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Development of a Pilot Plant Solar Liquid Desiccant Air Conditioner for the Northern Region of Iran

Shahab Alizadeh*, Hamid Reza Haghgou

Department of Energy, Materials & Energy Research Centre, Karaj, Iran

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ABSTRACT

In a 10-ton capacity pilot plant solar liquid desiccant air conditioner (LDAC) developed, dehumidification of the outside air is achieved through a honeycomb packed-bed heat and mass exchanger, using lithium chloride solution as the desiccant. The dry air obtained from the dehumidification process is evaporative cooled inside a cooling pad and directed into the conditioned space. The dilute solution thus produced and is concentrated in a honeycomb packed-bed scavenger air regenerator using hot water from flat plate solar collectors. Carryover the desiccant particles has been avoided by using eliminators .

The air conditioner was installed in a 250 m^2 area of the fluid mechanics laboratory of Babol University of Technology, a hot and humid location in the north on the Caspian Sea. The obtained experimental data was compared with the predicted results of a model developed for the air conditioner based on HYSIS and CARRIER energy soft-wares. The comparison reveals that there is good agreement between the experiments and the model predictions.

The above tests further reveal that the unit has a satisfactory performance in independently controlling the air temperature and humidity of the conditioned space. The inaccuracies are well within the measuring errors of the temperature, humidity and the air and solution flow rates. An efficient heat recovery within the air conditioner resulted in a thermal COP of about 1.5 and an electrical COP of 7 .

A commercialization study reveals that the operating cost of an LDAC is significantly lower than its conventional counterpart. The costs would further reduce if a storage system was used to store the concentrated solution of liquid desiccant. A simple payback of five years was determined for the solar components of the liquid desiccant system in this study.

1. INTRODUCTION

Much work has so far been conducted in the area of solar cooling and air dehumidification using liquid desiccant and a cross-flow, packed-bed type honeycomb heat and mass exchanger, as the absorber unit as well as the regenerator [1-2]. The use of the solar liquid desiccant air dehumidification /cooling system also appears to be promising in hot and humid locations of Iran, such as the Persian Gulf and the Caspian Sea regions, due to high availability of solar energy in summer.Considerable laboratory experiments, computational analysis and design work have been carried out on a liquid desiccant system at the Sustainable Energy Centre of University of SouthAustralia [3-7] and Queensland University of Technology [8]. These involved modelling and experimental work on both cross flow and packed-bed dehumidifiers as the absorber units as well as the solar regenerator [9]. In the cross flow type, polymer plate heat exchangers (PPHE) were used as indirect evaporative cooling systems and lithium chloride was used as the liquid desiccant. In the packed-bed system, different packing materials could be considered. These include the polymer type usually used in cooling tower applications and the counter flow type with a layer of wick applied to the heat exchanger surfaces to reduce the carryover of the desiccant particles into the conditioned space as well as to increase the dehumidification efficiency of the air

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*CorrespondingAuthor’smail:Shahab_alizadeh@hotmail.com conditioning unit. In this study, however, cross-flow honeycomb packing has been used in both the absorber unit and the regenerator.

In a solar liquid desiccant system the weak desiccant can be concentrated, stored and then used in later time; therefore, energy is stored as concentrated solution in the system rather than thermal.

The system provides the options of using the solar LDAC either as a packaged roof top air conditioner for domestic or commercial use or as an air handler unit in commercial applications such as conditioning large volumes of ventilation air.

The LDAC could also be used for space heating in winter due to the property of desiccants to provide heat when it is wet and, thereby, indirectly heat the supply air.

The heating capacity is modulated within the absorber unit by temperature adjustment .

The results obtained from a previously developed LDAC demonstration system at Materials & Energy Research Centre (MERC, 2006) are now used in a solar liquid desiccant pilot plant project of about 10 refrigeration tons (35 kW) capacity.

The project aimed to build, install and operate the system in nominated site in a hot and humid region of the country.

The system, also used for heating during the winter, has been tested and monitored for a full year operation [12-13].

It is deemed such this equipment should be installed and tested on the Persian Gulf region in the South in which a high temperature and humidity occurs during most of the year.

2. DESCRIPTION OF THE SYSTEM

A schematic diagram of the air conditioning system is shown in Fig. 1. As seen from the figure, outdoor air is dehumidified and cooled and supplied to the conditioned space.

Return air from the conditioned space is humidified and heated in a heat recovery process within the air conditioner and used in the regeneration of the weak solution in the regenerator section and is finally exhausted into the atmosphere.

The heat exchangers used for heat recovery in the air conditioner are of plate types as seen in Fig. 2 Cross flow honeycomb heat and mass exchanger are used in the absorber unit, the regenerator and the cooling pad, a sample of which is shown in Fig.4 . The cooling and heating coils are of fin & tube type made of copper tubes and aluminium fins, which make the heat exchanger have high heat transfer coefficient (see Fig. 4).

A hot water package is used to produce hot water at about 80 °C to be used as the regenerator ackup when there is insufficient solar energy available

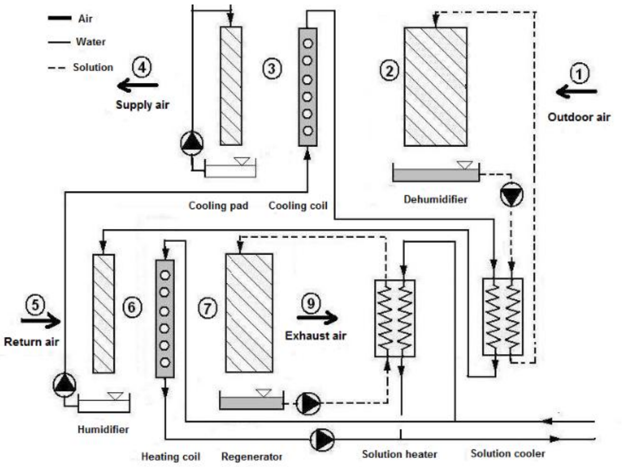

Figure 1. Schematic diagram of the 10-ton capacity liquid desiccant air conditioning system

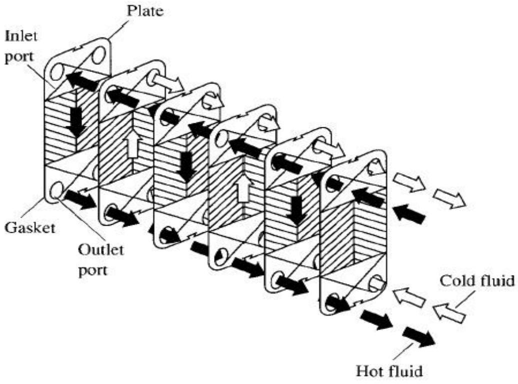

Figure 2. Schematic diagram of the plate heat exchanger used in the system

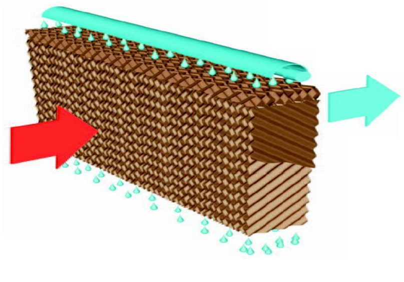

Figure 3. Honeycomb material used in the absorber unit, regenerator and the cooling pad

2-1. Governing Equations

The 3-D schematic cross flow heat and mass exchanger with the height H, width L and thickness W used in the absorber unit and the regenerator are shown in Fig. 4. An elemental section of the heat exchanger is also depicted in Fig. 5. The governing equations for the flow of air and solution in the element are the continuity and energy balance relations, which can be written as follows:

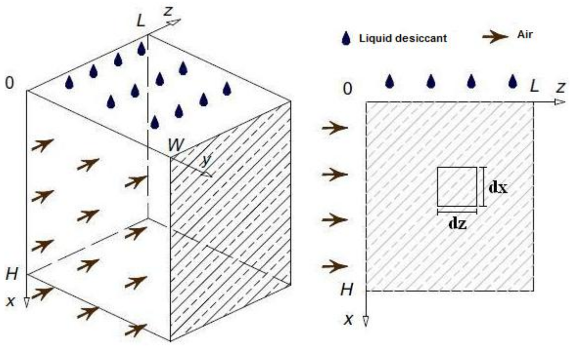

Figure 4. The cross flow heat and mass exchanger

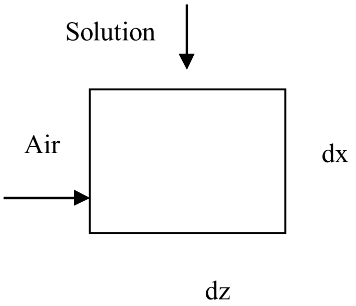

Figure 5. A differential element of the heat and mass exchanger

Energy equation,

$$\frac{\dot{m}_a}{H}.\frac{\partial h_a}{\partial z}+\frac{1}{L}.\frac{\partial(\dot{m}_s h_s)}{\partial x}=0 \qquad (1)$$

Mass balance equation,

$$\frac{\dot{m}_a}{H}.\frac{\partial w_a}{\partial z}+\frac{1}{L}.\frac{\partial \dot{m}_s}{\partial x}=0 \qquad (2)$$

Combining the heat and mass transfer equations we obtain,

$$\dot{m}_a\frac{\partial h_a}{\partial z}=\frac{\alpha A}{L}(T_s-T_a)+r_{ts}\,\dot{m}_a\frac{\partial w_a}{\partial z} \qquad (3)$$

$$\dot{m}_a\frac{\partial w_a}{\partial z}=\frac{\alpha_m A}{L}(w_e-w_a) \qquad (4)$$

Combining the above two equations we obtain the following relations,

$$\frac{\partial h_a}{\partial z}=-\frac{NTU.Le}{L}.\left[(h_a-h_c)+(\frac{1}{Le}-1)\,.\,(w_a-w_e)\,.\,r_{ts}\right] \qquad (5)$$

$$\frac{\partial w_a}{\partial z}=-\frac{NTU}{L}.(w_e-w_a) \qquad (6)$$

In the above equations h_e and w_e represent the enthalpy and humidity ratio of the air in equilibrium with the solution. In Equations (5) and (6) Le, the Lewis number and NTU, number of transfer units, are defined as follows,

$$Le=\frac{\alpha}{\alpha_m\,C_{p,m}} \qquad (7)$$

$$NTU=\frac{\alpha_m.A}{\dot{m}_a} \qquad (8)$$

In which $C_{p,m}$ is the specific heat of the air and α and α_m are the heat and mass transfer coefficients, respectively.

3. TESTING THE CONDITIONER PROTOTYPE

In the experimental tests carried out on the developed solar LDAC, dehumidification and cooling are both achieved within the absorber unit by using liquid desiccant and the cool air from the conditioned space, respectively. A photograph of the installed absorber unit showing the system main components is demonstrated in Fig. 6. The conditioner casing is made of an insulating material to protect the system from heat transfer with the environment. As it can be observed from Fig. 6, the packing material is incorporated inside and in front of the dehumidification duct with the weak solution plastic container at the bottom. The cooling coil Fig.7 and the cooling pad are located next to the packing material in the duct, and are used to cool and humidify the dry air and a fan directs the supply air into the conditioned space. The conditioner prototype was optimized for the air and solution flow rates, reducing electrical power consumed by the unit [8].

Figure 6. Photograph of the solar LDAC absorber unit as viewed on the site

Preliminary tests have been carried out on the system with water to ensure a smooth operation of the unit. These involved running the air conditioner at variable fan speeds by reducing the applied voltage from 220 to 110 V. The air velocity on the entrance and exhaust sides of the conditioner and on a face area of approximately 0.4 m^2 was measured. The power consumed by the fan during the system operation was also measured and recorded.

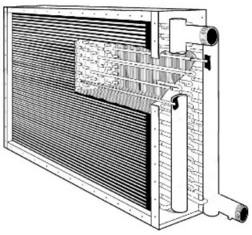

Figure 7. Fin & tube type heating and cooling coil used in the air conditioner

The fluid mechanics laboratory where the system is installed and operated has an area of 250 m^2 with a peak cooling load of approximately 20 kW for Babol summer design conditions. Thermocouples and humidity sensors were used to monitor the air dry bulb temperature and relative humidity inside the building and at the inlet and outlet of the unit on both the supply and return sides. The thermocouples were calibrated against a digital platinum resistance thermometer. The accuracy of the measured temperatures and relative humidity is estimated to be within $\pm 0.5\ ^{\circ}C$ and 1%, respectively. Temperature and humidity signals were collected from the thermocouples and humidity sensors using digital temperature and relative humidity meters. To find out the effect of variable air and solution flow rates on the system performance, a transformer was used to change the speed of the fans and solution pump by changing the applied voltage. A control panel inside the building was used to monitor and display the unit operation via appropriate signals and indicators.

Two sets of experiments were carried out with liquid desiccant. In the first set of the experiments, the absorber unit was tested with desiccant only delivered onto the packing material, while the cooling coil and the pad were inactivated. The experiments were aimed to investigate the air temperature rise due to condensation of the air moisture content, and reduction in the air relative humidity.

In the second set, the system was operated with the cooling coil and the cooling pad activated, while lithium chloride solution was delivered onto the honeycomb packing using a distributing tray. The test was to investigate the effect of dehumidification and direct evaporating cooling on the supply air temperature and humidity. The process of dehumidification / cooling of the outside air for this experiment have been shown on the psychrometric chart in Fig. 8.

Following each set of experiments with liquid desiccant, the concentration of the dilute solution was measured, using a conductivity meter. A plot of conductivity-concentration was then produced for diluted samples and for several conductivity measurements as shown in Fig. 9.

The plot was used to determine subsequent values of concentration for new desiccant solutions using a correction factor to be accounted for higher concentration values. The weak solution obtained from the dehumidification process in the above experiments was regenerated in a honeycomb packed-bed solar regenerator. This will be described in section 5.

Experimental values of the indoor, outdoor and the supply air temperature and humidity as well as the solution concentration as a function of time are shown in Fig. 10 to 17.

The effect of air flow rate on the dehumidification process of the outdoor air is depicted in Fig. 18. The air temperature and relative humidity on this figure are denoted by T_{bp} and H_{bp}, respectively, which are the air conditions before entering the packed-bed. As seen from the figure a substantial reduction in the air relative humidity is achieved after it passes through the packed-bed, which is due to contact with the desiccant solution delivered over the packing material. Following the dehumidification process, values of the air temperature and relative humidity in Fig. 18, are denoted as T_{ap} and H_{ap}, respectively.

In Fig. 19 and 20 comparisons are made between the experimental results for the supply air temperature and humidity and the predicted values from the developed model.

As can be seen from these figures good agreement exists between the model and the experimental results.

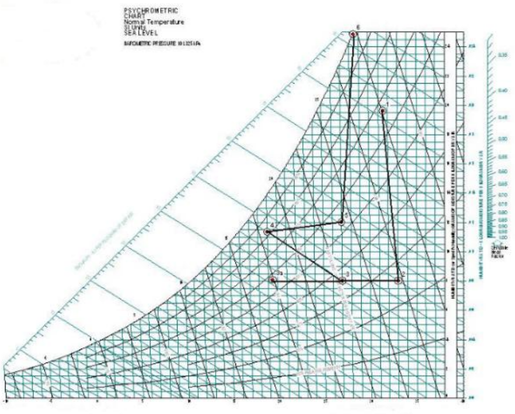

Figure 8. Psychrometric paths for the tests with liquid desiccant

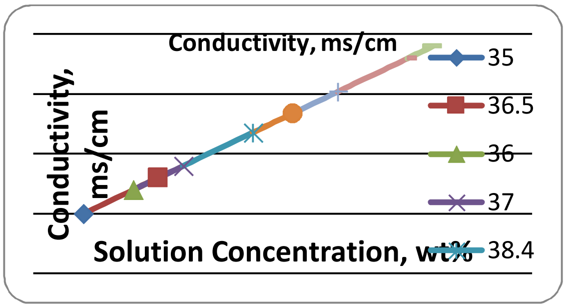

Figure 9. Conductivity-concentration chart for the lithium chloride solution

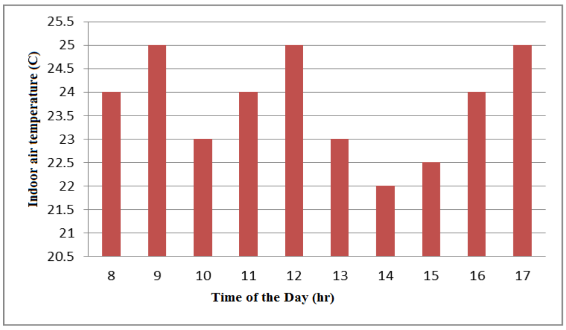

Figure 10. Average indoor air temperature measured at different hours of the day

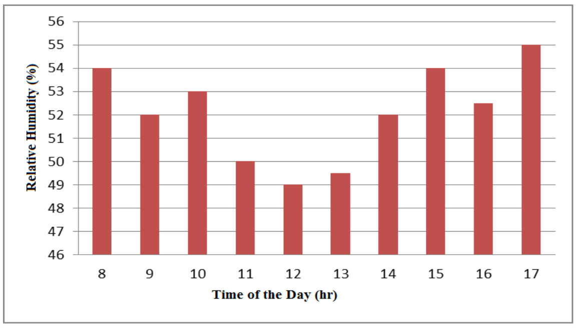

Figure 11. Average indoor air relative humidity measured at different hours of the day

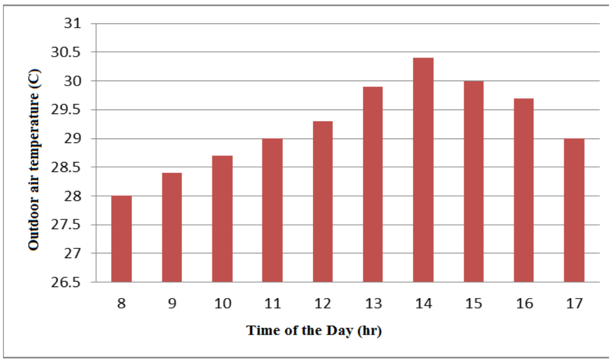

Figure 12. Average outdoor air temperature measured at different hours of the day

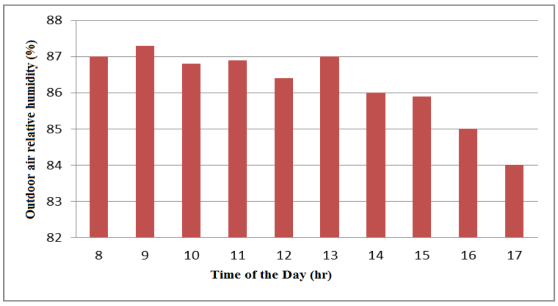

Figure 13. Average outdoor air relative humidity measured at different hours of the day

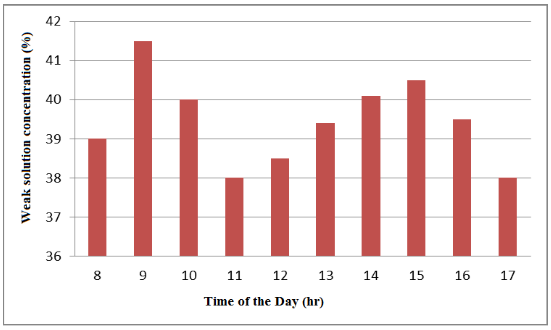

Figure 14. Weak solution concentration measured at different hours of the day

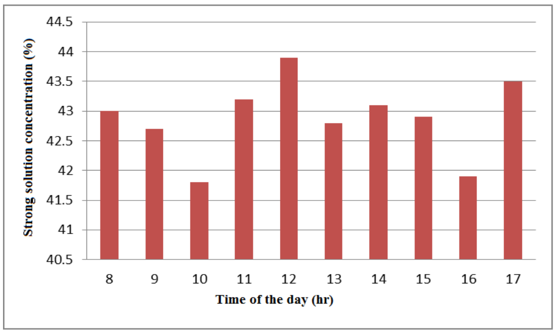

Figure 15. Strong solution concentration measured at different hours of the day

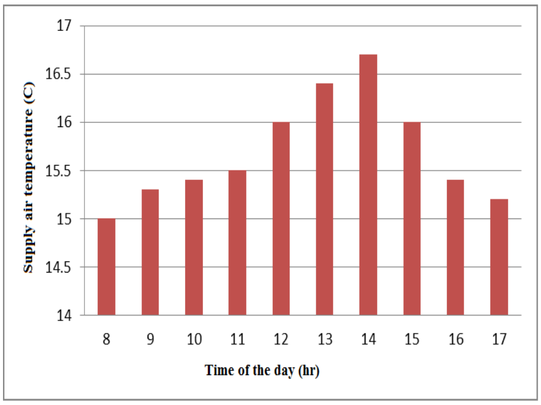

Figure 16. Supply air temperature measured at different hours of the day

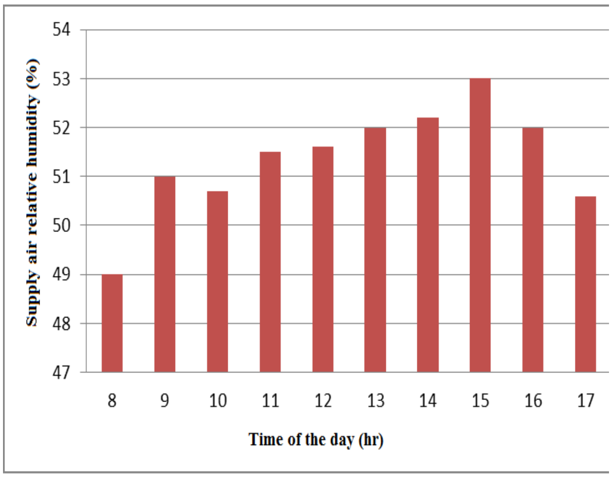

Figure 17. Supply air relative humidity measured at different hours of the day

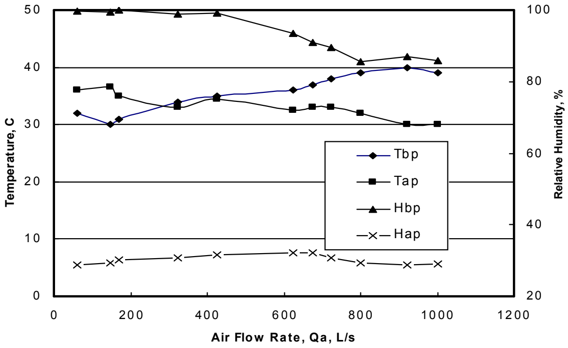

Figure 18. The effect of air flow rate on dehumidification process of the outside air

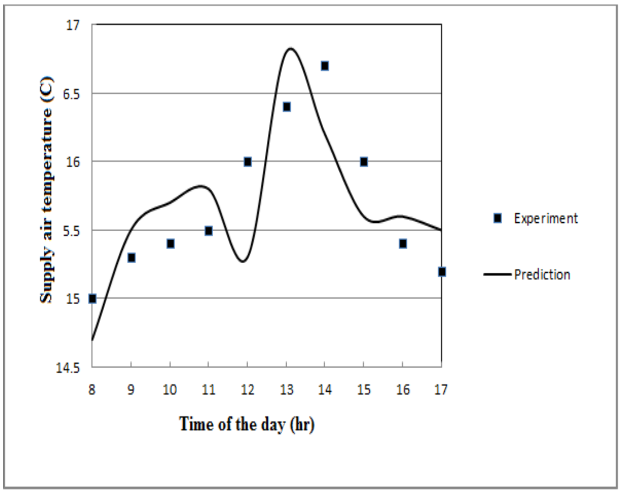

Figure 19. Experimental and predicted supply air temperature vs. time

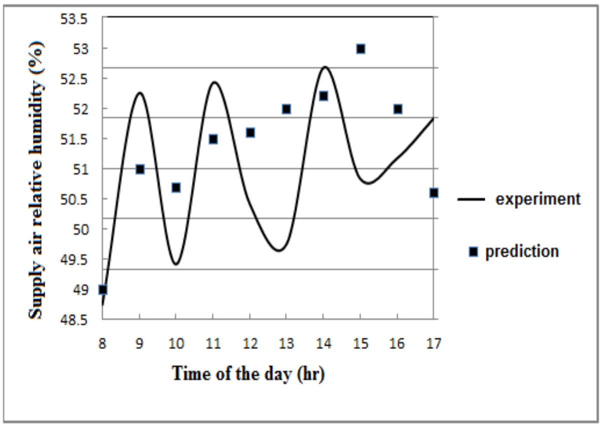

Figure 20. Experimental and predicted supply air

4. DISCUSION OF THE TEST RESULTS

The results from the tests with evaporative cooler and desiccant prove a satisfactory performance of the unit in a tightly control of the air temperature and humidity and maintaining the building air conditions within the comfort zone (dry bulb temperature of about 25 °C and 50% relative humidity).

It can be shown that there are optimum values of air and solution flow rates, where the conditioner performance is enhanced [8].

In a system which uses return air from the conditioned space, it has been shown that by increasing the ratio of the return to supply air, the unit performance is also This is due to the increase of cooling air flow rate through the system, which can be used in a heat recovery process to simultaneously cool the supply air as well as the desiccant solution.

To quantify the confidence level of the experimental data, the results of an uncertainty analysis are presented in Table 3.1 for the experimental values obtained from testing the conditioner prototype. In this analysis, the fixed errors are assumed to be calculated and accounted for via calibration against known standards.

Hence, the remaining error is solely due to the precision error.

The precision errors were determined by statistical means or from data provided by equipment manufacturers or by the best estimate based on experimental observations.

Since the prototype testing of the absorber unit was under many uncontrolled environmental conditions, the results are quite acceptable.

Table 3.1. Experimental results obtained from the air-conditioner testing and the uncertainty values

Conditioner performance parameters	Measured values	Precision errors	Uncertainty values %
Supply and return air flow rates, L/s	1000	100	10
Supply air temperature °C	15.2	1	6.7
Supply air humidity ratio, kg/kg	0.0094	0.0005	5.3
Return air temperature, °C	22	1	4.5
Return air relative humidity, %	95	4	4.2
Solution flow rate, L/min	3	0.2	6.8
Exit solution concentration	0.412	0.008	2
Total cooling, kW	35	0.7	2
Maximum electrical energy used, kW	5	0.1	5.3
Electrical COP	7	0.2	2.8

5. PERFORMANCE OF THE SOLAR REGENERATOR

The regeneration of the dilute solution in this study is carried out in a honeycomb packed-bed regenerator, using hot water from flat plate solar collectors (see Fig. 21). A fan is used to blow the air over the solution through the regenerator and the hot and humid air is finally exhausted into the environment. Both the air and the weak solution are preheated in the regenerator; however, solution regeneration will be more effective when preheating the air than preheating the solution [9]. It is notable that the lithium chloride desiccant can be concentrated using waste heat or solar energy at temperatures as low as 40 °C, however the flat plate solar collector used in this study can produce hot water at 90 °C or more in summer.

Honeycomb is used as the packing material to increase the contact area between the solution and the air, which facilitates the regeneration process. A stream of outside air is passed through the packing material, using a fan, in a counter current operation to pick up the water evaporated from the solution, and the hot moist air is, subsequently, exhausted from regenerator into the environment. A mist eliminator can be used at the outlet of the regenerator to prevent the carryover of the desiccant particles. Alternatively, liquid-to-air membrane energy exchangers (LAMEEs) are used for humid air dehumidification and dilute desiccant solution regeneration [11]. The corrosion problem of traditional liquid desiccants hinders the development of solar liquid desiccant air conditioning system. Ionic liquids (ILs) could be possible substitutes because of their low corrosion in metals [14]. As a back up for the regenerator during the peak cooling hours we could use gas or electricity.

Fig. 19 demonstrates the assembled pilot plant system which shows the absorber unit and the regenerator on the left end and middle, respectively, as well as the solar collectors in the front view of the figure. The system on the right end of the photograph is an auxiliary hot water system that can be automatically activated once the collectors fail to produce the required hot water temperature.

Eliminators, such as demister, are used to avoid carryover of desiccant into the environment. Alternative method in preventing the carryover is the use of indirect cooling, in which the supply air does not contact the desiccant [10]. The latter could also be used to produce potable water from the atmospheric air in remote areas when a cross flow polymer plate heat exchanger (PPHE) is used. The water can either be used for human consumption or returned to the conditioner for evaporative cooling of the air. A payback of approximately 5 years could be determined for solar components of the system in their study.

A cost analysis [13] performed in this study indicates a total first cost for the 10-ton system to be around $20,000. The operating cost using a storage system is about $1500 per year. This reveals an annual saving of about $4000 per year when compared with a conventional vapour compression air conditioner. A pay back ofapproximately 5 years could be deemed for the solar LDAC in this study.

Figure 21. Flat plate solar collectors used for heating and regeneration of dilute liquid desiccant

6. CONCLUSION

In this paper the performance of a 10-ton capacity pilot plant solar LDAC developed using honeycomb cross flow packed-bed heat and mass exchanger for air dehumidification as well as the solution regeneration. It was found that the solar liquid desiccant system is an efficient and cost effective alternative to the conventional air conditioner. Elimination of carryover of the desiccant particles within the absorber unit in this study was performed through the cooling pad used as the filter as well as the direct evaporative cooler of the supply air.

Experimental results obtained from prototype testing of the solar LDAC absorber and regenerator units indicate that the system has a satisfactory performance in controlling the temperature and humidity when installed on a 250 m^2 area located in a hot and humid area on the Caspian Sea. The tests further reveal that the experiments are in good agreement with the prediction results obtained from a model developed using HYSIS and CARRIER. The maximum electrical energy utilization of the unit, which was determined through the above experiments, is 5 kW with a thermal and electrical COP of 1.5 and 7, respectively.

7. Acknowledgement

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