EXPERIMENTAL INVESTIGATIONS ON WATER RECOVERY FROM THE ATMOSPHERE IN ARID HUMID REGIONS

Esam Elsarrag*[1], PhD, MCIBSE and Yousef Al Horr[2], PhD
Gulf Organisation for Research and Development, Qatar Science & Technology Park, P O Box 27776, Doha (Qatar)
1 Research Manager, e.elsarrag@gord.qa 2 Chairman, alhorr@gord.qa
* Tel.: 00442081234193, 0097430196002

Abstract:

The Gulf region is one of the most arid regions in the world. The lack of water is considered as the most important problem. Annual rainfall is slight and erratic, with an annual average of 81 millimetres in Doha. As a result, renewable ground water resources are extremely limited and, in addition, there are problems with groundwater salinity. The atmosphere, endless source of water, contains a large quantity of water in the form of vapour in varying amounts especially in Gulf coastal region.
In this paper two methods of collecting water from the atmosphere are presented. First by collecting condensate water, which is usually discarded, from existing air conditioning systems. Experimental measurements of water recovered from the atmosphere by existing air conditioning systems have been carried out. The average rate of condensed water collected during the experiments is found to be about 7.2l/day per kW cooling. The experiments demonstrate a cost efficient means of water recovery which can be implemented in air conditioned buildings. The second method is a novel tilted solar absorption/desorption system, modified from conventional solar still, which used to collect water from the atmosphere. Air is entered to the system at night where water is absorbed by the desiccant. In the daytime the desiccant is heated by solar energy to evaporate the absorbed water. Calcium chloride is used as the desiccant and a corrugated blackened surface is used to heat the desiccant in daytime. It is found that the factors have the greatest effect on the evaporation of water from the desiccant are the temperature difference between the desiccant and the glass and the desiccant flow rate. The higher evaporation rate from the solar tilted unit is found to be about 0.18l/min per m^2 of solar collector area.

Keywords: Water recovery, solar, desiccant, absorption, air conditioning

Nomenclature

m	Mass flow rate, kg/s
T	Temperature, ^oC
X	Desiccant concentration, kg desiccant/kg solution
ω	Humidity ratio, gm water/kg dry air
Subscripts:	
a	Air
DB	Dry Bulb
e	Evaporation
i	Inlet
L	Liquid
o	Out, outdoor

w	Water
WB	Wet Bulb

1.0 Introduction

Water is crucial for sustainable development, including the preservation of our natural environment and the alleviation of poverty and hunger. The lack of water in the Gulf Region has been considered as the most significant for the following reasons: the dryness of the place; the small amount of rainfall; the small amount of underground water; the high consumption of water and the increase of the number of population. In the last two decades, however, the Gulf Cooperation Council, GCC, countries have seen rapid economic and social development, which has led to a sharp increase in population levels, both national and expatriate. The rising population, together with increased agricultural development in order to achieve self-sufficiency in food supplies, has put enormous pressure on traditional water reserves. As a result, the GCC countries have begun increasingly to rely on non-conventional water resources such as desalination, to meet its needs. Only 3 countries in the world produce less water than Qatar from freshwater sources (1), the United Arab Emirates is now the world's second largest producer of desalinated water after the Kingdom of Saudi Arabia (2). Costs and risks of desalination dependence on technology installing, operating and maintaining desalination plants are extremely expensive. It is estimated that the six members of the GCC have collectively spent more than 40 billion US dollars on building seawater desalination stations over the last 25 years (3). Yet such installations may not represent the most cost-effective way of managing water resources in the region. The operation of desalination plants has a negative impact on the local environment. In addition, over-reliance on desalination technology could lead to serious consequences in the event of breakdown or failure of a large desalination facility.

Seawater desalination, however, is expensive in terms of plant installation, maintenance and running costs and has been criticized for its negative impact on the environment. Recently, two major sustainability assessment systems were launched in the Gulf region, ESTIDAMA, Arabic word means sustainability) in Abu Dhabi and QSAS, Qatar Sustainability Assessment System, in Qatar. These systems give more attention to water conservation and collection as well as energy. Figure 1 compares the percentage of the water criteria in these systems to BREEAM, Building Research Establishment Environmental Assessment Method, in the United Kingdom and LEED, Leadership in Energy and Environmental Design, in the United States. The water category represents 20% of the total impact of the build environment in Qatar according to QSAS and 25% in Abu Dhabi according to ESTIDAMA. New sources of water that have a low cost and are renewable are needed. Since major power consumption is for air conditioning, the power loads peak during the summer months due to intensive use of air conditioning, raising loads to more than double those in winter. The atmosphere is an endless source of water, the extraction of water from the atmosphere can be accomplished by several methods. This paper investigates two methods of obtaining fresh water from the atmosphere: i) water recovery from existing air conditioning systems and ii) testing a novel solar desiccant system which is modified from the solar still.

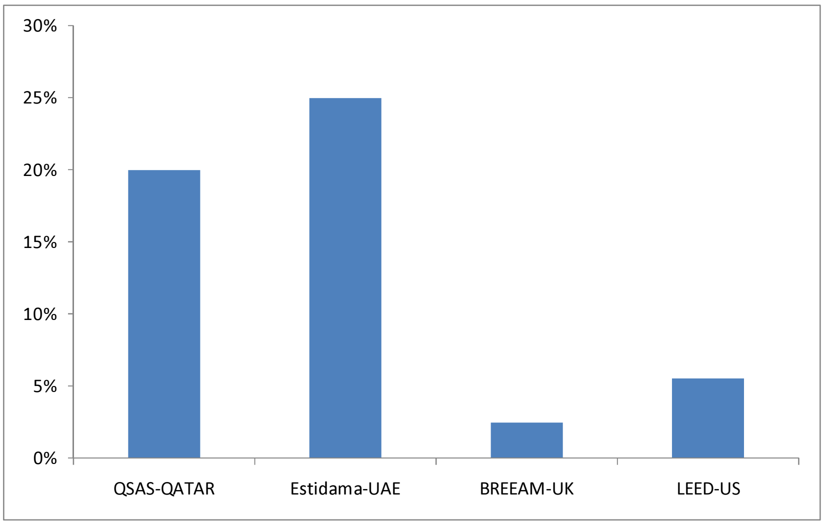

Fig 1 Water consideration in different sustainability systems

2.0 Existing air conditioning systems

In hot humid climates, such as the Gulf coastal regions, the air cooling process can result in considerable amounts of water. When moist air is cooled below its dew-point by bringing it in contact with a cold surface as shown in Fig. 2, some of the water vapour in the air condenses and leaves the air stream as liquid, as a result both the temperature and humidity ratio of air decreases. This is the process air undergoes in a typical air conditioning system. The mass transfer rates can be expressed in terms of the initial and final conditions by applying the conservation of mass equation as given below.

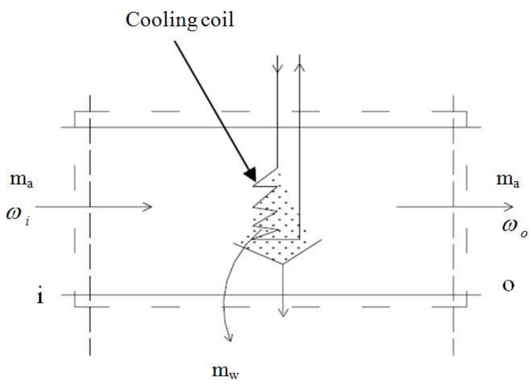

Fig 2 Cooling and dehumidification coil mass balance

By applying mass balance for the water:

$$m_w = m_a(\omega_i - \omega_o) \qquad (1)$$

Khalil (4) analysed the cooling and dehumidification process and the parameters controlling the heat and mass transfer rates are optimized for the climatic conditions in humid regions in the United Arab Emirates.
Milani et al. (5) investigated the feasibility of using thermoelectric devices in

dehumidification process to refrigerate ambient air and provide clean freshwater from air's moisture.

This paper investigates the actual condensate water quantities that produced and collected from existing air conditioning systems in Abu Dhabi. An office block with an existing air conditioning system of 70kW (20 nominal tons) package air conditioning unit is selected for the case study. For the weather data of Abu Dhabi shown in Fig. 3, the percentage of yearly hours of relative humidity between 60 and 100 % exceeds 60%, the moisture content in the ambient air exceeds the 26gm/kg dry air in summer season, cooling is, however, required all the year around mainly to maintain certain levels of humidity which consumes a lot of energy.

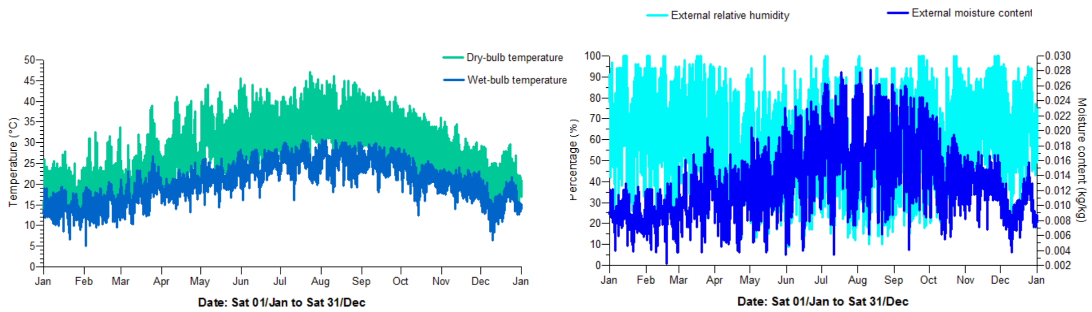

Fig 3 Abu Dhabi weather data

The schematic diagram of the air flow of the package air conditioning unit is shown in Fig. 4. Digital thermometers with resolution of 0.1°C are used to measure the dry and wet bulb temperatures and a vane anemometer, accuracy of 2%, is used to measure the air velocity. The condensate drain pipe of the existing air conditioning system is connected to a 250 litres tank. The supply and return air humidity ratio were obtained from the psychrometric chart, as shown in Fig.5, at given dry and wet bulb temperature. The mixed air and water mass balance humidity ratio is calculated by applying equations between return, outside and mixed air, the fresh air represents 15% the supply air.

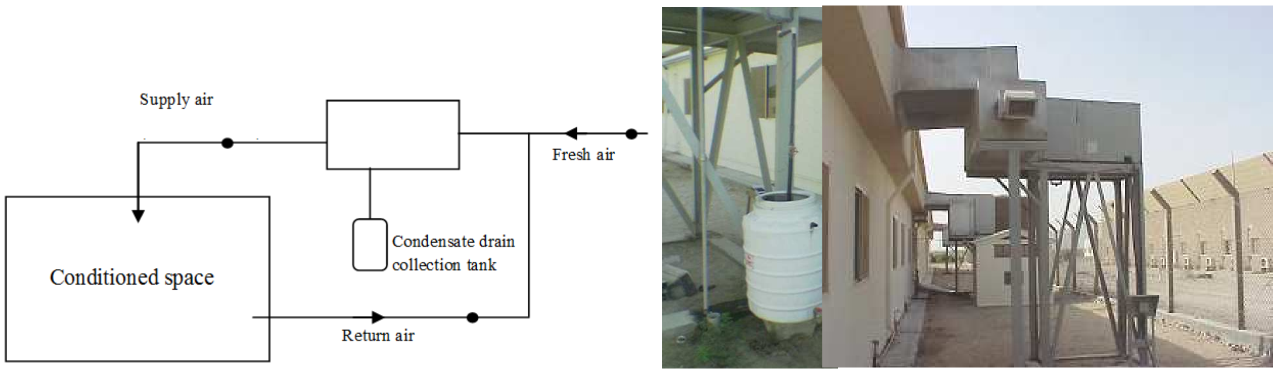

Fig 4 Schematic of the tested air conditioning system

The rate of moisture removal in the cooling and dehumidification process is affected by the initial and final conditions as well as coil design and flow conditions. The measurements of the dry and wet bulb temperatures for the outdoor air, return air and the supply air were placed during the months of

June and July. The measured parameters were used to calculate the amount of water removed from the air. The mass of water condensed is also measured within the tested period. As shown in Fig. 6, the mass of condensate water increased (0.15 to 0.68l/hr per kW cooling or 10.5 to 48l/h for the 70kW unit) with the increase of the on coil humidity ratio (16 to 22.3 gm/kg).
The average daily collected water per kW cooling is about 7.2l/day which suggests separate collection of the condensate water for human use. Alternative air dehumidification systems, e.g. desiccant systems, could be used for both fresh air dehumidification and water production using renewable sources.

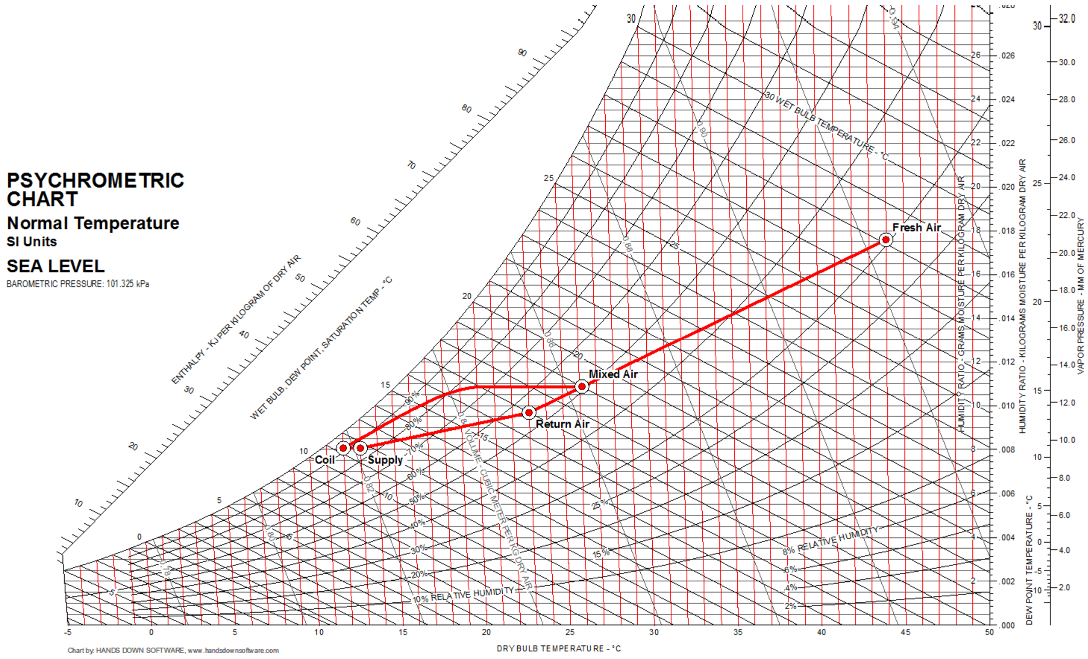

Fig 5 Air conditioning process in the psychrometric chart

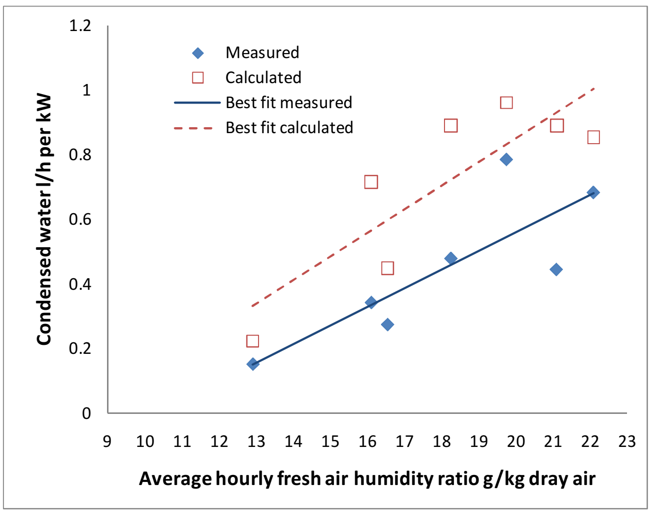

Fig 6 Relation between average hourly outdoor humidity ratio and collected water

3.0 Solar absorption/desorption system

Desiccant dehumidification removes humidity from ventilation air. Thus, air conditioning requirements are reduced to meet the demands of sensible cooling and smaller air conditioning plants are required. Reducing humidity in the air handling system and the building spaces during the cooling season will improve indoor air quality by preventing condensation and reducing the growth and propagation of micro-organisms. Liquid desiccant systems commonly use two chambers, normally conditioning and regeneration, with air/liquid contact surfaces. In the conditioning chamber, ventilation air is dehumidified as the concentrated desiccant absorbs moisture from the air. In the regeneration chamber, the air is humidified as moisture is transferred from the dilute desiccant to the scavenging air. The desiccant or exhaust air is usually heated to promote desiccant regeneration. The heat required for regenerating the desiccant can be supplied by fossil fuel, waste heat and solar energy.

Water can be collected from the atmosphere by using desiccants which absorb water vapour in the atmosphere. The water can then be extracted by heating the desiccant and condensing the evaporated water.

Several liquid desiccants, including aqueous solutions of organic compound (e.g., tri ethylene glycol) and aqueous solutions of inorganic salts (e.g., lithium chloride), have been employed to remove water vapour from air. Research and development in the field of the use of liquid desiccants in solar energy applications have been receiving much attention in recent years. Many attempts have been made to use solar energy for regenerating weak absorbent solutions. In humid climates, the performance of the open solar regeneration system is poor due to low potential for mass transfer; this potential can be increased by heating the desiccant. An alternative to the regeneration towers, Gandhidsan (6) derived a simple expression by using approximations to calculate the amount of water evaporated from the weak absorbent solution in a theoretical closed type tilted solar still solar regenerator as a function of climatic conditions and initial conditions of the absorbent solution. Gandhidsan and Al-Farayedhi (7) proposed a modified open regeneration system suitable for humid climates. They discussed briefly the effects of some of the operating parameters on the regenerator efficiency. From the literature review it is observed that a limited number of experimental studies on solar liquid desiccant regeneration systems have been developed. However, there is a need for research and development in the field of use of liquid desiccants in solar energy applications especially experimental studies. Gad et al. (8) assessed the performance of a desiccant/collector system with a thick corrugated layer of blackened cloth to absorb water vapour at night from atmospheric air with subsequent regeneration during the day, using solar energy. They recorded that their solar system can provide about 1.5 litre of fresh water per square meter per day. Abualhamyel and Gandhidsan (9) presented an analytical procedure for calculation of the mass of absorbed water from atmospheric air using a liquid desiccant as a function of meteorological data and initial desiccant conditions.

Hall (10) proposed a cycle for an absorbent to produce palatable water from the air and constructed a Composition-Psychrometric chart. The chart was employed to combine atmospheric conditions, conditions in a solar-still recovery unit and equilibrium properties of the absorbent.

Hamed (11) investigated the natural absorption of water vapour of the gaseous-air mixture on the horizontal surface of a sandy layer impregnated with calcium chloride as the working desiccant. His experimental results showed that the mass transfer coefficient is highly affected by the desiccant concentration in the bed and the mass transfer rapidly decreases with a decrease in the mixing ratio. Kabeel (12) explored the capability of a glass pyramid shape with a multi-shelf solar system to extract water from humid using pyramid shape using 30% concentrated Calcium Chloride and produced 2.5 litre per m^2 per day. Sultan (13) used forced convection absorption and regeneration packed beds through multi-layers of cloth material impregnated with calcium chloride solution of different concentrations. He developed a numerical model to predict the performance of the system under various operating conditions. Ji et al. (14) presented a new composite adsorbent for solar-driven fresh water production from the atmospheric air. Their experimental data demonstrated that adsorption capacity of the new composites is as high as 1.75 kg/kg dry adsorbent and more than 90% desorption at 80ºC with a daily fresh water productivity more than 1.2 litres per m^2 of solar collector area.
In this paper a novel solar desiccant system, modified from the solar still, is tested for water production.

3.1 Unit description and operation
The schematic diagram of the proposed unit is shown in Fig. 6. The unit has a corrugated blackened tilted surface and an effective solar area of 1 m^2. The galvanized corrugated steel sheet is coated by a thin layer of anticorrosion material and is covered by a single glazing with an air gap of about 420 mm above the corrugated surface. Galvanized steel corrugated sheeting was selected for its strength and resistance to corrosion. It has reasonably low weight per unit area and it is commercially available. The sheets, however, are not stiff enough by themselves and need to be supported by a frame. Here, the corrugated sheet was riveted on a support plain sheet. The results reported by Ishibashi and Ishida (15) and Asai (16) confirmed that a V-corrugated Teflon film provides significantly improved solar transmission compared with a flat film of the same material and that it reduces the collector heat loss. The bottom of the unit is insulated with 50 mm thick fibre glass. A copper distributor was used to distribute the desiccant uniformly over the width of the regenerator. Small channels where distributed and fixed below the distributor and in other different locations on the corrugated surface to assist in spreading the chemical over the surface and increase the wetted area. A centrifugal pump (350W) is used to circulate the stored calcium chloride solution in the 80 l tank. An axial fan (80W, 300mm diameter) is fixed between the blackened corrugated surface and the glass. It is used to extract the air from the bottom of the tilted surface just above the corrugated sheet. Non return dampers with seals are fixed on the side of the fan and the bottom side of the tilted surface to minimize air leakage at heating times. An immersed type auxiliary heater is used to control the desiccant temperature when required. The distributor design has a great effect on the system performance; therefore it was designed and fixed after balancing the unit in several steps to ensure good distribution of the desiccant over the surface. However, the greater the width of the regenerator the more difficulty was

found to ensure uniform liquid distribution but on another hand it has the advantage of reducing the time of solar heating by providing greater surface area. A 550 mm wiper for the glass is used to collect condensate on the glass cover, its function is to remove condensate on the glass cover to the water collection tray and it works automatically.

The relative humidity increases during the night time and decreases during the day as shown in Fig. 7. At night, the fan draws ambient air from the bottom of the tilted surface in counter manner to the desiccant flow which is distributed uniformly at the top of the tilted surface. The corrugated surface retards the liquid flow and increases the time of contact. The vapour pressure of the strong desiccant is less than that of water in the air hence; the mass transfer takes place from the air to the desiccant. Due to absorption of moisture from the ambient air during the night, the absorbent becomes diluted. The water-rich absorbent is heated during the day to recover the water from the weak calcium chloride using solar energy. The desiccant circulating pump is controlled by a digital controller using the sensor fixed on the blackened surface. The controller is set to the required regeneration temperature. When the blackened surface temperature reaches the set point, the pump circulates the weak desiccant from the storage tank to the tilted solar surface.

The weak desiccant flows as a thin film over the blackened corrugated surface where its temperature rises while it comes down to the bottom. As the blackened surface is cooled down, the controller switches off the pump and a slight increase in the desiccant temperature occurs. This procedure continues automatically until the desiccant reaches the desired regeneration temperature (the set temperature). The auxiliary heater has two functions, either to rise up the desiccant temperature to the desired limit when required or to keep a uniform temperature in the tank.

When the desired regeneration temperature is attained the calcium chloride solution is re-circulated to remove any temperature and concentration gradients, the water that evaporates from the solution rises to the glass cover by convection where it is condensed on the underside of the glass cover and the absorbent leaving the unit becomes strong. While hot water evaporates and under the surface of glass the wiper operates automatically and collects the condensate in the water tray. The vapour pressure of water to be condensed on the glass cover is a function of the temperature of the glass therefore; it must be kept to a minimum.

Before each experiment, the desiccant temperature and concentration were measured and a sample from the tank was taken for analysis. The dry bulb and wet bulb temperatures of the outdoor air were also measured before and during experiments. The measurements were taken after allowing enough time for steady state readings. The measurements during the experiment and the specifications of different measuring devices are shown in Fig. 6 and Table 1, respectively.

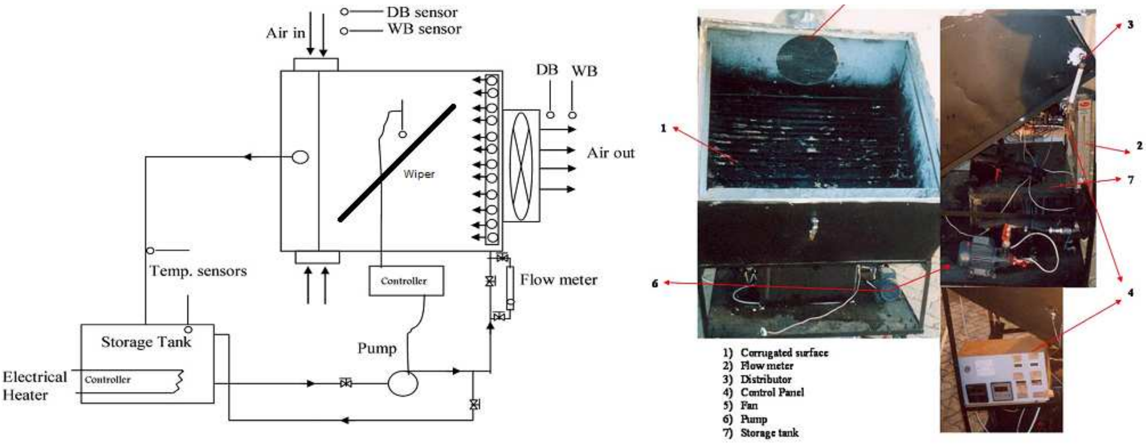

Fig 6 Schematic of the tested unit

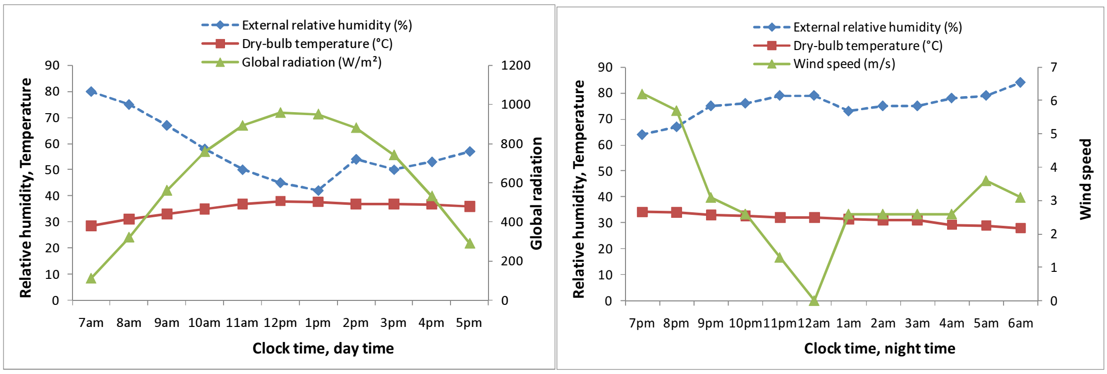

Fig 7 A summer day in Abu Dhabi

Table 1 Measuring devices specifications				
Device	**Type**	**Accuracy**	**Operative range**	**Fluid**
Thermometers	Digital RTD	0.1°C	0-100°C	Air (DB &WB) and solution
Flowmeter	Rotameter	2%	0- 0.4 l/s	Solution
Anemometer	Vane	2%	0-5 m/s	Air
Densimeter	Immersed	0.01	1-1.5 gm/cm^3	Solution

3.2 Results and discussion

The mass of water evaporated from the desiccant is calculated by using the following equation, Elsarrag and Abdalla (17):

$$m_e = m_L \frac{(X_o - X_i)}{X_i} \qquad (2)$$

The measured variables and calculated results are shown graphically in Figs. 8–10. The evaporation rate and flow rate are calculated per unit area of the corrugated surface. As shown in Fig. 8, the evaporation rate increased with the slight increase of liquid flow rate, [m_L=4.4-5.2 l/min.m^2] and additional increase did not show any significant effect on the evaporation rate, [m_L>5.2 l/min.m^2]. This can be explained by several reasons; a slight increase in the liquid flow rate produced a good wetting of the corrugated tilted surface and a

higher evaporation rate was achieved; applying high liquid flow rates a thick layer of the desiccant on the corrugated tilted surface was obtained which resists the mass transfer in addition to the decrease of the time of contact between the desiccant and air.
The effect of the solution and glazing temperatures on the water evaporation and condensation is very critical. The increase of the solution temperature increases the vapour pressure, higher driving force of mass transfer and hence, higher water evaporation rate can be obtained. Here, the evaporation rate decreased with the increase of the solution temperature as shown in Fig. 9, because the vapour pressure of water to be condensed in the glass cover is function of the glass cover temperature. A higher temperature difference between the blackened surface and the glass cover results in higher evaporation rates, as shown in Fig. 10.

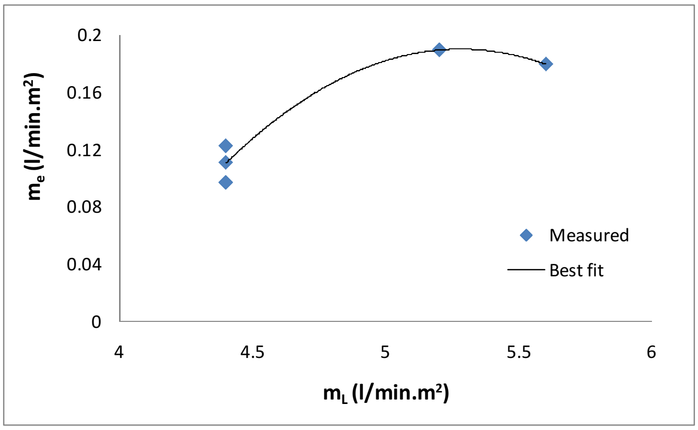

Fig 8 Relation between liquid flow rate and evaporation rate

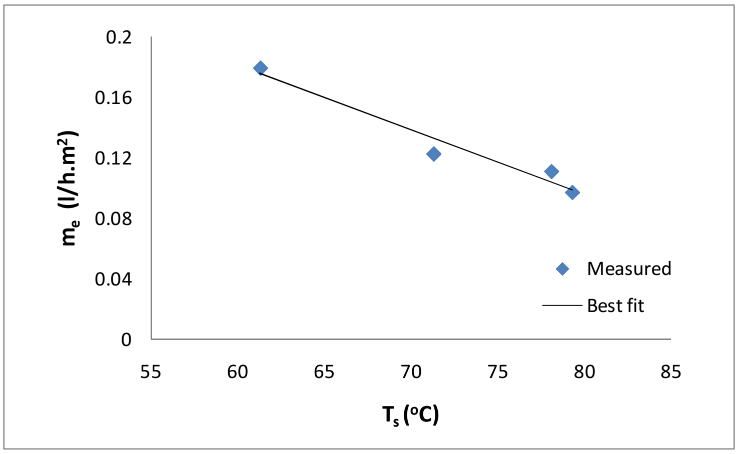

Fig 9 Relation between temperature difference and evaporation rate

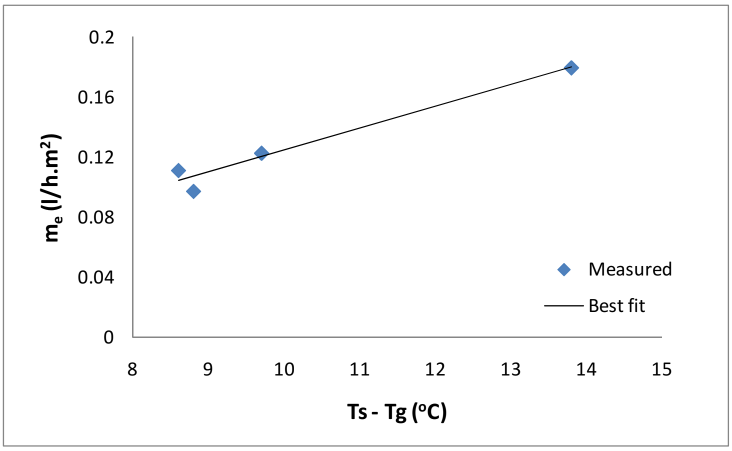

Fig 10 Relation between humidity ratio and evaporation rate

4.0 Conclusions

The lack of renewable water resources in Gulf Cooperation Council (GCC) countries is one of the most critical problems. A great portion of the freshwater demands is covered by desalinated water with a growth gap between supply and demand. Water of higher quality should be preserved for drinking purposes and should not be utilized for other purposes that may tolerate water of lower quality. The atmosphere in the Gulf coastal region contains large amounts of water.

This paper investigated experimentally two methods of water recovery from the atmosphere in hot humid climates. The water condensed from an existing 70kW air conditioning package unit was collected and compared with the calculated values. The quantity of water recovered showed a cost efficient means of water recovery, which can be implemented in the Gulf coastal regions as a means of water conservation.

A novel tilted solar absorption/desorption system, modified from conventional solar still, was tested to extract water from humid atmosphere. It was found that the main factors that have the greatest effect on the evaporation of water from the desiccant are the temperature difference between the desiccant and the glass, the desiccant flow rate. For higher evaporation rates it is vital to maximise the temperature difference between the plate and glass cover. Further investigations and modification to the tested system are essential to enable high evaporation rate and efficient condensate collection.

Buildings in the region consume a lot of energy due for air conditioning. Water condensed from air conditioning systems could be separated from grey and black water and treated for human use. Further analysis and studies are essential in the Gulf region to enhance the use of renewable and sustainable methods for obtaining drinking water.

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