Investigation of Water Vapour Harvesting Unit Using Solar Energy

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Abstract water-harvesting unit is built and the effects of design parameters are studied experimentally and theoretically under Baghdad conditions (33.3°N, 44.33° E). The unit consists of desiccant materials contained in many trays that enclosed in a metal container covered by a glass cover. The desiccant materials aim to adsorb the water vapor that associated with the air, an axial fan is used to blow the ambient air over the desiccant. The unit container is built from aluminum of 0.6 mm thickness; the dimensions of the container are 27 cm wide, 93 cm length and 10 cm height. Two gets are installed in the unit for the inlet and outlet of air. The front face of the container is covered by a glass cover of 4 mm thickness. Different types of desiccant materials are used to adsorb the water vapour from the air, namely; silica gel powder, silica gel pellets, zeolite 13X, zeolite 3A and MCM-41 Nano powder. The effect of the mass flow rate of air over the desiccant materials and the types of desiccant material on the amount of freshwater production is studied in this work. Tóth model is used to build a mathematical of the adsorption/ desorption process. The mathematical model aims to cover the performance of the water-harvesting unit around the year. The results show that the maximum daily production of the water-harvesting unit using MCM-41 is 0.5 kgw/kgads when the mass flow rate of air is 14 kg/hr, as the mass flow rate of air increases more than 14 kg/hr the daily water production reduces. The use of other desiccant materials like Zeolites and silica gels shows encourage results in the daily production of water of less than 0.1 kgw/kgads. The mathematical modelling of the water-harvesting unit shows the maximum water production about 0.55 kgw/kgads in December. The error between the experimental and mathematical models for daily water production is in the range of 12.5 to 17.8% for the desiccant materials used in this work.

Keywords: water vapor harvesting unit, solar energy, drinkable water

1. Introduction:
The next challenge to human life in the world is how to solve future problems expected to emerge. The most three critical problems are energy crisis, water crisis and pollution [1]. Water and energy are two of the most important topics on the international environment and development agenda. The estimation growing of the annually water demand in the world is around 3–4% [2]. Three methods can be used to provide the remote areas with fresh water, namely; water transportation from other locations, desalination of saline water (ground, or underground) and extraction of water from humid air. The transportation of fresh water from other locations to those remote areas is expensive with a high initial cost [3]. Ground and underground water desalination is an expensive method, high initial cost, as well as related to the problems of water existence. Water extraction from atmospheric air is an effective method for providing fresh water to the remote areas, and small communities and it does not depend on the existence of water resources. At any moment, the atmosphere contains an astounding 37.5
million billion gallons of water, as invisible vapor phase. That is enough water to cover the entire surface of the Earth (land and ocean) with one 2.5 cm of rain [4]. There are large quantities of water loaded with air even in very dry desert lands. The amount of water vapor and water droplets that associated with air is represents about 10% of the fresh water in the lakes and rivers [5]. The problem of water scarcity is severe in arid zones and many countries such as Iraq. The changes of climate such as; global warming and lack of rainfall, as well, as complains about the lack of water and lack of descent rain, reflected negatively on the reality of life in all its facilities. Neighboring countries control water flow into Iraq according to their interests, needs and circumstances without adhering to any quota or consideration. From 2003 to 2009 [6], Tigris and Euphrates lost about 144 km$^3$ of fresh water; this amount of lost water equals the size of Dead Sea. Figures (1) and (2) show the shrinking of the Haditha Reservoir between September 7, 2006 and September 15, 2009 [6]. The Ministry of Water Resources -Iraq, shows that the average water discharge by Tigris was 49.2 billion m$^3$ at 2009 [6], and the estimated at 2025 will be 9.16 billion m$^3$. While, for Euphrates was 19.34 billion m$^3$ at 2009 and it will reduced to about 8.54 billion m$^3$ at 2025.

This simple review shows the problem of the scarcity of potable water that Iraq will face in the next few decades. The problem can be solved of through desalination of water wells, sea water and non-potable water. Desalination could be done in several ways, using fossil fuels or renewable energies, as presented in the following paragraphs.

**Figure 1.** Haditha reservoir at September 7, 2006 [6].

**Figure 2.** Haditha reservoir at September 15, 2009 [6].

Different materials of water production were tested by [7]. The desiccant materials molecular sieve 13 X, silica gel, and activated alumina were studied experimentally and theoretically to find amount of the water harvesting by the system. The water produced were 20, 35 and 160 ml/kg.day for the desiccant materials activated alumina, molecular sieve 13 X respectively. While for the water productions for the theoretical work were 28, 60 and 600 ml/kg. day for activated alumina, Molecular sieve 13X and Silica gel, respectively. The synthesizer between the ultra-large pore crystalline material MCM-41 and calcium chloride (CaCl$_2$) was introduced by [8]. The MCM-41 was a host material while CaCl$_2$ was hygroscopic salt. The experimental results showed that the composite can desorb more than 90% of water vapor at relatively low heating temperature of 80 °C, as well as the production of the fresh water was about 1.75 kg/kg of dry adsorbent, which is equal to about 1.2 kg/m$^2$ of the area of the solar collector.

[9] Investigated metal–organic frameworks (MOFs) with metal–carboxylate bonds, including Cu-BTC, Mg-MOF74 (Mg/DOBDC), and UiO-66, and found to have varying degrees of water stability. Three MOFs were studied in their work namely; Cu-BTC at the lower temperature of 25°C and 90% RH, and water uptake of 32 mmol/g. However, the external surfaces of Cu-BTC degrade more readily at temperature 40°C and 90% RH but the water uptakes of 16mmol/g was assigned. Mg-MOF-74 has a nearly complete loss of surface area after just one day of exposure to each of the conditions studied. The uptake of Mg-MOF-74 at 25°C and RH 90% was 20mmol/g. as the adsorption temperature increases to 40°C and the same RH above the water
uptake was 19mmol/g. It was conclude that UiO-66 was stable for 28 days to each of the aging conditions of the study, with water uptake 20mmol/g and 16mmol/g at 25 and 40 °C both at 90% RH respectively.

In this work, the performance of the water vapor harvesting unit is studied under Baghdad conditions (33. 3°N, 44.33° E), to investigate the effect of mass flow rate of air over the desiccant materials and the types of desiccant materials on the amount of freshwater production. As well as a mathematical model is built to estimate the daily water production around the year.

2. Experimental work

This work focuses on the using of desiccant materials that enclosed in a metal container to desorb the moisture associated with ambient air, solar radiation is used to heat up the saturated desiccant, as the desiccant materials temperature increases the adsorb water vapor desorbs and condensate on the container glass cover as fresh water. The water-harvesting unit consists of; unit container that built from aluminum sheet of 0.6 mm thickness, the dimensions of the container is 27 cm wide, 93cm length and 10 cm height as shown in figure 3. Two round ducts are installed at the upper and lower of the container each of diameter of 6 cm in diameter, and 7 cm length. The first one is used to intake the moist ambient air. The second one with the same dimensions as of the first is used to exhaust the dry air. A glass sheet of 4 mm glass thickness covers the front face of the container. The aims of the glass cover is to condensate the desorb water vapor as well as to protect the desiccant materials from the ambient effects. Desiccant materials container is built to allow the largest contact area between the desiccant materials and humid air. The container is divided into 12 sub-containers. The sub-containers are hanged on a joint that allows a free movement and ensures horizontal positions of the sub container, as shown in figure 3.

The sub containers consist of two sides of dimensions of 50 mm in length and 30 mm in width, a rectangle shape is cut from the side bottom to increase the contact area between the air and the desiccant. Two sides are connected together by five shafts of 2 mm in diameter and 230 mm in length. A steel mesh of grade of 0.5 mm. is lining the outer part of the container to contain the desiccant, as shown in figure 3. Figure 4 shows the final shape of the water-harvesting unit.

The unit is installed in a stand; the tilt angle of the stand can be adjusted manually to give the required tilt angle of the unit that gives the maximum gain of solar radiation. An axial fan is used to intake the ambient air and blow it through the unit, the capacity of fan is 1.8 W, with maximum current 0.15 A DC, and 12V DC. The volume flow rate of air is controlled by controlling the fan speed using a Variac. The water-harvesting unit is contained in a cork case to reduce the heat loss from the unit. The cork case dimensions of 2.5cm thickness, 32 cm wide,
98cm length and 12.5cm height. Solid desiccant materials are powder and bullets such as silica gel and zeolites used in the current work. The physical and chemical properties, as well as the shape of the desiccant used are shown in Table 1.

Table 1. Chemical and physical properties of desiccant used in this work.

| Type                  | Silica gel | Zeolite          |
|-----------------------|------------|------------------|
|                       |            | 13X  | 3Å  | MCM-41    |
| Shape of particle     | Spherical  | powder | Pellet | Pellet | Powder |
| Size range (mesh)     | 3-5        | 40-120 | 2-6   | 2-6    | 60-120 |
| Bulk dry density (kg/m³) | 585     | 300   | 650-700 | 680-750 | 250-400 |
| Average pore diameter (mm) | 2-4     | 0.125-0.25 | 6.35  | 6.35  | 3.8×10⁻⁶ |
| Surface area (m²/kg)  | 800        | 300-550 | 700   | 700   | 1000   |
| Sportive capacity (kgₜₖg/kgₜₖ_dry) | 0.45 | 0.40-0.55 | 0.355-0.415 | 0.30 | 0.960 |

Two types of silica gel are used, as follows: a crystals shape silica gel is used, the color of silica gel is dark blue, and the size of the crystals is in the range of 2 to 4 mm. The sportive capacity of 0.45 kgₜₖg/kgₜₖ_dry, with a bulk dry density of 385 kg/m³. A white powder silica gel of a particle size in the range of 0.125 to 0.25 mm is used. The sportive capacity of 0.4 to 0.55 kgₜₖg/kgₜₖ_dry, with a bulk dry density of 300 kg/m³.

Three types of zeolite are used, as follows: light brown zeolite pellets are used in this work, the particle size of 6.35 mm, and the size of the crystals is in the range of 2 to 4 mm. The sportive capacity of 0.355 to 0.415 kgₜₖg/kgₜₖ_dry, with a bulk dry density of 650 to 700 kg/m³. Alight brown Zeolite 3Å pellets of a particle size 6.35 mm are used in this work. The sportive capacity of 0.4 kgₜₖg/kgₜₖ_dry, with a bulk dry density of 680 to 750 kg/m³.

A white Nano powder Zeolite MCM-41 of size 3.8*10⁻⁶ mm. The sportive capacity of 0.96 kgₜₖg/kgₜₖ_dry, with a bulk dry density of 250 kg/m³.

A digital anemometer of model DA40 is used to measure the velocity of airflow over the desiccant materials. The average velocity can be obtained for 2 or 16 sec. Three sensors of type DHT-22 are used to measure the dry bulb temperature and relative humidity of air at inlet and outlet for the water harvesting unit. Desiccant materials surface temperature and the inner surface temperature of the glass are measured using sensors of type DS18B20. The bed surface temperature and the outer surface temperature of the glass are measured using sensors of model MAX6675. The locations of measuring points are shown in figure 5.
solar power meter are stored in an Arduino in a time step of 15 min. The error analyses of the experiments are shown in Table 2.

3. Adsorption Model:
Tóth model [10] is commonly used to correct the wrong behavior of the substance at both the low and high pressure ends. This equation is well describes many systems with sub monolayer coverage. Tóth model can be represented as follows [11]

\[ \theta = \frac{p \cdot b}{(1 + (p \cdot b)^n)^n} \]  

Where:
\[ \theta \]: Empirical isothermal Tóth model.
\[ p \]: Water vapor partial pressure (kPa).

The parameters \( b \) and \( n \) are specific to dsorbate adsorbent pairs.

\[ \theta = \frac{C}{C_o} \]  

Where:
\[ C \]: Uptake of the water (kg\textsubscript{w}/kg).
\[ C_o \]: Saturated amount adsorbed (kg\textsubscript{w}/kg).

\[ b = k_o e^{(H/RT)} \]  

Where
\[ k_o \]: Equilibrium constant.
\[ H \]: heat of adsorption (kJ/kg).
\[ R \]: Universal air constant (kJ/kg K).
\[ T \]: Temperature (K).

\[ \therefore A = 1 - \frac{(p \cdot b)^n}{1 + (p \cdot b)^n} \]  

\[ \frac{d\theta}{dt} = \theta \cdot A \cdot \left( \frac{1}{p} \cdot \frac{dp}{dt} + \frac{H}{R \cdot T^2} \cdot \frac{dT}{dt} \right) \]

The vapor enthalpy can be calculated by [12].

\[ h_v = (2501 + 1.84T_b) \]

The moisture content of air can be calculated by:

\[ \omega = 0.622 \cdot \frac{p}{p_{atm} - p} \]

\[ \dot{m}_w = -M_{sg}C_o \frac{d\theta}{dt} \]

Where \( \dot{m}_w \) is mass flow rate of water vapor in air mass (kg/s).
The net of heat transfers out of the bed can be expressed by:

\[ q_{\text{net}} = q_{\text{rad}} - q_{\text{conv}} \]

Where
\[ q_{\text{net}} \]: Net of heat transfers of bed (W).
\[ q_{\text{rad}} \]: Radiation heat transfers (W).
\[ q_{\text{conv}} \]: Convection heat transfer (W).

The convection heat transfer from the bed can be calculated by:

\[ q_{\text{conv}} = hA_b(T_b - T_{air}) \]

Where
The solar incidence on the collector is:

\[ q_{\text{rad}} = I \tau \alpha \quad (11) \]

Where
- \( I \): Incident solar intensity (W/m²).
- \( \tau \): Glass cover transmissivity.
- \( \alpha \): Glass cover absorptivity.

The heat transfer between glass and air can be calculated by:

\[ q_{\text{ag}} = \frac{1}{h_t} (T_a - T_{\text{amb}}) \quad (12) \]

\[ T_g = T_a - \frac{q_{\text{ag}}}{h_2 A} \quad (13) \]

The dew point temperature of water vapor associated with air is [13]:

\[ D_p = [6.54 + 14.256 \ln(p_s) + 0.7389(\ln(p_s))^2 + 0.09486(\ln(p_s))^3 + 0.4569p_s^{0.1984}] \quad (14) \]

Where:
- \( p_s \): vapour pressure (kPa).
- \( p_{\text{sw}} \): Saturation vapour pressure at wet bulb temperature (kPa).
- \( p_{\text{at}} \): barometric pressure (kPa).
- \( A \): constant (\( A = 6.66 \times 10^{-4} \)).
- \( T_d \): dry bulb temperature (°C).
- \( T_w \): wet bulb temperature (°C).

### Table (2): Absolute Accuracy of instruments

| Sensor type                  | Error       | Sensor type                  | Error       |
|------------------------------|-------------|------------------------------|-------------|
| DHT22 Outlet Air Temperature. | ±0.3°C      | DHT22 Inside box Air Temperature. | ±0.5°C      |
| DHT22 Outlet Air Relative Humidity. | ±2%        | DHT22 Inlet Air Relative Humidity. | ±2%        |
| DHT22 Inlet Air Temperature.   | ±0.5°C      | DS18B20 Waterproof temperatures sensor. | ±0.5°C      |
| DHT22 Inlet Air Relative Humidity. | ±2%        | MAX6675 Thermocouple temperatures sensor. | ±0.5°C      |
| DHT22 Inlet Air Relative Humidity. | ±0.3°C     | Digital anemometer to measure the velocity | 1%          |
| DHT22 Environmental Air Humidity. | ±2%        |                              |             |

The model of equations mentioned above were solved using MatLab R2018.B Program, the special laws of desorption and adsorption model was used to calculate the amount of water content of each material vs time.

### 4. Results and discussions:

The ability of different types of desiccant materials in local market of moisture capture are studied, the desiccant materials are Silica gel powder, Silica gel pellets, Zeolite13x and Zeolite3Å. As well as a Nano powder, MCM-41 is exported from the Chain since this material is not available in the local market. The weather data for selected day in December at Baghdad 33.3152° N, 44.3661° E is shown in figure 6. While the yearly weather data are shown in figure 7. Figure 8. shows the variation of the moisture content and relative humidity of intake and enclosed air in the unit when Zeolite 13 X pellets is used with a mass flow rate of air of 12.5 kg/hr. The principle of unit operation is to blow the intake air over the desiccant materials.
starting from 0 to 9 hr. During the period extended from 07:00 to 16:30 the fan turn off and the inlet and outlet gets of the unit are closed. At this period of time the Zeolite 13 X pellets subjected to the solar radiation, as the temperature of the Zeolite 13 X pellets increases the adsorbed water vapour is desorbed and the moisture content of the enclosed air increases rapidly as shown in the figure. In the same time the relative humidity of the enclosed air reduces as a result of increasing the pressure in the unit due to increases of air temperature. As the moisture content of the enclosed air increases the water vapour condenses on the glass cover, the latent heat of condensation gained by the glass cover and the temperature of the glass cover increases to be more than the dew point and ambient temperature as shown in figure 9.

Figure 6. Weather data at Baghdad at 21st December 2019.

Figure 7. Annual weather data for Baghdad.
The same experimental procedures are achieved on the reset desiccant materials mentioned above to find the maximum water vapour adsorption by the desiccant materials as shown in figure 10. The main factors that affecting the ability of uptake water for the desiccant materials are, the ability of materials to uptake water relative to its weight or volume, the uptake of water should be achieved at relatively low humidity, and the water vapour should be desorbed at low temperature. Zeolites of both types used in this work can uptake water at low relative humidity; there is a strong interaction force between the water molecules and the zeolite surface, so it is not easy to get water from Zeolites, the figure shows that the uptake of water for Zeolite is about
2.5%. Similar results with less difficulty in releasing of water vapour can be seen for silica gel with maximum uptake of water of 8%. But from the figure it can be seen that MCM-41 has the maximum water uptake of 25% and the ability of releasing water vapour at low temperature. So from that fact the performance of MCM-41 is studied in details, and the compared with the water production for the rest desiccant materials.

![Figure 10. Mass water uptake ratio of e for different desiccant materials](image)

The comparison between the daily productivity of water per one kg of desiccant materials is shown in figure 11. It can be seen that the maximum water production is for MCM-41 due to the high uptake of water as well as due to the ability of MCM-41 in releasing of water at relatively low temperature. The effect of air volume flow rate on the moisture content inside the water harvesting unit when using MCM-41 is shown in figure 12. The figure shows that the moisture content of the air increases with the increasing of the mass flow rate of the air. But this increase is maximized at the flow rate of 14 kg/hr. After the mass flow rate of air of 14 kg/hr, which the moisture content of the air begins to decrease. It is believed that the increased in the air flow rate leads to the drying of the MCM-41 instead of moistening it.

The moisture content of the enclosed air with the water harvesting unit reflects on the daily water productivity, as shown in the figure 13. It can be seen from the figure that the maximum daily water productivity is about 0.5 kg$_{w}$/kg$_{MCM-41}$ when the mass flow rate of air is 14 kg/hr, i.e. the best mass flow rate of air seems to be 14 kg/hr of air per 1 kg of MCM-41.

![Figure 11. The daily productivity of water per one kg of desiccant materials](image)
Figure 12. Moisture content of the unit enclosure at different mass flow rate of air when using MCM-41

Figure 14 shows the desorption process on the psychometric chart, the desorption process starts at time 8 hr in which the releasing of water vapour starts, and the water vapour tends to accumulate in the enclosure, as the solar radiation increases the desorption of water vapour increase gradually until time 10 hr. From the period extended from 10 to 11 hr a significant releasing of water vapour occurs due to the increases of solar radiation. It seems that most of water vapour adsorbed by the MCM-41 is desorbed as shown during the period extended from 11 to 12 hr. The condensation process stars after 12 hr in which most of water vapour condenses as fresh water. Since the end condensation process does not reach the starts desorption process, thus the glass cover falls in condensation of the whole water vapour in the enclosure, this due to the reduction in vapour pressure inside the enclosure, so the a significant lost in the water vapour shows in the figure.

Figure 15. shows a comparison between the experimental and mathematical daily water production per one kg of adsorbent. Three types of adsorbent are used, namely silica gel of both type powder and pellets, and MCM-41 when the mass flow rate of air is 12.5 kg/hr. It can be seen from the figure that maximum error is about 17.83% for silica gel pellets and the minimum is for MCM-41. It is believed that the source of error is due to the ideal assumption that there is no heat loss and that all water vapor inside the unit condenses completely.
The partial pressure for water vapour in the water harvesting enclosure is calculated from the experimental results using the psychometric equations and the results are compared with that obtained from the mathematical model, as shown in figure 16. The figure shows that the partial vapour pressure is a direct function with the day time, or in another word, with the solar intensity. This is due to that the amount of desorbed water vapour increases with the increasing of solar radiation. As the water vapour condenses on the glass cover the vapour pressure tends to reduce, and reaches the minimum at 17hr. The comparison between the experimental and mathematical model enclosure temperature is shown in figure 16, it can be seen from the figure that there is a direct relation between the incident solar radiation and both the MCM-41 and air temperature. The figure shows a good agreement between the experimental and mathematical model at beginning of the day, the error tends to be increases at the end of the day, this is due to the accumulated of error in calculation of the temperature.
Figure 16. The variation of calculated and modeled vapour partial pressure with the daytime.

The daily water production for selected months of the year is studied mathematically, as shown in figure 17. The figure shows that the maximum daily production is for winter season, since the winter in Iraq is characterized by high humidity compared to the rest of the year. The minimum daily water production is for the summer, that characterized by low relative humidity.

A comparison between the current work and [8]. work for the daily productivity is shown in figure 18. It can be seen from the figure that the maximum daily productivity of water when using MCM-41 is about 1.5 kg per meter square of collector area, while it was about 1.26 for [8], this figure shows a deviation between the two works is about 16%.

Figure 17. The mathematical modeling is to investigate the performance of the water harvesting unit under the annual conditions of Iraq for four-month.
Figure 18. Comparison between the daily productivity for the current and another work for MCM-41 [8].

6.1 Conclusions:

From the experimental and mathematical modeling it can conclude that:

1. The maximum daily production of water harvesting unit using MCM-41 is 0.5 kg/w/kg_{ads}, when the mass flow rate of air is 14 kg/hr, as the mass flow rate of air increases more than 14 kg/hr the daily water production reduces.

2. The mathematical modeling of the water harvesting unit shows the maximum water production is about 0.55 kg/w per kg of MCM-41 at December.

3. The use of another desiccant materials like Zeolites and silica gels shows encourage results in daily production of water of less than 0.1 kg/w/kg_{ads}

4. The error between the experimental and mathematical model for daily water production are in the range of 12.5 to 17.8% for the desiccant materials used in this work.

5. The deviation between the current work and another work is 16% for MCM-41.

References

[1] A. A. A. Attia, “Thermal analysis for system uses solar energy as a pressure source for reverse osmosis (RO) water desalination,” Sol. Energy, vol. 86, no. 9, pp. 2486–2493, 2012.

[2] J. J. Hermosillo, C. A. Arancibia-Bulnes, and C. A. Estrada, “Water desalination by air humidification: Mathematical model and experimental study,” Sol. Energy, vol. 86, no. 4, pp. 1070–1076, 2012.

[3] M. H. Mohamed, G. E. William, and M. Fatouh, “Solar energy utilization in water production from humid air,” Sol. Energy, vol. 148, pp. 98–109, 2017.

[4] J. Ameis, “How Much Water Is in the Skating Rink?..” Math. Teach. Middle Sch., vol. 10, no. 4, pp. 164–168, 2004.

[5] R. Li, Y. Shi, L. Shi, M. Alsaedi, and P. Wang, “Harvesting Water from Air: Using Anhydrous Salt with Sunlight,” Environ. Sci. Technol., vol. 52, no. 9, pp. 5398–5406, 2018.

[6] A. J. Talib, A. H. N. Khalifa, and A. Q. Mohammed, “Performance study of water harvesting unit working under iraqi conditions,” Int. J. Air-Conditioning Refrig., vol. 27, no. 1, pp. 1–9, 2019.

[7] M. Kumar and A. Yadav, “Comparative study of solar-powered water production from atmospheric air using different desiccant materials,” Int. J. Sustain. Eng., vol. 9, no. 6, pp. 390–400, 2016.

[8] J. G. Ji, R. Z. Wang, and L. X. Li, “New composite adsorbent for solar-driven fresh water production from the atmosphere,” Desalination, vol. 212, no. 1–3, pp. 176–182.
2007.

[9] J. B. Decoste, G. W. Peterson, B. J. Schindler, K. L. Killops, M. A. Browe, and J. J. Mahle, “The effect of water adsorption on the structure of the carboxylate containing metal-organic frameworks Cu-BTC, Mg-MOF-74, and UiO-66,” J. Mater. Chem. A, vol. 1, no. 38, pp. 11922–11932, 2013.

[10] D. D. Do, Adsorption Analysis: Equilibria and Kinetics, vol. 2, no. Imperial College Press. 1998.

[11] O. R. F. Cevallos, “Adsorption Characteristics of Water and Silica Gel System for Desalination Cycle,” King Abdullah University of Science and Technology Thuwal, Kingdom of Saudi Arabia, 2012.

[12] M. J. Lampinen, “Thermodynamics of humid air,” Dep. Energy Technol. Ene-39.4027-Mass Transf. P, vol. 23, pp. 2015–2019, 2015.

[13] J. F. Kreider and P. S. C. Heating, “Refrigeration and Air-conditioning Engineering References.”

Nomenclature

A Heat transfer area. (m²)
A₀, Aₙ Cross section area of bed and glass. (m²)
b, n Specific to Absorbent-adsorbent pairs -
C, C₀ Uptake of the water and Saturated amount adsorbed. (kg/w/kgₐₙₜₜ)
Cₚ Specific heat of air at constant pressure. (J/kg.°C)
Td&Tw Dry and wet bulb temperatures. (°C)
H Isostatic heat of adsorption. kJ/kg
h Heat transfer coefficient. (W/m².°C)
hₑ Latent heat of evaporation. (J/kg)
h₀ Overall heat transfer coefficient between humid and ambient air. (W/m².°C)
I Incident solar intensity. (W/m²)
kₔ Thermal conductivity of glass. (W/m.°C)
kₒ Equilibrium constant.
L Characteristic length (m)
mₐ Mass of air. (kg)
mₑ Condensation mass flux. (kg/m²)
mₚ Mass of water vapor in the air mass. (kgₚ)
P Water vapor partial pressure. (kPa)
Pa barometric pressure. (kPa)
Pₐₜₜₜ Atmosphere pressures respectively (kPa)
P₃ Vapor pressure. (kPa)
Pₛₜₜ Saturation vapor pressure at wet bulb temperature. (kPa)
q₁ Heat transfer between bed and air. (W)
q₂ Heat transfers between glass and air. (W)
qₑ Convection heat transfer. (W)
qₚₜₜ Net of heat transfers from the bed. (W)
qᵣᵣᵣ Radiation heat transfers. (W)
qₛ Heat storage. (W)
R Universal air constant. (kJ/kg.K)
T Temperature. (K)
T₁, T₂ different equilibrium temperatures adsorbate/adsorbent pair. (°C)
Tₐ Temperature of ambient (°C)
Tₕₕₕ Temperature of air.(°C)
Tₙₙ The bed and glass temperatures (°C)
Tₜₜₜ Temperature of humid air(°C)
tₚₙThem Thickness of glass (mm)