used for supplying electrical power and reducing fossil fuels needed in compression refrigeration cycle. Compression cooling systems are conventional systems used in various areas which are based on compressing a fluid and changing its phases from liquid to vapor:

Table 1: Summary of results and comparison of predecessors in the field of liquid desiccant

Findings	L/G ratio	Experiment/theory	Liquid desiccant	Reference
Air humidity ratio ↑	4.9-5.6	Experiment	LiCl	[12]
Desiccant flow rate ↑	2.6-11.5	Experiment	TEG	[13]
Air temperature ↓	1.2	Theory	LiBr	[14]
Air humidity ratio ↑	0.2-2.3	Experiment	LiCl	[15]
Desiccant temperature ↑	1.9-2	Experiment	$CaCl_2$	[16]
Desiccant flow rate ↑	0.3-1.5	Theory	LiBr	Present study

↑: Increasing trend, ↓: Decreasing trend

$$Q_{eva} = m_3(h_3 - h_2) \tag{8}$$

$$m_{R-134a} = \frac{Q_{eva}}{h_{14} - h_{13}} \tag{9}$$

$$W_{comp} = m_R - 134_a(h_{15} - h_{14}) \tag{10}$$

Organic Rankine cycle: For low temperature working fluid (100-400°C) organic fluids are the best for the Rankine cycle. For selection of working fluid in Rankine cycle the flowing parameters should be considered:

- Fluid cost should be low
- No corrosion
- Is stable
- Have High efficiency
- Have high density in vapor phase
- Have a low viscosity
- Have a High heat transfer coefficient

Using organic fluid is more efficient for producing heat from low temperature heat. By reviewing the literature and considering that thermal energy supplied by solar energy, n-pentane was selected in this investigation; it has been also used in organic Rankine cycle with solar energy supply (Quoilin *et al.*, 2012). The governing equations in organic Rankine cycle are:

$$Q_{eva} = m_3(h_3 - h_2) \tag{11}$$

$$m_{R-134a} = \frac{Q_{eva}}{h_{14} - h_{13}} \tag{12}$$

$$W_{comp} = m_R - 134_a(h_{15} - h_{14}) \tag{13}$$

Summary of the results is listed in Table 2.

Simulation of cycle: All thermodynamics equations governing the organic Rankine cycle, compression refrigeration cycle, regenerative desiccant dehumidifier in the system was written by EES. Simulation of energy in the sample building under Bushehr's weather was done in TRNSYS. The thermal energy produced by the solar system is used for two purposes, one to set up an organic Rankine system and the other to provide the required heat in reducing the liquid desiccant system. Solar design by using TRNSYS software is pictured below. As can be observed from Fig. 2 the defined cycle includes solar collector, pump and auxiliary heater.

According to the Fig. 2 solar heating system which is simulated in TRNSYS is constituted of different components. In this system, solar collector concentrators (Type 74) are used to provide 270°C. Temperature of working fluid (oil) increases by passing through the solar collector and then

Table 2: Summary of results and comparison with its predecessors in the field of organic Rankine cycle

$\eta_{Rankine}$ (%)	Q_{eva} (kW)	W_p (kW)	W_t (kW)	Fluid	Reference
19.8	878.69	7.82	385.51	MDM	[11]
21	161.88	1.31	77.13	Pentane	Present Study

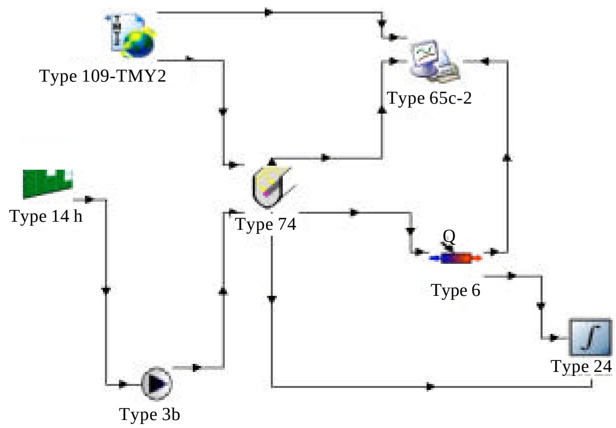

Fig. 2: Solar heating system

leaves the collector into the auxiliary heater (Type 6). When the collector outlet temperature is insufficient for the organic Rankine cycle, the Auxiliary heater increases the fluid temperature up to design temperature. Exhaust fluid (oil) then enters the regenerator of liquid desiccant cycle and by losing heat it is pump back into the collector. If the pump (Type 3b) which is controlled by controller is turned off according to scheduled plan for the building (Type 14 h), the entire cooling system stops working. In addition, the component (Type 24) is used for data collecting throughout the year, especially when system is working. Furthermore, component (Type 109-TMY2) is utilized for gathering weather properties for selected city and links the collector to the next stage of process. At the end, component (Type 65c-2) demonstrates results of analysis of cycle dynamically at specific time period.

Building cooling cycle optimization: For optimization of the cooling system, cycle is divided into two parts, one is liquid desiccant system with compression cooling cycle and organic Rankine cycle and the other is solar heating system. This is because of the fact that the system was modeled in two parts in two different software. As a result, optimization of each section is completed in its pertinent software. The mass rate of absorber fluid, air temperature and air flow can be defined using the basic equations of heat and mass transfer and the parameters that can influence the design of absorber tower and its efficiency.

Basic equations of heat mass transfer show that the main parameters in the design of absorbent tower are absorbent fluid rate, temperature of absorbent fluid, air temperature and also air flow rate. Furthermore, capacity and dimensions of the tower and rate of air mass to absorber fluid are the main design parameters, by these parameters; efficiency of dehumidifier can be defined. By increasing rate of liquid desiccant in HVAC systems which use liquid desiccant solution, more air volume in dehumidification can be dried, therefore more moisture can be removed. On the other hand, greater amount of liquid desiccant solution leads to more energy consumption and extra costs for instance in regenerator section. In other words, although more mass rate of fluid can absorb moister but system efficiency does not necessarily leads to a good performance. By using optimization methods, the optimal ratio between air mass flow rate and fluid flow rate can be obtained for increasing the performance coefficient of the tower.

Effect of regeneration temperature on the efficiency of regenerator: As shown in the Fig. 3, by increasing of regeneration temperature, efficiency of regenerator increases. The parameters are moist air flow of 1.5 kg sec^{-1}, hot fluid (oil) flow rate of 0.4 kg sec^{-1}, ambient humidity of 0.6 and ambient temperature of 40°C.

Effect of room temperature on energy consumption in the compressor: By increasing room temperature (comfort design) energy consumption in compressor is reduced. Parameters here are air flow rate of 1.5 kg sec^{-1} and relative humidity of 0.4.

As can be seen from Fig. 4, by changing room temperature from 20-28°C the amount of energy consumption in the compressor is decreased. Therefore, in accordance with national regulations regarding building energy consumption it is better to insulate the walls and the doors, use double layer windows and, set room temperature at 28°C in summer.

Effect of moist air mass flow rate on the compressor consumption: As seen in Fig. 5, by rising moist air flow rate inflow to dehumidifier, energy consumption in compressor is increased. The oil flow rate 0.4 kg sec^{-1}, relative humidity equal to 0.6 and ambient temperature 38°C were used.

Effect of increasing turbine inlet pressure (pressure ratio) on the performance of organic Rankine cycle: As illustrated in Fig. 6, by increasing pressure of inlet fluid working at turbine in an organic Rankine cycle, efficiency of the cycle is increased considerably.

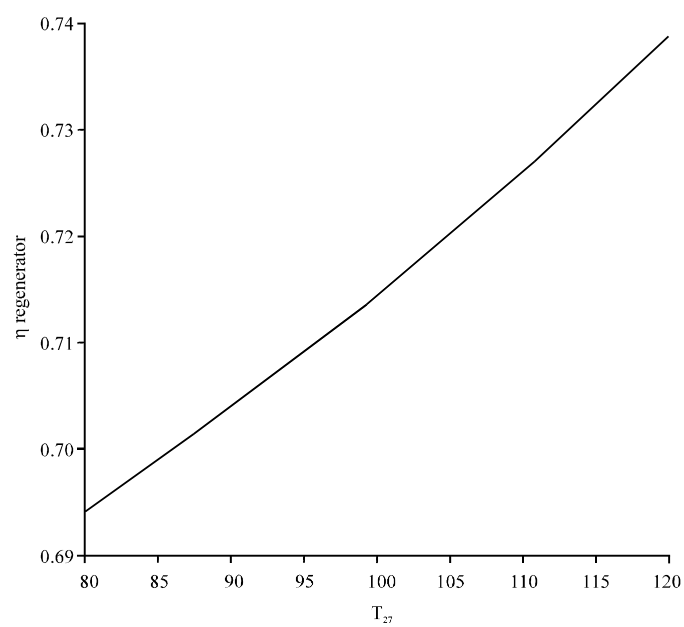

Fig. 3: Effect of regeneration temperature on the efficiency of regenerator

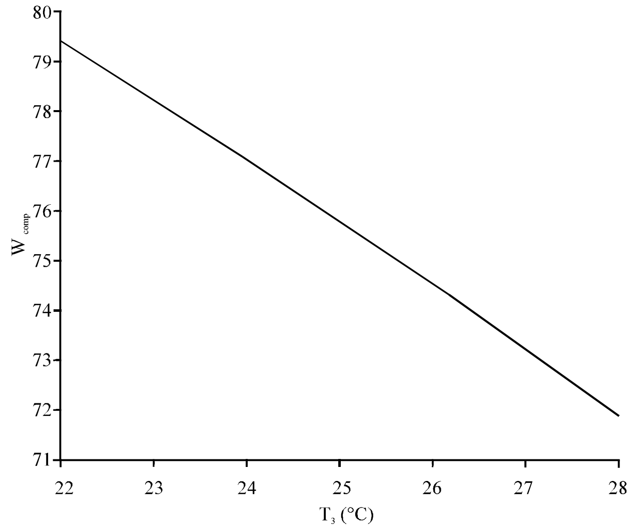

Fig. 4: Effect of room temperature on energy consumption in the compressor

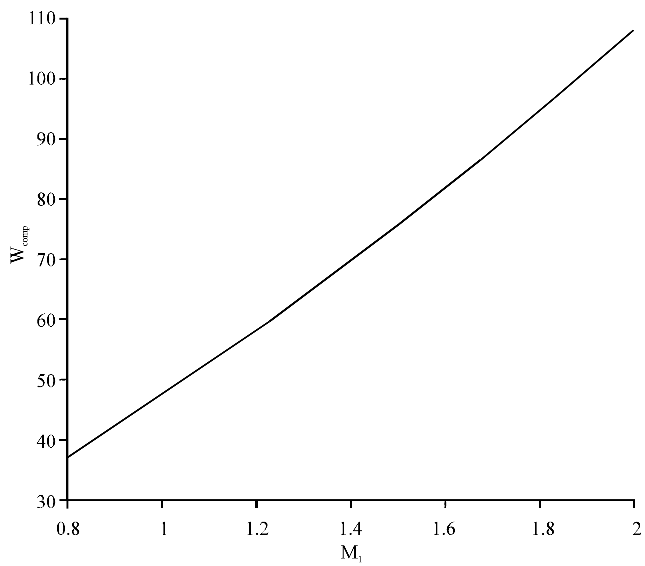

Fig. 5: Effect of moist air mass flow rate on the compressor consumption

By increasing the fluid inlet pressure to the turbine, work output of the turbine increases, due to the pressure difference and causes increases in the efficiency of the organic Rankine.

Effect of dehumidification besides cooling in hot and humid weather condition: Considering that the most of the cooling of buildings is done by compression refrigeration cycle, in this study, the advantage of using desiccant cycle besides compression refrigeration cycle is reduction of the cooling load of the building (Fig. 7). Using the dehumidifier besides the vapour compression refrigeration cycle led to reduction of building cooling load by about 13%.

$$\text{Cooling load reduction} = \frac{(h_1 - h_g) - (h_2 - h_g)}{(h_1 - h_g)} = 13\% \qquad (14)$$

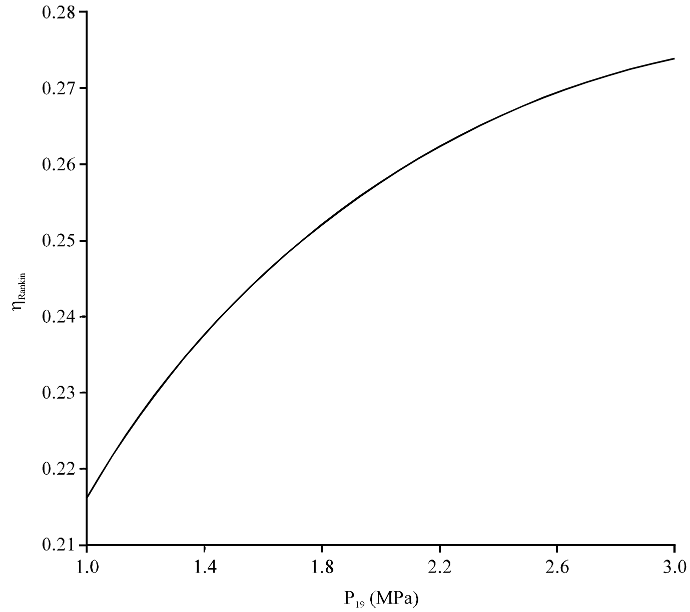

Fig. 6: Effect of increasing turbine inlet pressure (pressure ratio) on the performance of organic Rankine cycle

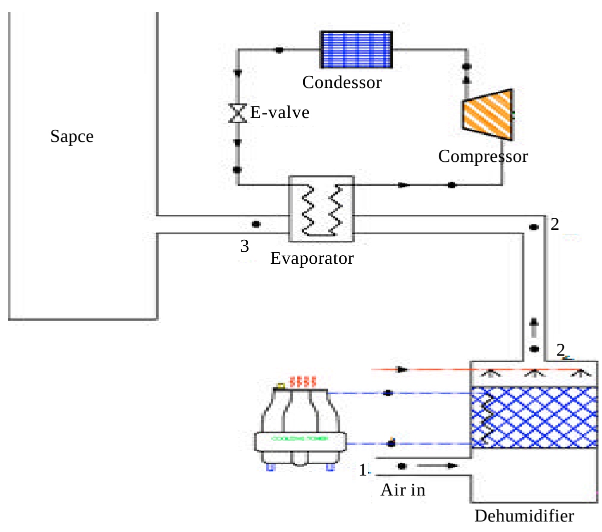

Fig. 7: Using desiccant cycle besides vapour compression refrigeration cycle

Structural optimization of solar heating system: Optimization of the structure solar system, such as the area and acceptance angle of the collector was studied. Oil with fixed flow rate was considered as working fluid and given that the fluid rate is used to supply energy for Rankine cycle and regeneration heat, it was remained fixed as with its variation, other parameters change considerably. Solar system structure and its changes are discussed below.

Solar fraction index was defined at the outset which is defined as the share of energy consumed by cooling systems which can be supplied by the collector. Optimization was based on the amount of solar fraction. When the auxiliary heater has the lowest energy consumption or SF has the highest value, the model is optimal. Different studies have proposed different definitions of solar fraction. In this study, the following definitions were under consideration:

$$\text{Solar fraction} = \frac{q_{solar}}{q_{solar} + q_{aux}} \tag{15}$$

Optimal collector acceptance angle: Collector acceptance angle based on the heat absorbed by the collector during the cooling period is shown in Fig. 8. The picture shows the climatic conditions in Bushehr with latitude of about 30 degrees and oil as the fluid used in the collector with the working hours of 7 am to 18 pm.

As pictured in Fig. 8 with increasing acceptance angle up to 90°, the amount of useful energy gain increases. However, there are few changes up to 70°. Therefore, 70° angle is considered as the optimum angle. Schematic diagram of CPC collector is depicted in Fig. 9. As can be seen the red angle indicates acceptance angle of the CPC collector.

Optimal collector area: To optimize collector area, change of SF was examined by varying the values of collector area. The variations of SF based on changes of the collector area are pictured below.

As shown in Fig. 10, with increase of the solar collector area, contribution of solar energy to meet the increased cooling requirements of the building increases and the share of auxiliary heater decreases. By taking the cooling load of building approximately 50 tons of refrigeration for hottest months as a reference of designing solar collector system, variation of collector area was input in the software and an area of approximately 350 m^2 was considered as the appropriate choice. By this way the optimum collector area is obtained.

Solar system simulated results: In this section, components of the solar heating system during the performance of an office unit in Bushehr and area in 1000 square meters for 48 h and cooling

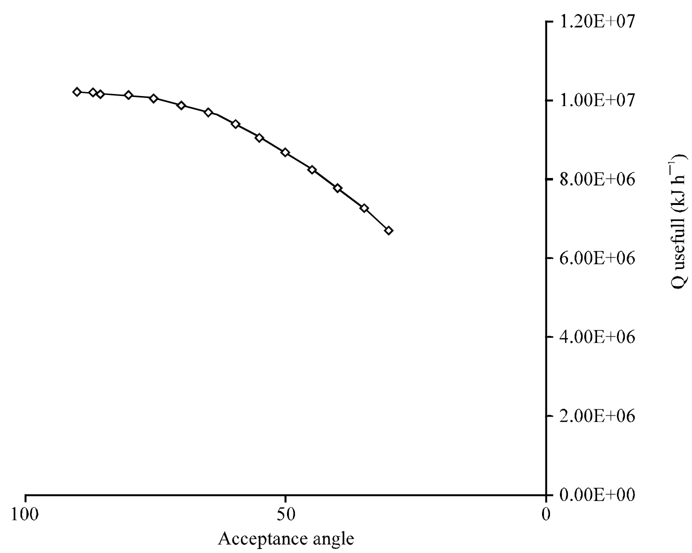

Fig. 8: Effect of increasing acceptance angle of collector on useful energy gain

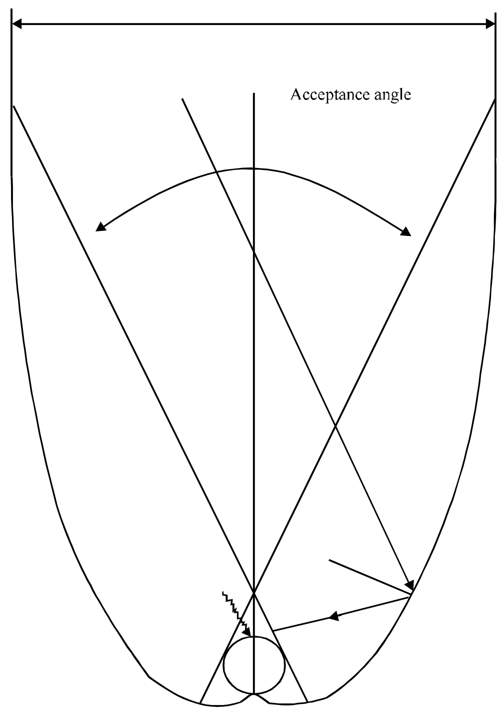

Fig. 9: Schematic diagram of CPC collector

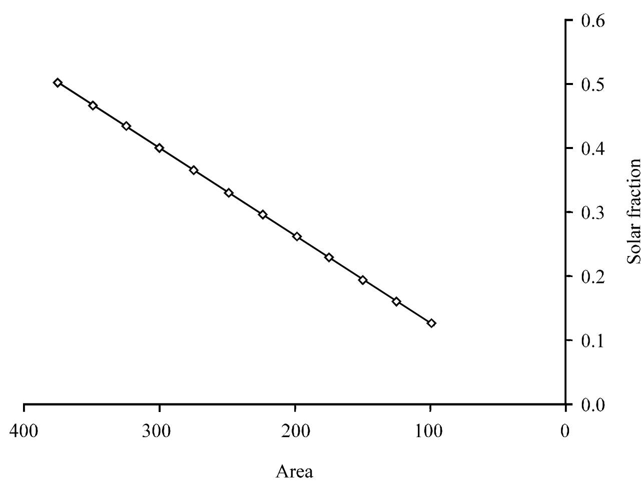

Fig. 10: Effect of increasing collector area on solar fraction

capacity of 50 ton in August was analysed. The optimum operating conditions of the cycle, on the basis of solar fraction are summarized in Table 3 as follows.

The graph in Fig. 11 compares the amount of heat transfer rate which is supplied by solar energy, with the amount of heat supplied by auxiliary heater in the first days of August. As an overall trend, it is clear that at the end of working hours the system automatically switches off and restarts the next working day. Clearly, in some days the collector can provide even more than what

Table 3: Solar simulated results

Cooling capacity (t)	Collector area (m^2)	Acceptance angle (°)	Mass flow rate of oil (kg sec^{-1})	Solar fraction
50	350	70	0.5	0.53

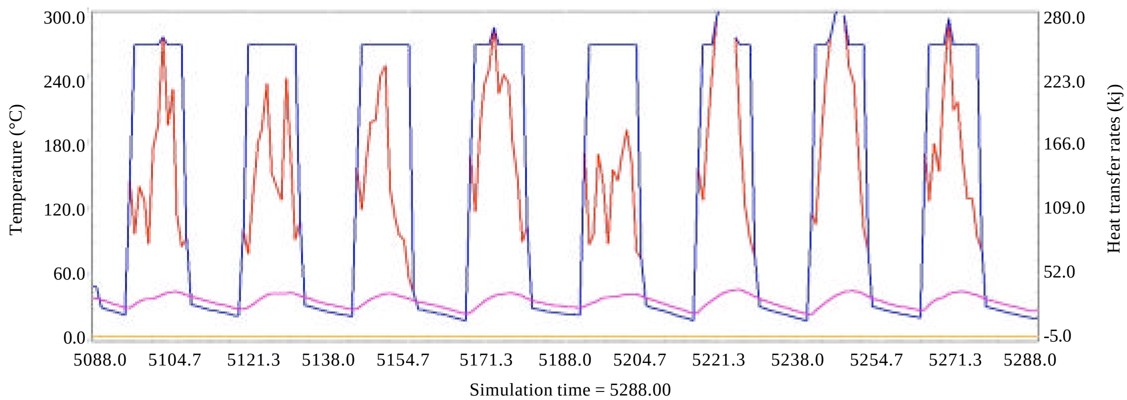

Fig. 11: Dynamic performance of the solar system

is needed to the system setup and the oil temperature is higher than set point temperature. The purple line indicates ambient temperature in Bushehr at this time of year.

CONCLUSIONS

It was demonstrated that it is feasible to use solar liquid desiccant cooling cycle in hybrid mode with vapour compression cycle to meet cooling load of the building in hot and humid climate. Merits of using suggested cycle in comparison with vapour compression cycle are: considerable decrease of cooling load of the building by dehumidifying supply air; and decrease in fossil fuel consumption by using solar energy.

Because of load latency in the traditional vapour compression systems, the air needs to be cooled below the dew point. High latent needs low temperatures to evaporate at the cooling cycle. There are limitations to the low temperature and the temperature cannot be less than the freezing temperature range. However, the cold air cannot enter the space. Thus in traditional methods when the latent heat is high, reheating should be used. Therefore, efficiency is not promising by any mean. By combining vapour compression cycle and absorbent system, higher efficiency is obtained. By comparison, solar liquid desiccant cooling cycle in hybrid mode with vapour compression cycle and vapour compression cycle resulted in 13% reducing of cooling load of case study building.

NOMENCLATURE

P	=	Pressure (MPa)
T	=	Temperature (°C)
A	=	Area of CPC collector (m^2)
SF	=	Solar fraction
q	=	Heat transfer (kJ)
W	=	Work (kJ)

X	=	Concentrate of liquid (kg kg^{-1})
Le	=	Lewis number
aux	=	Auxiliary heater
comp	=	Compressor
eva	=	Evaporator
h	=	Enthalpy (kJ kg^{-1})
M	=	Flow rate (kg sec^{-1})
$\dot{W}$	=	Power (kW)
ω	=	Humidity ratio (kg kg^{-1})
cp	=	Specific heat capacity (kJ $kg^{-1}K^{-1}$)
η	=	Efficiency
Q_{useful}	=	Useful energy gain from solar collector (kJ h^{-1})

REFERENCES

Andrusiak, M., S.J. Harrison and L. Mesquit, 2010. Modeling of a solar thermally-driven liquid-desiccant air conditioning. Proceedings of the 39th ASES National Solar Conference, May 17-22, 2010, Phoenix, Arizona, USA., pp: 1722-1729.

Chebbah, A.A., 2002. Theoretical analysis of a liquid desiccant air dehumidifier. Proceedings of the 6th Saudi Engineering Conference, December 2002, Dhahran, Saudi Arabia, pp: 547-559.

Gandhidasan, P. and M.A. Mohandes, 2010. Artificial neural network analysis of liquid desiccant dehumidification system. Energy, 36: 1180-1186.

Mago, P. and D.Y. Goswami, 2003. A study of the performance of a hybrid liquid desiccant cooling system using lithium chloride. J. Solar Energy Eng., 125: 129-131.

Quoilin, S., S. Declaye, A. Legros, L. Guillaume and V. Lemort, 2012. Working fluid selection and operating maps for Organic Rankine cycle expansion machines. Proceedings of the 21st International Compressor Conference at Purdue, July 16-19, 2012, Indiana, pp: 1-10.

Wang, L., N. Li and B. Zhao, 2010. Exergy performance and thermodynamic properties of the ideal liquid desiccant dehumidification system. Energy Build., 42: 2437-2444.

Yin, Y., X. Zhang and Z. Chen, 2007a. Experimental study on dehumidifier and regenerator of liquid desiccant cooling air conditioning system. Build. Environ., 42: 2505-2511.

Yin, Y., X. Zhang, D. Peng and X. Li, 2007b. Model validation and case study on internally cooled/heated dehumidifier/regenerator of liquid desiccant system. Elsevier Int. J. Thermal sci., 48: 1664-1671.

Yin, Y. and X. Zhang, 2010. Comparative study on internally heated and adiabatic regenerators in liquid desiccant air conditioning system. Build. Environ., 45: 1799-1807.

Yutong, L. and H. Yang, 2010. Experimental study of an open-cycle solar collector/regenerator using liquid desiccant for air conditioning. Int. J. Green Energy, 7: 273-288.