



EXPERIMENTAL STUDY OF HYBRID LIQUID DESICCANT BASED VAPOR COMPRESSION COOLING SYSTEM

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ABSTRACT

In the kingdom of Saudi Arabia, a vast amount of energy is used for air-conditioning and this paper describes a new approach to air conditioning. In the proposed hybrid cooling system, liquid desiccant is used to remove the latent load and the conventional vapor-compression system is used to provide sensible cooling only. In this experimental study, calcium chloride solution is used as the desiccant to dehumidify the air. Gauze-type structured packing towers are used for the dehumidification of air and also for regeneration of the weak desiccant. The designed packed bed dehumidifier and the regenerator are combined with a 5-ton capacity vapor compression system along with the heat recovery units. This paper presents results from a detailed experimental investigation of the heat and mass transfer in a structured packing dehumidifier and regenerator under a variety of operating conditions. In the present study, for the sake of comparison between hybrid and conventional cooling systems, the COP for the cooling system is defined as the heat removed from the space to be cooled divided by energy input for the cooling system. Three different modes of regeneration are considered for the hybrid cooling system and the COP values are compared with conventional vapor compression system. Results show that the ratio of the outlet-to-inlet absolute humidity reaches a steady state value of about 0.6 and the temperature of air decreased from 48 to 38° C in the dehumidifier of the hybrid system. Moreover, it is found that hybrid cooling system provides higher COP compared with conventional system.

Keywords: air-conditioning, dehumidification, liquid desiccant, regeneration, vapor-compression

1. INTRODUCTION

The summer climate of the Eastern and Western Provinces of Saudi Arabia is hot and humid. Air conditioning is required to control simultaneously the temperature, humidity, motion, and purity of air. In the Kingdom of Saudi Arabia, a vast amount of energy is used for air conditioning of buildings. Over the last several years the use of energy for air conditioning has risen and it will continue to rise in the future. The annual Saudi consumption of air conditioners is estimated at 600,000 - 700,000 units. By consuming this amount, air conditioning requires about 65% of total electricity consumed in the Kingdom of Saudi Arabia [Ahmad and Elhadidy 2002]. Hence, a new approach to air conditioning is required due to growing concern for conservation of energy, improved comfort and environmental control, and increased ventilation requirements. For the country like Saudi Arabia, heating can easily be provided with conventional heaters since they may be needed only for 2 to 3 months.

In humid climates the air conditioning load is principally one of dehumidification, which is an energy intensive process. Traditional vapor compression type air conditioners are used to cool and dehumidify the air. The air is passed through the cooling coil, where the dry bulb temperature of the moist air decreases, while the moisture content remains constant. The dry bulb temperature continues to decrease as moisture begins to condense out of the air onto the cooling coil, resulting in a simultaneous decrease in the moisture content. For a typical humidity ratio of 0.007, this occurs at 9°C, which is usually below the desired temperature. Therefore, the air has to be reheated to a comfortable temperature before it is introduced into the conditioned space in order to avoid excessive sensible cooling. Although this is generally done by using free waste heat or by mixing with return air, the cooling process itself requires more energy. Hence, the evaporator in the vapor compression system operates at a lower temperature than what is required to meet the sensible cooling load, resulting in a lower coefficient of performance. Although dehumidification is quite effective at high temperatures, it become more difficult at lower temperatures since the condensed moisture would freeze on the cooling coil. Furthermore, energy efficient vapor compression systems designed to operate at higher evaporator temperatures, have been found unable to maintain the indoor relative humidity within a comfortable range in hot and humid climates [Marsala et al., 1989]. This paper describes the development of a new technique to be combined with the existing air conditioning system.

2. HYBRID AIR CONDITIONING SYSTEMS

Recently a number of hybrid air conditioning systems have been suggested and some are being actively studied. In the hybrid cooling system, desiccants are used to remove latent cooling load and conventional air conditioners are used to provide sensible cooling. Desiccant technology has excellent potential for cost-effective application in buildings located in hot, humid climates to make major contributions to energy conservation, improve indoor air quality through reduced microbial growth and by removing air pollutants [Kovak et al., 1997]. A detailed review of desiccant cooling systems and the possible combination of desiccant

dehumidification with conventional air conditioning systems has been presented by Waugaman et al.[1993] Advances in heat-activated cooling systems, namely desiccant cooling systems, are described by Worek et al.[1996]. Two types of desiccants namely solids and liquids can be used for dehumidification of air and two types of conventional air conditioners namely vapor-absorption and vapor-compression units can be used for sensible cooling. Hence, hybrid air conditioning systems can be classified as follows:

1. Hybrid vapor-absorption/solid desiccant air conditioning system.
2. Hybrid vapor-absorption/liquid desiccant air conditioning system.
3. Hybrid vapor-compression/solid desiccant air conditioning system.
4. Hybrid vapor-compression/liquid desiccant air conditioning system.

Desiccant systems have major advantages. They offer significant potential for energy savings and reduced consumption of fossil fuels. The electrical energy consumption is small. With desiccant systems the use of CFCs is eliminated if used in conjunction with vapor absorption units or reduced if integrated with vapor compression units. It is to be noted that CFCs contribute to depletion of earth's ozone layer. Indoor air quality is improved because of higher ventilation and fresh air rates associated with desiccant systems. Such systems also offer lower humidity levels and the capability to remove airborne pollutants. With desiccant systems, air humidity and temperature are controlled separately, enabling better control of humidity. Recently Dai et al. [2001] reported that a hybrid air conditioning system, which combines the desiccant dehumidification, evaporative cooling and vapor compression air conditioning, might have more cooling production than the conventional vapor compression system alone by 20 to 30%. However, the type of packing material and the type of desiccant used for experimentation are not given. It is worth mentioning that, to the best of the authors' knowledge, a hybrid cooling system using liquid desiccant, namely calcium chloride solution, with gauze-type structured packing dehumidifier and regenerator was not reported in the literature and that this experimental study is the first one on such system.

Different types of dehumidifiers are available for solid desiccants and the regeneration temperature required for such systems is about 70 - 80°C. Solid desiccant systems can operate at relatively low regeneration temperatures, but require large volumes of desiccant and also entail significant operating costs for the parasitic systems of blowers required. Further as time progresses, efficiency of the desiccant bed can be reduced due to dust and foreign matter deposited in the pores. To avoid this, additional air filtering can be added but only at the cost of additional air pressure drop through the system. Air dehumidification with liquid desiccants has some significant advantages. The regeneration temperature required for liquid desiccants is lower than solid desiccants. An interesting feature of the liquid desiccant system is that part of weak desiccant can be over concentrated and then mixed with remaining liquid. Another advantage of using liquid desiccants is that they can be used as a heat transfer medium in a heat exchanger. Hence the desiccant can be pre-cooled or pre-heated when required. The ability to pump the liquid makes it possible to connect several small

dehumidifiers to one large regeneration unit [Harriman, 1990]. Also, dehumidifying with a liquid desiccant usually scrubs the air stream, not only providing conditioning but also cleaning and disinfecting the air. Further, the energy is stored as chemical energy rather than thermal energy. The energy storage capacity in liquid desiccants such as lithium chloride or calcium chloride is up to 3.5 times higher compared to solid desiccants such as zeolites or silicagel related to the same dehumidification process [Kessling et al., 1998]. The pressure drop through a liquid desiccant system is smaller than the pressure drop through a solid desiccant wheel [Howell, 1987]. These reasons make liquid desiccant dehumidification system more attractive.

Sensible cooling can be provided with either vapor-absorption or vapor-compression system. The vapor absorption system operates on thermal energy, a comparatively much cheaper form of energy as compared to the energy required for the operation of the vapor compression system. However, vapor-absorption system is not familiar in the Kingdom of Saudi Arabia and further, the COP of the vapor-absorption system is much lower than the vapor compression system. Hybrid vapor-compression/liquid desiccant air conditioning systems are promising because they take advantage of the high efficiency for heat transfer inherent in vapor-compression systems and the high mass transfer potential of the liquid desiccants. Hence a hybrid vapor-compression/liquid desiccant air conditioning system is chosen. This research attempts to combine the moisture removal capabilities of liquid desiccants and sensible cooling capabilities of traditional vapor-compression air conditioning system in such a way that each process complements and enhances the other. The dehumidification is no longer dependent on the limits of the vapor-compression unit. Further the initial cost of the conventional air conditioner is reduced by desiccant technology because of downsized compressors and the system operating cost will be reduced.

3. HYBRID COOLING CYCLE

The hybrid liquid desiccant cooling system combines a structured packing liquid desiccant dehumidifier with a vapor compression unit. The system utilizes the desiccant to meet the latent load and a vapor compression unit to handle the sensible load. The schematic of the cooling system is shown in Fig. 1. The system consists of a conventional vapor compression unit, an auxiliary heater, a packed bed regenerator, a packed bed dehumidifier, pumps for the desiccant, two blowers, the ducts, and two heat exchangers.

The hybrid liquid desiccant-based vapor compression cooling system is designed to provide cooling for a building of 5-ton cooling capacity. The assumed ambient conditions are 40° C and 0.028 kg of water per kg of dry air (relative humidity of 59%). The indoor design conditions of the conditioned space are 23° C and 0.0088 kg of water per kg of dry air (relative humidity of 50%). The mixture of return air from the building (state '1') and fresh air from the ambient (state '11') enters the dehumidifier at '2' as shown in Fig. 2. After the dehumidification process, the warm, dry air is not suitable for comfort conditions. Hence, after removing the latent-cooling load in the dehumidifier, the dried air at state '3' is passed

over the evaporator coil in the conventional vapor-compression unit. The air is sensibly cooled to state '4' and the conditioned air is then delivered to the building.

Structured packing towers are used in the cooling system for dehumidification of air and the regeneration of weak desiccants. The weak desiccant from the dehumidifier is pumped through a desiccant-to-desiccant heat exchanger and sprayed in the regenerator. To regenerate the weak desiccant, the waste condenser heat is used to preheat the ambient air and an auxiliary heater provides further heating. The regenerative air stream is humidified as it passes through the regenerator and then exhausted to the ambient.

4. EXPERIMENTAL APPARATUS

The dehumidification system is made up of a counter-flow packed bed dehumidification tower, a circulation pump, a strong desiccant tank, a weak desiccant tank, and a main blower. Polyethylene tanks with a capacity of about 60 gallons were used as strong and weak desiccant containers. The tower made of fiberglass was selected because of advantages in this material including light weight, ability to withstand chemicals without reacting with them, non-corrosive nature, and can be easily shaped. The tower is 2.6 m high, 50 cm in diameter and 0.5 cm thick. The tower is filled with 50cm diameter gauze-type BXPFP structured packing of height 34 cm between two stainless steel wire supports. Above the packing material section, a PVC distributor with about 30 of 3mm orifices is placed in the dehumidifier. The strong desiccant is sprayed in a counter-flow direction and is brought in contact with air stream through packing material. It is covered with a removable top cover to allow for changing the packing material and for any maintenance required for the column and the pipes inside. It is air and desiccant leak free and the bottom part of the dehumidifier is used as an additional storage tank for the weak desiccant. The dehumidifier is also equipped with two view windows. An upper one to check the desiccant nozzles and a lower one to check the level of the weak desiccant in the tank. A mist eliminator is used to minimize the liquid entrainment before exiting the dehumidifier.

Next, this solution is sent to the structured packing regenerator through a heat exchanger. The regeneration system is made up of a counter-flow packed bed regeneration tower similar to dehumidifier, a circulation pump, a strong desiccant tank, a weak desiccant tank, and a main blower in conjunction with a 10 kW electric heater to regulate the air inlet temperature. The condenser waste heat is used to heat the air for regeneration of weak desiccants in the regenerator and auxiliary heat is also supplied by an electric heater to increase the air temperature for maintaining a high regeneration rate. The tower is filled with two elements of stainless steel (AISI 316L) 50cm diameter gauze-type BX structured packing between two stainless steel wire supports. The height per element is 17 cm. Above the packing material section, a PVC distributor with about 30 of 3mm orifices is placed in the regenerator. The weak desiccant is sprayed in a counter-flow direction and is brought in contact with hot air stream through packing material. The bottom part of the regenerator is used as an additional

storage tank for the weak desiccant. The hot solution exiting the regenerator is cooled in the heat exchanger by exchanging heat with the solution from the dehumidifier. After passing through the heat exchanger, the warm solution is further cooled by the coil-type heat exchanger.

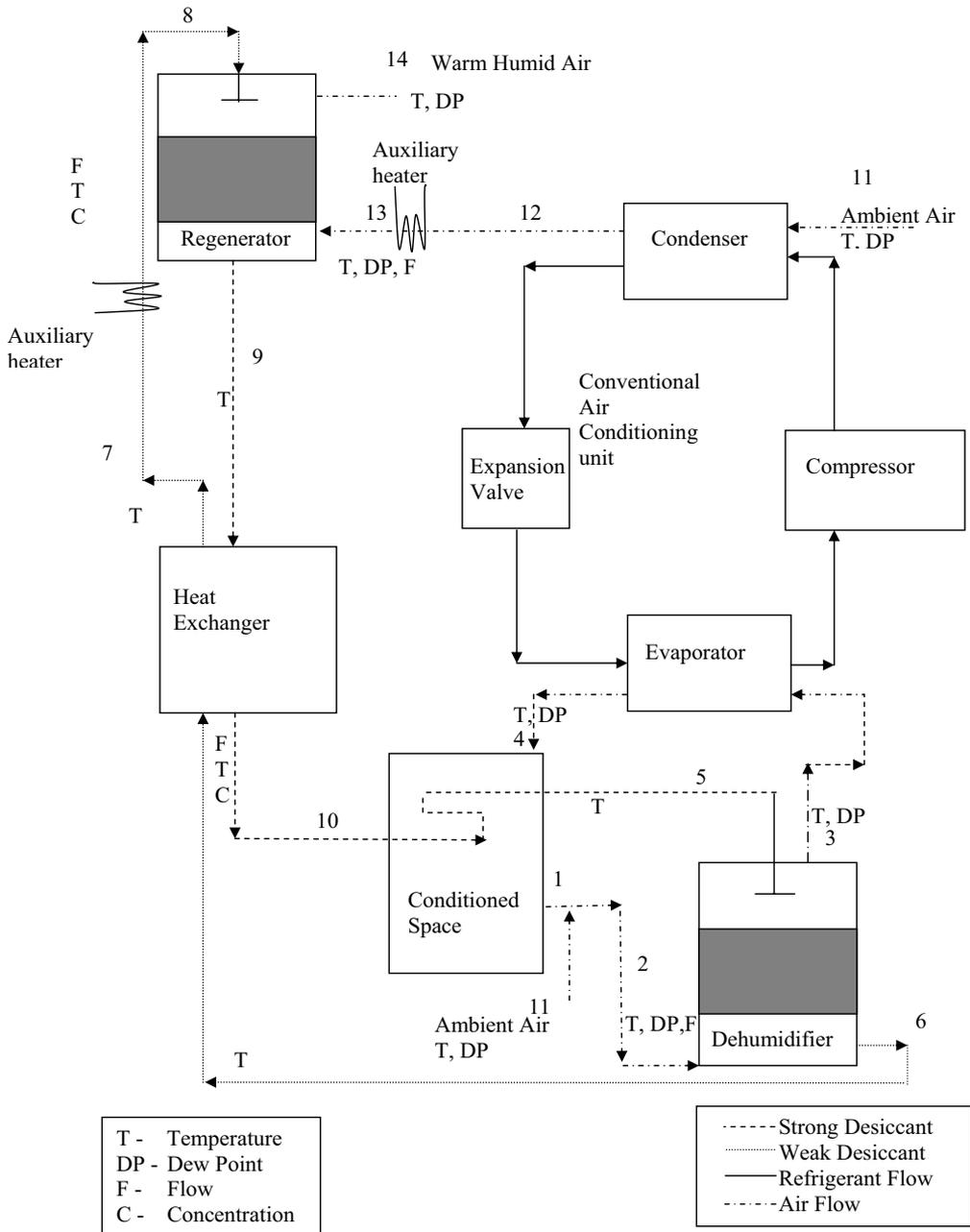


Fig. 1: Experimental Set-up for Hybrid Cooling System

Calcium chloride solution is used as the liquid desiccant. Close to the end of each run, a sample of desiccant is taken at the dehumidifier and regenerator outlet for desiccant concentration determination. The desiccant concentration is determined from specific gravity measurements by a hydrometer having an accuracy of ± 0.02 , which corresponds to the concentration difference of $\pm 0.1\%$ and the temperature with K-type thermocouples connected to digital display having an accuracy of $\pm 0.1^\circ\text{C}$. The relative humidity is measured with “VelociCalc” having an accuracy of $\pm 0.1\%$ to obtain absolute humidity and the same device is used to measure flow rate of air as well as the temperature of air. Liquid flow rate is measured by an axial flow meter connected to a flow rate monitor having an accuracy of ± 0.1 l/min. More detailed information about the experimental set-up is given [Al-Farayedhi et al., 2000].

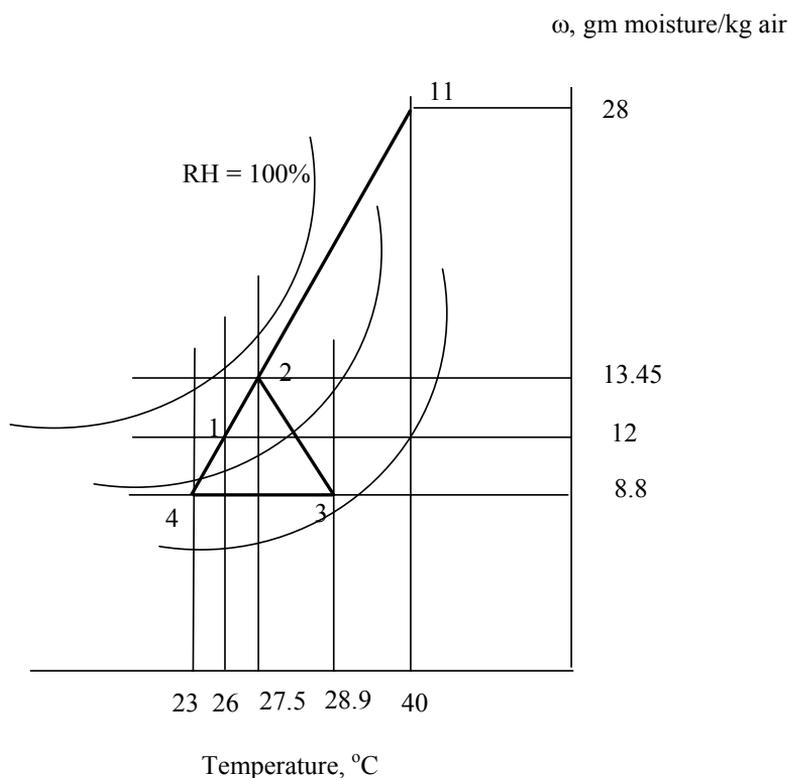


Fig. 2: Proposed system Processes on the psychrometric chart (not to scale)

5. RESULTS AND DISCUSSION

A set of experiments is conducted using the above-mentioned set-up to investigate the performance of the hybrid cooling system. From the trail experiments conducted for high humid conditions of the air entering the dehumidifier, it is found that the optimum desiccant

flow rate for the dehumidifier is 14 l/min and for the regenerator is 13.3 l/min. Hence experiments are conducted for these optimum flow rates for the hybrid system. A humidifier is used to obtain the inlet conditions of the air before entering the dehumidifier at about 47 to 48° C with humidity ratio of 0.048 kg of water per kg of dry air. The weak desiccant from the dehumidifier is passed through a heat exchanger before it enters the regenerator. The condenser waste heat is used to preheat the regeneration air and an electrical heater is used for increasing the air temperature to 70° C. The hot air entering the regenerator is relatively dry with the absolute humidity of 0.015 kg of water per kg of dry air. The experimental results are shown in Figs.3 to 6.

Figure 3 shows the time variation of concentration and desiccant temperature in the dehumidifier for the hybrid system. Since the desiccant absorbs water vapor from the air its concentration decreases significantly at the beginning but after approximately 20 minutes it reaches a steady state condition at 43 % since the regeneration process effectively maintains the desiccant concentration, which indicates that the regeneration process is effective. Using the two heat exchangers, the desiccant inlet temperature is maintained at 36 to 38° C as shown in the figure. Figure 4 shows the time variation of air outlet temperature and its relative humidity from the dehumidifier. The air outlet temperature reaches a temperature of 38° C because of the high desiccant inlet temperature and the air outlet relative humidity is about 30% while it enters the dehumidifier with a value of 65 %.

Figure 5 shows the time variation of outlet absolute humidity of air and the ratio of absolute humidity of air in the dehumidifier for the hybrid system. It is to be noted that the air entering the dehumidifier is very humid and the air absolute humidity at the outlet approaches a steady state value of 0.028. Since at the beginning of the experiments the desiccant concentration is high (about 45%), the air is dehumidified rapidly and then the outlet absolute humidity of air is almost constant since the inlet desiccant concentration is constant at 43%. The results indicate that the dehumidifier is performing well with the regenerator in the hybrid system.

The weak desiccant from the dehumidifier is reconcentrated simultaneously in the regenerator after being preheated in desiccant-to-desiccant heat exchanger. The time variation of inlet and outlet desiccant concentrations in the regenerator is shown in Fig. 6 for the hybrid cooling system. It can be seen from the figure that the desiccant concentration before entering the regenerator is maintained at a steady state value of about 42.5% and it is regenerated simultaneously to 43%.

5.1 Coefficient of performance (COP)

It is to be pointed out that the definition of coefficient of performance (COP) reported for desiccant cooling system varies among the researchers. For example, some authors defined a daily COP as amount of cooling supplied by the system divided by the solar energy incident on the solar collectors, so that the COP includes the collector efficiency. However, some also defined their COP, as the amount of cooling divided by the amount of heat supplied to the regenerator, that is, the COP is independent of the heat source.

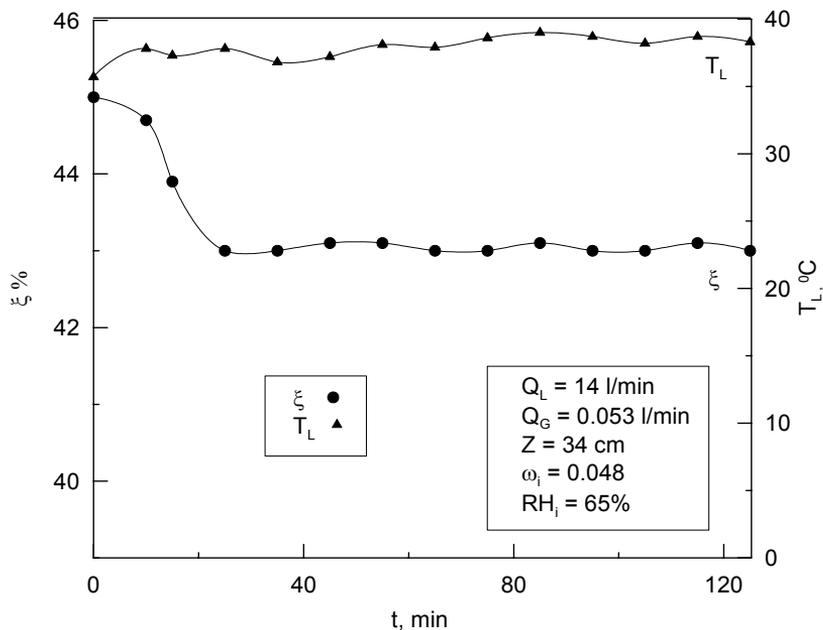


Figure 3: Variation of concentration and desiccant temperature with time for 14 l/min desiccant flow rate in the dehumidifier.

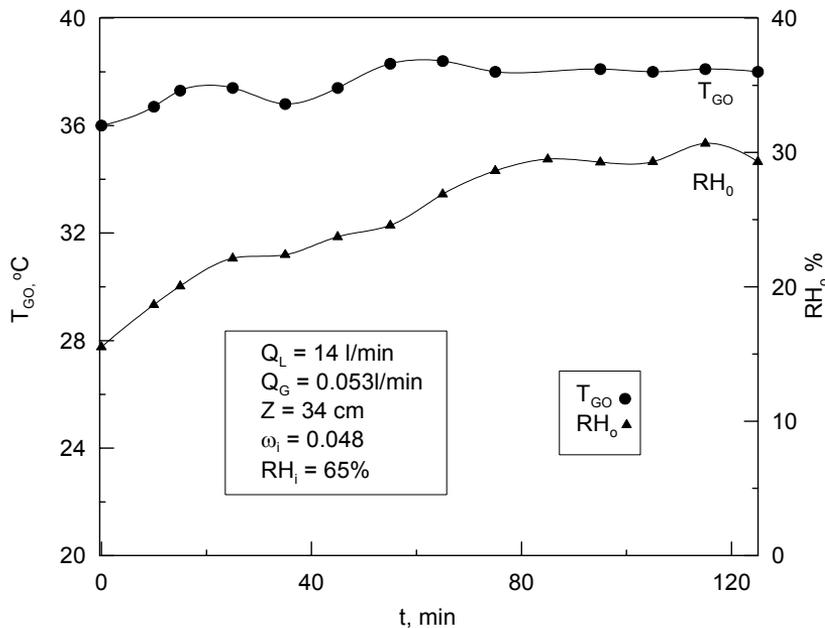


Figure 4: Variation of outlet air temperature and humidity with time for 14 l/min desiccant flow rate in the dehumidifier.

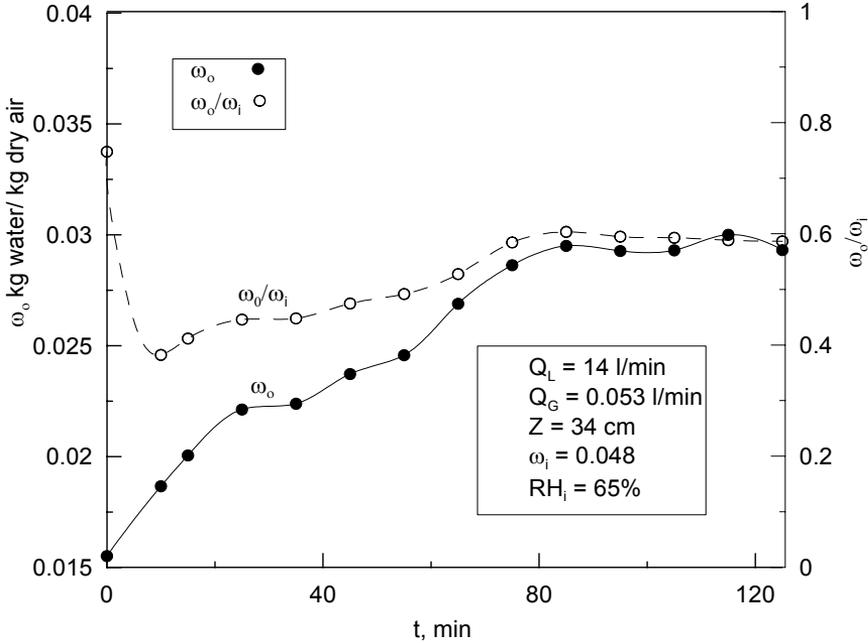


Figure 5: Variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity with time for $Q_L=14$ l/min in the dehumidifier.

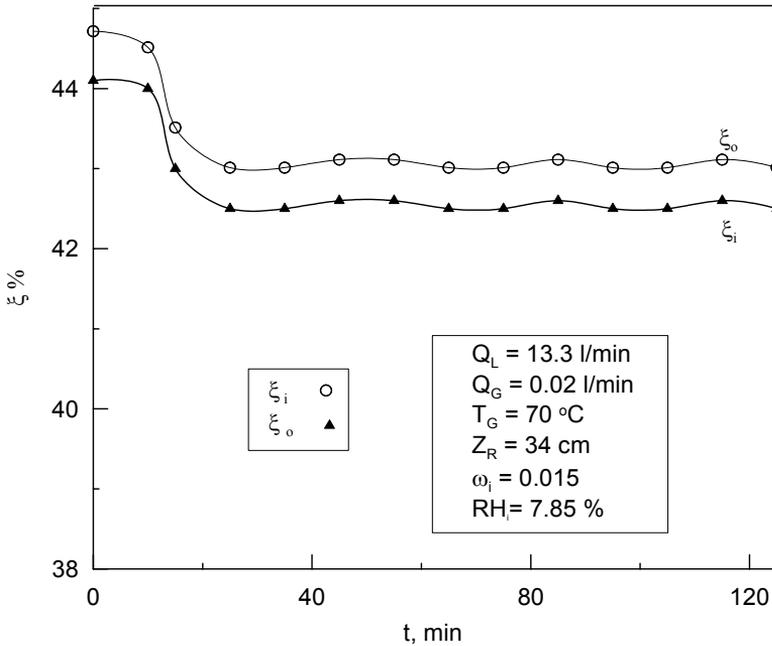


Figure 6: Variation of inlet and outlet concentration with time for $Q_L=13.3$ l/min, $T_G=70^\circ\text{C}$ in the regenerator.

In the present study, for the sake of comparison between hybrid and conventional cooling systems, the COP is defined as the heat removed from the space to be cooled divided by energy input for the cooling system. Energy input includes electrical energy used to circulate air, water, and desiccant, the auxiliary energy used for regeneration and the energy used to operate the conventional vapor compression unit. On this basis, the COP is defined as,

$$COP = \frac{\text{heat removed by the system from the space}}{\text{power input to the system}} \quad (1)$$

With reference to Fig. 2, the total heat removed from the space to be cooled is given by,

$$\text{Total heat removed from the space to be cooled} = m_4(h_1 - h_4) \quad (2)$$

Three different modes of regeneration are considered for the hybrid cooling system. For these three modes of operation, an extensive energy analysis has been carried out along with the conventional vapor compression cooling system [Al-Farayedhi et al., 2000] and the COP is calculated. The results are given in Table 1. It is to be noted that these values are the maximum COP values and in actual practice, it is expected that the COP will be less than the maximum value. The uncertainty is estimated in the calculated results on the basis of the uncertainty in the primary data. The accuracy of the direct measurements is reported. The uncertainty and error analysis for the dependent variables such as effectiveness and the ratio of outlet-to-inlet humidity ratio are estimated. It is found that the maximum percentage of uncertainty in calculating the effectiveness of the dehumidifier and the regenerator is 0.082. The maximum percentage of uncertainty in calculating the ratio of outlet-to-inlet humidity ratio is 3.76.

Table 1
COP for the cooling system

Cooling system /Mode of regeneration	Total power input, kW	COP
Hybrid system - Heating the desiccant	11.24	1.164
Hybrid system - Heating the air	8.15	1.615
Hybrid system - Heating both the desiccant and air	9.20	1.422
Conventional vapor compression system	13.23	0.989*

* based on the heat removed by the system from the space

6. CONCLUSIONS

Experiments are conducted to investigate the performance of the cooling system using calcium chloride as the desiccant with the optimum desiccant flow rate for the dehumidifier as well as for the regenerator. The experimental results indicate that both dehumidifier and the regenerator are working effectively in the hybrid system for high temperature and high humidity conditions. The ratio of the outlet-to-inlet absolute humidity reaches a steady state value of about 0.6 and the temperature of air decreased from 48 to 38° C in the dehumidifier of the hybrid system. The COP for the hybrid cooling system with three different modes of regeneration is compared with the conventional cooling system based on the heat removed from the space and it is found that hybrid cooling system can provide higher COP compared with conventional system. The experiments are currently underway to study the effect of different desiccants namely lithium chloride and the mixture of calcium chloride and lithium chloride and the performance of the hybrid system.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by King Abdulaziz City for Science and Technology (KACST) through Project No. AT-17-30 and the facilities provided by the King Fahd University of Petroleum and Minerals (KFUPM).

NOMENCLATURE

h	enthalpy of air, kJ/kg
m	mass flow rate of air, kg/s
Q	volumetric flow rate, l/min
RH	relative humidity, %
T	temperature, °C
t	time, h
Z	packing height from the bottom, cm
ξ	concentration of the desiccant by weight, %
ω	absolute humidity of air, kg of water/kg of dry air

Subscripts

G	air
i	inlet
L	desiccant
o	outlet
1,4	state points

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