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`FEASIBILITIES OF OBTAINING WATER FROM HUMID AIR

Essa S. Bin Essa[1] and Abouelyazed M. Kulaib[2]

[1]The public authority for applied education and training, Construction Training Institute Mechanical Works Dept.

[2]College of Technological Studies,

ABSTRACT

Clean drinking water is essential to humans and other life forms, so this paper investigates the methods of obtaining fresh water from the humid atmosphere. The study was carried out experimentally and theoretically. It was designed and manufactured a simple construction unit for this purpose. The unit was manufactured and tested in Kuwait. The study was extended to analyze the effect of ambient temperature and humidity on the system performance. As the ambient humidity decreases, the mass of water absorbed by the system also decreases due to low potential for mass transfer. The heat transfer analysis was covered. The night-time moisture absorption and the day-time moisture desorption take place in the same unit. The unit was consisted of a flat, blackened, tilted surface and is covered with a single glazing. During the night, the strong absorbent flows down as a thin film over the glass cover in contact with the humid ambient air. Due to absorption of moisture from the ambient air at night, the absorbent becomes diluted. The results are compared with different previous studies.

Keywords: Fresh water, Humid air, Producing, Device

Symbols

A	area, m^2
b	width, m
C	specific heat, kJ/kg K
d	depth, mm
m	mass, kg
M	mass flow rate, kg/s
V	volume, m^3
t	temperature, ^oC
P	water vapor pressure, mm Hg
Q	heat transfer rate, W
h	heat transfer coefficient, W/m^2K
G	mass flow rate, kg/m^2hr
h_{fg}	Latent heat of vaporization, kJ/kg
h_{fgl}	latent heat of condensation, kJ/kg
I	incident solar flux, kJ/m^2hr
m	mass of water evaporated, kg/hr m^2
m_l	mass of water absorbed, kg/hr m^2
RH	relative humidity, %
U_L	overall heat loss coefficient, W/m^2 K
v	wind velocity, m/s

Greek

$(\tau\alpha)$	effective transmittance-absorptance product
β	mass transfer coefficient between the absorbent film and the glass cover, kg/mmHg hr m^2
β_l	mass transfer coefficient between the ambient air and the absorbent film, kg/mmHg hr m^2
ξ	concentration of the absorbent solution by weight, %
P	reflectance of absorbent solution for solar radiation

Subscripts

g	glass cover
$g-\infty$	glass to ambient
i	beginning of the unit
s	absorbent solution
s-g	absorbent solution to glass cover
∞	ambient

1. INTRODUCTION

Access to safe drinking water has improved steadily and substantially over the last decades in almost every part of the world [1]. There is a clear correlation between access to safe water and GDP per capita. However, some observers have estimated that by 2025 more than half of the world population will be facing water-based vulnerability [2]. A method by which water may be extracted from the air even without a supply of electricity from a power source or even without a supply of fuel, as well as an apparatus therefor, is disclosed, [3]. The apparatus used for the method for extracting water from the air comprises at least a rotatably mounted hygroscopic moisture-absorbing rotor having at least one region through which air can pass in the direction of thickness thereof; a passage for regeneration through which air for regeneration is circulated, of which both ends are opened at the opposing two surfaces of a regeneration region, respectively, the regeneration region being a part of the moisture-absorbing rotor, at which the moisture-absorbing rotor that absorbed moisture is regenerated; and a drain hole for taking out condensed water from the passage for regeneration.
A recent report (November 2009) suggests that by 2030, in some developing regions of the world, water demand will exceed supply by 50%. Water plays an important role in the world economy, as it functions as a solvent for a wide variety of chemical substances and facilitates industrial cooling and transportation. Approximately 70% of freshwater is consumed by agriculture.
This study is performed theoretically and experimentally. The test rig is designed and manufactured in Kuwait. Then the unit will be test at night and during day time. Different factors affect on the performance of system. A schematic of the test rig is shown in Fig.1. Lithium–Bromide is used as an absorbent solution to absorb humidity from air.

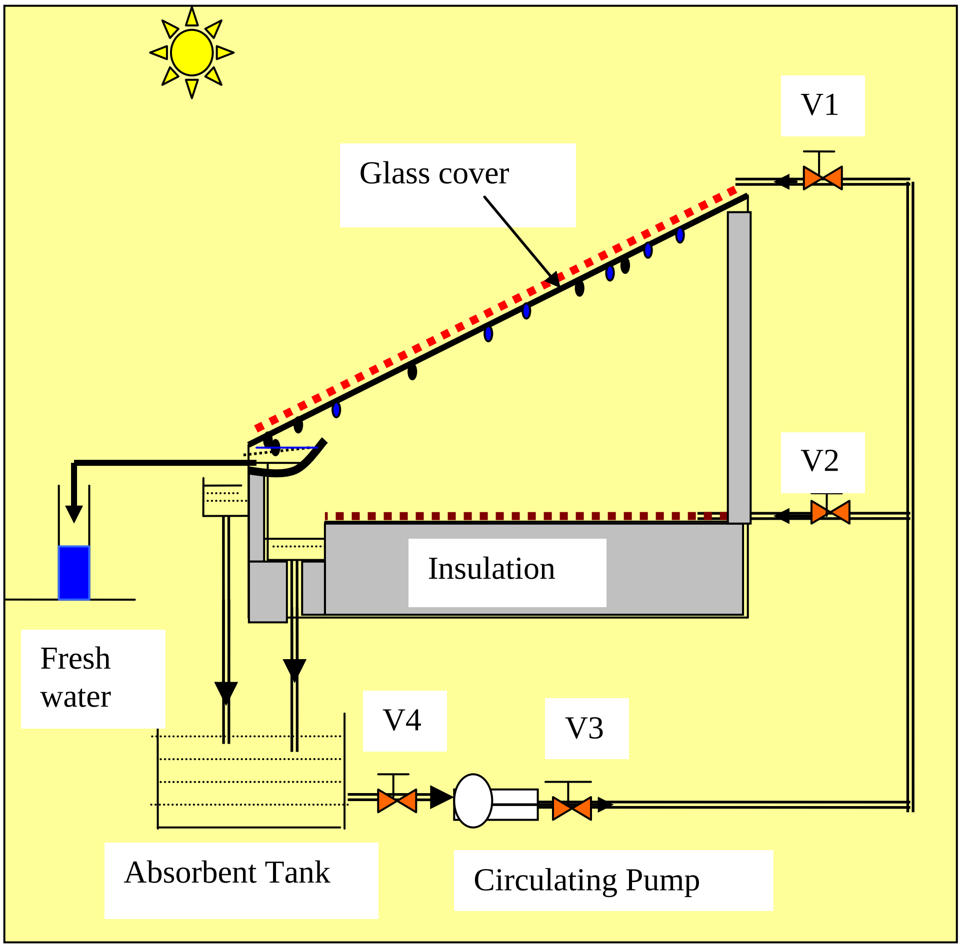

Figure (1) Arrangement unit for water generation from air

The main components of device, shown in Fig. 1, are: evaporation basin, glass cover, circulating pump, absorbent solution (lithium bromide), tanks, valves for control, and collector tubes.

The study goal is to design a simple solar system for extracting water from moisture in atmospheric air. The unit does not contain any cooling surface. A chemical material such as lithium bromide, silica gel, or ammonia is used to absorb water vapor from air. During night, the absorbent solution flows over the outer surface of the glass cover to absorb water vapor from humid air. Then, the absorbent solution is heated directly during day time to vaporize the water contained in the absorbent solution. Solar energy is used for heating the absorbent solution and an electrical DC source operates the circulating pump.

2. METHODS OF OBTAINING FRESH WATER FROM HUMID AIR

For climatic conditions with high temperature and humidity (e.g. most Gulf countries), the process of obtaining fresh water from the atmosphere seems to be very attractive because the ambient atmosphere contains water in the form of vapor in amounts, ranging at saturation temperatures between 10-48^{o}C from 9.6 to 55.3 g per m^{3} of dry air. The extraction of water from the humid atmospheric air can be accomplished by different methods. Some of these methods are:

2.1. Mechanical Method

In this method the fresh water is obtained from the atmosphere by the compression of humid air. When humid air is compressed, the partial pressure of the water vapor in the water-air mixture is raised to the point where moisture can be condensed from the air at a higher temperature. However, the cost of the compressor, high power requirements, and the cooling water requirement make this system to be impractical.

2.2. Refrigeration Method

In hot, humid climates the possibility of obtaining fresh water as a by-product of an absorption cooling machine is reported by Ali [1989]. This is achieved by using a $LiBr-H_2O$ absorption cooler with an open absorber where the outside humid air is dehumidified by being in direct contact with the strong absorbent solution. It is to be noted that, in Gulf States, the cooling is almost entirely provided by a vapor compression air conditioning system. Thus, an absorption refrigeration system is not widely used.

Different mechanical systems are disclosed for extracting freshwater from atmospheric humidity in extremely hot and humid climates and supplying freshwater to a small group of people, a building, a farm, or forestation area. The freshwater is treated to provide drinking water by disinfecting to eliminate microorganisms and filtration to remove suspended particulates from air, erosion or corrosion products, and disinfected waste.

Compact units provide drinking water for individuals, passengers in cars, vans, trucks, or recreational boats, or crewmembers on a seagoing cargo ship whether from atmospheric humidity or from moisture-laden gases. Furthermore, systems are disclosed for the ample supply of freshwater with minimal treatment for small- to large-sized buildings in a manner that alleviates the heat load on buildings. Collection of freshwater from hot humid ambient air is also provided for other uses, such as irrigation and farm animal drinking.

Various methods are used for condensation of water vapor suspended in the air as alternative to conventional refrigeration cycles using CFC refrigerants. Devices are disclosed using naturally occurring brackish cold water, circulation of cooling water cooled by thermoelectric cooling or thermo acoustic refrigeration as well as evaporative cooling and transpiration cooling. Water produced by the systems may flow under gravitational forces entirely or with the assistance of boasting pumps.

In vapor compression method, fresh water is obtained by lowering the humid air temperature below its dew point temperature. AGU [3] has reported experiments on the condensation of moisture from the air using conventional fuel-driven vapor compression refrigeration machinery.

The air entering the unit flows over the elements of the cooling system and the water condensing on the evaporator coil is collected as the fresh water. It is also reported that the energy consumption was high due to low heat exchange process. Since the amount of water collected was low with small units, this method was suggested for emergency use only.

A similar study was recently conducted analytically [4] for the climatic conditions of UAE coastal regions, and it was reported that the quantity of fresh water obtained depends on the properties of humid air, air velocity, cooling coil surface area, and the heat exchange arrangement. It is to be noted that this system uses chlorinated fluorocarbon compounds (CFCs) identified as contributors to depletion of the ozone layer.

2.3. Adsorption Method

One of the methods which have also been considered for obtaining fresh water from the humid air is adsorption. In this method, humid air is passed over a hot adsorbing material where water can be adsorbed while cooling the adsorbing material. In the regeneration process, the adsorber material is heated while its water is adsorbed by an air stream that then flows on a colder condenser to condense the carried water. Ali [1998] has proposed a method with silica gel using this principle and found that about 30g of water can be adsorbed by 100 g of silica gel in equilibrium in air having a relative humidity of 60% or more. He conducted experiments at Riyadh with a unit developed on open cycle for water collection based on this adsorption-desorption phenomena. The cycle consists of three processes.

Different process is carried by the system to produced water from humid air. In the first process, the ambient air is introduced into the adsorption chamber and in contact with the desiccant bed. The second process is heating the air to about 300°C using gasoline burner and circulated with fan through the bed. It evaporates the captured water in the desorption process. Finally, the hot water vapor is condensed and cooled in the third process using air-cooled condenser. The water production and fuel consumption are shown for various climatic conditions and cases.

A similar practical system using composite material for produced of water from the moist air is suggested by Alayli et al. However, the evaporation was accomplished by solar energy and about 1 liter of water per square meter of the composite material was produced. It is to be noted that this system can operate at lower temperatures but it requires large volumes of desiccant and also entails significant operating costs for the parasitic systems of blowers required to circulate air streams.

Further, as time progresses, the efficiency of the desiccant bed will 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 drops through the system.

2.4. Absorption Method

The absorption method was chosen for the proposed research due to various advantages over the adsorption method such as:

1. the absorbent (desiccant) can be readily circulated by means of a small pump;
2. the requirement of low regeneration temperature (50-65 ^{o}C); and
3. the absorbent can be used as a heat transfer medium in a heat exchanger and hence, it could be precooled or preheated when required.

A cycle using liquid s in the production of fresh water from the atmosphere was proposed by [5]. A simple vertical plane, such as a sheet of plywood, was considered as the absorber and the strong absorbent namely ethylene glycol was flowing as a thin liquid film, making contact with and while absorbing water from the air. The weak desiccant was then transferred by suitable tubing to the entrance of the conventional roof-type solar still to separate the product water from the absorbent. A composition-psychometric chart was constructed and used to demonstrate how water recovered can be changed with change in different operating conditions. Many researchers investigated the regeneration of a liquid desiccant in a roof-type solar still. It is reported that when the still was acting as a desalinate for producing potable .water from brackish water, the efficiency was 56% and when it was used for regenerating the weak desiccant, the efficiency was in the range of 5-20% depending upon the insolation and the concentration of the desiccant. The reduction in efficiency is attributed to the lower partial pressure of the desiccant compared with saline water at a given temperature. An analytical procedure for calculating the mass of water absorbed by a desiccant from the atmosphere in a slanted absorber is reported by the authors [6]

3. ABSORBENT CHARACTERISTICS

For designing a unit to produce fresh water from the atmosphere by absorption with subsequent recovery using solar energy, a number of factors have to be taken into account. They include climatic variables such as insolation, wind velocity, ambient temperature and humidity, concentration of the absorbent, initial temperature and the flow rate of the absorbent. Two processes are required to extract fresh water from the atmosphere by the absorption method. They are:

1. the absorption process,
2. the evaporation-condensation process.

In order to make the system attractive and cost effective, both processes must be conducted in the same unit. The absorption process will be carried out at night and the evaporation-condensation process will be carried out during the day in the same unit.

The desired absorbent characteristics for this research are:

- high solubility and low vapor pressure at absorbing conditions
- low viscosity and low heat of absorption under operating conditions
- high thermal conductivity and stability against thermal decomposition
- low density and low freezing point
- low toxicity and low corrosivity
- low cost and should be readily available.

Since calcium chloride satisfies most of the above requirements, it is chosen as the absorbent for this study.

4. SYSTEM DISCRIPTION

A picture of the unit used is shown in Fig. 2. The main body was made of a wooden box whose inside walls are covered with aluminum sheet. The box dimensions are 75 x 60 cm with a total area of 0.45 m^2. It consists of a flat, blackened, tilted surface and is covered by a single glazing with an air gap of about 45 cm. The bottom of the unit is well insulated. Fiber glass with thickness of 6 inch is used for insulation. The outer surface of inner basin was coated with black material to increase its absorptivity to solar radiation. The tilt angle is 45^o and the width of unit is 55 cm.

Figure (2) Experimental unit

A 4 mm-thick clear single glass cover with no shading effect is used.

At night, the strong (concentrated) absorbent flows down as a thin film over the glass cover in contact with the ambient air. If the vapor pressure of the desiccant is less than the vapor pressure of water in the atmospheric air, mass transfer takes place from the atmosphere to the absorbent.

Due to absorption of moisture from the ambient air during the night, the absorbent becomes diluted. The water-rich absorbent must be heated during the day to recover the water from the weak (diluted) absorbent. Therefore, during the day, the desiccant flows down as a thin film over the absorber surface.

The weak absorbent is heated by solar energy, and 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 retains its concentration.

The performance of the unit at night depends on the potential for mass transfer, which is the difference in water vapor pressure between the ambient air and the absorbent film on the glass cover, whereas the performance of the unit during day-time operation depends on the difference in water vapor pressure between the absorbent film and glass cover.

The vapor pressure of water to be condensed on the glass cover is a function of the glass temperature, and hence it must be kept minimum. For this purpose, the glass must be placed away from the absorber surface.

As an alternative to the proposed arrangement, the absorbent solution can be permitted to flow as a thin film over the absorber surface during the night-time operation by removing the glass cover.

5. PERFORMANCE ANALYSIS

In this study, an analysis has been carried out for predicting the performance of the unit. Using the energy balance equations, the rate of absorption at night and the rate of desorption at day-time have been computed for intervals of one hour. Any change in the pattern of climatic conditions results in a change in the performance of the unit. The variation of the desiccant temperature and the rate of water absorption as well as water desorption rate per unit area are determined for different flow rates of desiccant.

The results have been computed using the climatic data of Kuwait. When the absorbent flows over the glass cover at night and on the absorber surface in the daytime, its temperature, concentration, and hence its vapor pressure vary along the length of the unit. However in the present analysis, the arithmetic mean of these values between inlet and outlet of the unit are used. Further, it is assumed that the areas of the glass cover and absorber surface are equal, and steady-state conditions prevail in the unit. The back and edge losses are assumed to be small. The following energy balance equation for a unit absorber area can be, written for the day-time operation [5]:

$$I(1-\rho)(\alpha\tau) - U_L(t_s - t_\infty) + 2G_sC_s(t_s - t_{s,i}) - m_l h_{fg} = 0 \qquad (1)$$

When the absorbent flows down on the glass cover in the night-time, the energy balance equation becomes

$$U_L(t_g - t_\infty) + 2G_sC_s(t_s - t_{s,i}) - m_l h_{fgl} = 0 \qquad (2)$$

The values of U_L h_{fg}, and h_{fgl}, are assumed to be constant with respect to temperature and concentration of the absorbent solution encountered in the system. For the night-time operation, U_L is considered to be a function of the wind velocity only. For day-time operation, U_L, is given by

$$U_L = \frac{1}{R_{th}} = \left(\frac{1}{h_{s-g}} - \frac{1}{h_{g-\infty}} \right)^{-1} \qquad (3)$$

The mass of water evaporated from the absorbent during the day-time operation is given by

$$m = \beta \, (Ps - Pg) \qquad (4)$$

The mass of water absorbed by the absorbent from the ambient air during the night-time operation is given by

$$m_l = \beta \, (P_\infty - P_s) \qquad (5)$$

The vapor pressure of the absorbent solution is directly proportional to its temperature and inversely proportional to its concentration. The relationship between vapor pressure, temperature, and concentration of the absorbent solution is given by

$$P_S = a + bt_S + c / \xi_S \qquad (6)$$

where *a*, *b*, and c are empirical constants based on the operating conditions. For the day-time operation, the constants were found to be: *a=-463.2*, *b=4.52*, and c=10941.3; for the night-time operation, the constants were: a=-31.26, *b=0.629*, and c=1001.8.

An approximate equation which relates the rate of desorption, solution flow rate, initial and average value of concentration of absorbent solution is given by

$$\frac{1}{\xi_g} = \frac{1}{\xi_{s,i}} \left(1 - \frac{m}{2G_g} \right) \qquad (7)$$

To relate the rate of absorption at night, the above expression is modified as:

$$\frac{1}{\xi_g} = \frac{1}{\xi_{s,i}} \left(1 + \frac{m_l}{2G_g} \right) \qquad (8)$$

By combining equations (2), (5), (6), and (8), an expression for the mass of water absorbed by the absorbent solution from the atmosphere at night can be obtained in the form of

$$m_l = \frac{A / b (P_\infty - a - c / \xi_S) - D}{A / b \left(\frac{1}{\beta_l} + B \right) + h_{fgl}} \qquad (9)$$

Where

$A = (U_L + 2G_sC_S)$

$$B = \frac{c}{2G_S \xi_{S,i}}$$

$D = (U_l\, t_\infty + 2\, G_s\, C_g\, t_{s,i})$

In order to obtain the rate of desorption, an energy balance on the glass cover could be written as

$$h_{s-g}(t_s - t_g) + mh_{fg} = h_{g-\infty}(t_g - t_\infty) \qquad (10)$$

For the expected range of glass temperature, the vapor pressure of water to be condensed on the glass cover can be related by approximate relations. Heat transfer coefficients are calculated. An analogy between heat and mass transfer is used to calculate the convective mass transfer coefficients β and β_l. Combining equations (4), (6), (7), and (l0), the glass cover temperature can be computed. Using the glass cover temperature, the mass of fresh water collected can be calculated by combining equations (l), (4), and (6). It is given by

$$m = \frac{a + bR + (c / \xi_{s,i}) + 74.13 - (3.28 / H)(h_{s-g} R + h_{g-\infty} - t_{\infty})}{(1/\beta) + B + (bh_{fg} / H) + (3.28 h_{fg} / H)(1 - \frac{h_{s-g}}{A})} \quad (11)$$

Where

$$R = \frac{I(1-\rho)(\alpha\tau) + D}{A} \quad \text{and}$$

$$H = (h_{s\text{-}g} - h_{g\text{-}\infty})$$

6. OPERATION

6.1. Night-Time Operation:

Valve V2 is closed and valve V1 is open (Fig. 1). This process is required to absorb water vapor from ambient air. In low humid climate, the performance of the system will be bad. To overcome this problem, a very strong solution can be used by increasing the concentration of lithium bromide to 55%. During the present testing, 25% concentration-lithium chloride is used.

6.2. Day-time Operation:

Valve V1 is closed and valve V2 is open. During this process the solar radiation heats the absorbent releasing water vapor absorbed at night. Then, water vapor condensates as it touches the low temperature glass cover.
Very thin layer of absorbent is moved on the inner surface of basin using a very small pump while being heated by solar radiation. The pump operates with 12V DC electrical source. The pump has a capacity of is 0.5 lit/min and maximum head of 3 m.

7. RESULTS AND DICUSSIONS

A typical day for operation and testing the system is 21/6/2010. The relative humidity in this day reaches 65 % along with a high wind of 6.5 m/s a mean ambient temperature of 36^{o}C. The results are shown in Figures 3 through 5.

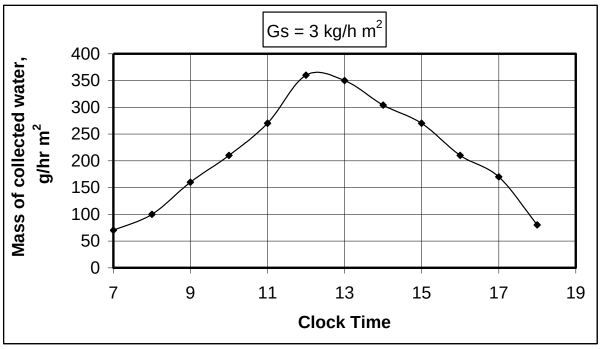

Figure (3) day-time performance for extractor unit (day-21/62010)

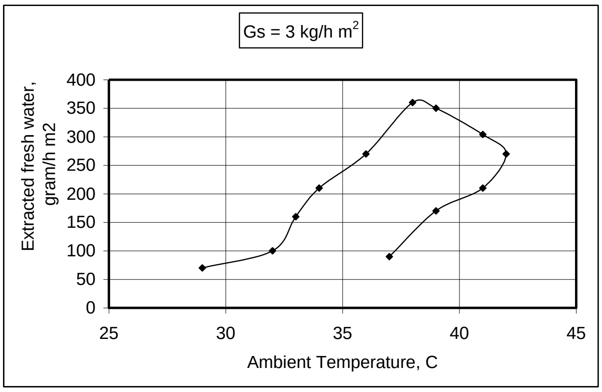

Figure (4) extracted fresh water rate with ambient temperature

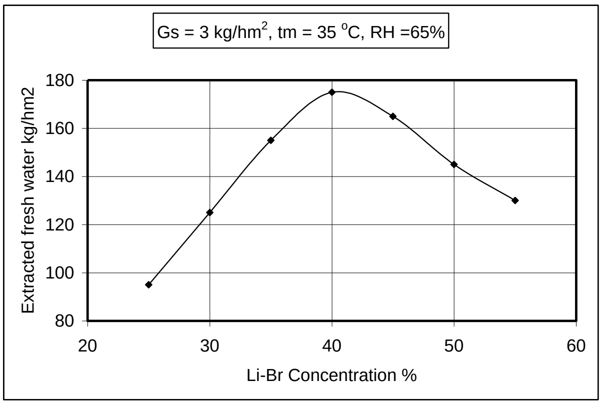

Figure (5) extracted water rate with Lithium Bromide concentration

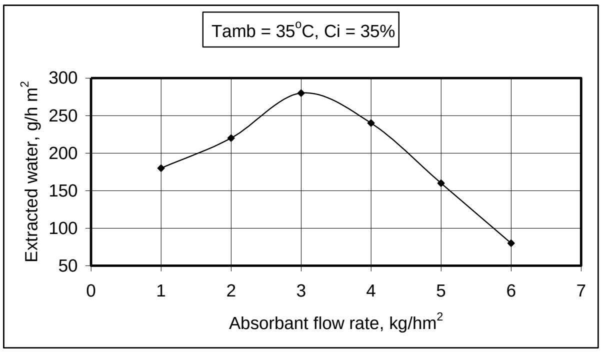

Figure (6) the extracted water rate with absorbent flow rate

8. CONCLUSION

As a method of extracting fresh water from the humid atmosphere, this investigation tests a way to absorb moisture from the atmosphere and then, drive off the moisture and condense the vapor stream in the same unit. For typical summer climatic conditions of Kuwait, the diurnal variation of rate of absorption of water at night and the water desorption rate during the day were calculated using the energy balance equations. It was found that the increase in absorbent solution flow rate increases the rate of absorption of water from the atmosphere but decreases the desorption rate of water during day-time operation. Experimental studies are in progress, and economic study is needed to determine its feasibility.

It is noted that the unit was affected by the following:

1. humidity ratio in atmosphere
2. solar glass cover angle
3. absorbent flowing during day-time
4. ambient temperature
5. available solar energy
6. concentration of absorbent
7. system design as type of glass, insulation, tanks
8. wind velocity in place

9. RECOMENDATION

It is recommended to re-test the unit around all year months especially in very higher relative humidity month and very high ambient temperatures. Also the angle of glass cover needed to be optimized. The concentration of absorbent needs more study.

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