



Harvesting water from air using adsorption material – Prototype and experimental results

Ahmad K. Sleiti^{*}, Hamza Al-Khawaja, Hassan Al-Khawaja, Mohammed Al-Ali

Department of Mechanical & Industrial Engineering, College of Engineering, Qatar University, Doha, Qatar

ARTICLE INFO

Keywords:

Air water harvesting
Adsorption based atmospheric water harvesting
Water harvester
Test setup
Condensation

ABSTRACT

Drinking water resources have always been limited in the gulf region of the Middle East and other desert regions around the world. In attempt to provide viable supplement, a device that harvests clean drinking water from air is designed, built and tested. The operation of the device is based on harvesting water naturally from air using adsorption materials. The prototype of this device consists of sorbent (silica gel is used in this study) exposed to radiant flux, water sorbent unit, condenser and reflector. Experimental studies of production of fresh water from air in controlled indoor environment have been carried out using the prototype. Several experimental tests were conducted under the conditions of 22 °C ambient temperature, a range of relative humidity (RH) from 30 to 60%, a range of silica gel thickness from 25 to 35 mm, surface area to volume ratio from 0.29 to 0.4 and radiant heat flux range from 509 to 556 W/m². The prototype was able to produce up to 159 g of water per 1 kg of silica gel in a 12 h cycle when exposed to 556 W/m² radiant flux. In terms of per one day (24 h), the harvester can produce 800 mL of water with an overall efficiency of 50% for 25 mm silica layer thickness. Increasing the relative humidity speeds up the adsorption cycle and increases the water capture, release and collection rates. The system can be improved by adding multiple layers of sorbent stacked on top of each other and by using sorbents with improved adsorption and desorption properties.

1. Introduction

Drinking water resources have always been limited in most countries of the Middle East, especially in the gulf region, and in many other regions around the world. For instance, in Qatar, more than 98% of the drinking water is produced from desalination [1,2], which is an energy intense and costly process. To provide sufficient drinking water in such regions, new technologies other than desalination have to be explored and developed. Several different studies and techniques for water harvesting from desert air were reported in open literature [3,4]. These techniques include: (a) atmospheric water harvesting using condensation technologies; (b) using sorption technologies and (c) other technologies such as using a wind turbine to produce water and electricity [5], solar chimneys [6], solar still powered by concentrator [7] and several other innovative technologies that were reviewed in [4] and reported in open literature. Another interesting idea to harvest water is the use of desert plants such as *Syntrichia caninervis* [8], which is a type of plant that thrives in hostile environments that lack fresh liquid water. This plant uses a tiny hair on the end of each leaf to collect water from thin air by turning the moisture in the air into liquid water. This

fundamental principle and phenomena of collecting water from air could be utilized to design and build innovative harvesters. Dehumidification using vapor compression or absorption refrigeration cycles is also a well-known technology to harvest water [9]. These simple refrigeration cycles can be used to cool the water vapor in the air and turn it into liquid water that can be collected as drinkable water. However, most of the refrigerants used in vapor compression cycle contribute to the ozone depletion and global warming, while absorption refrigeration cycles are bulky and have low coefficient of performance (COP).

In terms of utilization combustion technologies, Chaitanya et al. [10] proposed a theoretical model that uses biomass gasification thermal energy to operate a refrigeration system to condense moisture from air. They claimed that their proposed model showed about 1200 L of water production per 1000 kg of biomass. Wikramanayake et al. [11] proposed a model to use the US landfill gas to supply power to a refrigeration system to dehumidify the air for water harvesting at large scale. The CO₂ emissions associated with these combustion technologies makes them less attractive compared to free emission technologies.

Using adsorption materials such as silica gel, Zeolites and Metal-Organic Frame (MOF) materials such as MOF-801, MOF-303 and MIL-

^{*} Corresponding author.

E-mail address: asleiti@qu.edu.qa (A.K. Sleiti).

Nomenclature			
Acronyms		q_H	absorbed energy (kJ/mol)
COP	Coefficient of Performance	$q_{H,Latent}$	latent heat (kJ/mol)
MIL	Material from Institut Lavoisier	q_{st}	isosteric heat of adsorption (kJ/mol)
DEFROST	Microwave setting at 50% power	$q_{H,sensible}$	sensible heat (kJ/mol)
MOF	Metal-Organic Framework	$q_{H,loss}$	lost heat to the surroundings
NIST	National Institute of Standards and Technology	$q_{H,min}$	minimum energy to release all captured water
RH	Relative Humidity	$q_{C,sensible}$	condensation sensible heat (kJ/mol)
WHC	Water Harvest Cycle	$q_{C,latent}$	condensation latent heat (kJ/mol)
WSU	Water Sorption Unit	$q_{C,loss}$	condensation heat loss (kJ/mol)
Symbols		T_a	ambient temperature (°C)
A_c	condenser surface area (cm ²)	T_c	condensation temperature (°C)
A_s	surface area of sorbent (cm ²)	T_{wv}	water vapor temperature (°C)
C_p	heat capacity (J/kg·K)	T_{dew}	dew temperature (°C)
h_{fg}	enthalpy of condensation (kJ/mol)	V_{ol}	volume of sorbent (cm ³)
k	thermal conductivity (W/m·K)	Greek	
L	length (m)	η_C	water capture efficiency (%)
m_{cap}	masses of the captured water (g)	η_R	water release efficiency (%)
m_{col}	masses of the collected water (g)	η_{WHC}	overall efficiency (%)
m_{rel}	masses of the released water (g)	ω_{cap}	captured water per mass of the sorbent (unitless)
m_{sorb}	masses of the sorbent (kg)	ω_{rel}	mass of the released water per unit mass of sorbent (unitless)
P	Water production in g per kg of sorbent (g/kg)		

125(Ti)NH₂ [12] to harvest water from air has become a subject of heavy research [13]. These materials can trap water molecules in the air into their structure and hence, can be used to harvest fresh drinkable water from the air without harmful emissions. Metal-Organic Frameworks are mixtures of materials that can be used in technology capable of harvesting water using only the energy from ambient sunlight interacting with these porous metal-organic frameworks [14,15]. The technology produced 2.8 L of fresh water per kilogram of material per 12 h, even when humidity levels dropped as low as 20% [16]. Other materials such as super moisture-absorbent gel, a hygroscopic polypyrrole chloride penetrating in poly N-isopropylacrylamide, were investigated in [17]. They achieved a high-efficiency water production for a broad range of relative humidity. Harvesting atmospheric water vapor on silica gel surfaces was reported in [18], where they produced about 9.2 mL and 10.6 mL of water on hex grid and simple line gels, respectively. To overcome the limiting factor of incomplete daytime desorption for final water production, researchers in [19] used a combination of tailored interfacial solar absorbers with an ionic liquid-based sorbent. They were able to produce a high rate of water of about 0.5 L/m²·h for the outdoor environment.

The primary objectives of the present research study are to design a device that harvests clean drinking water from thin air and build, test and operate a prototype of the designed device as proof of concept and to produce experimental data (that are limited in open literature) to further advance the performance of the device. This device and the technique used to harvest the water should be most suitable for desert regions with reasonable amount of water production and cost and with no emissions. Thus, the method of harvesting water naturally from air using adsorption materials has been selected in the present study for its superiority in producing reasonable amounts of water, easiness of construction and operation and for its reasonable cost compared to other methods and technologies. The prototype is then tested experimentally to produce data for a wide range of parameters that are rather limited in open literature and it will be used as a benchmark for improved future designs and performances. The manuscript is structured as follows: in Section 2, the harvester design and its performance are presented followed by the prototype and the sorbent in Section 3. Section 4 details the experimental results and Section 5 discusses these results in depth.

2. Water harvester design and performance

2.1. Design of the harvester

To achieve the objectives outlined in the introduction section, a device was designed in the present study based on the prototype developed in [13] that consists of an adsorbent (silica gel) exposed to radiant flux, water sorbent unit, condenser and reflector, as shown in Fig. 1. The silica gel was selected as sorbent in this study for its attractive properties [20], availability and low cost compared to other MOFs, see Section 3 for more details. The condenser is made of acrylic plastic with 454 mm in depth and width and 255 mm in height. The Water Sorption Unit (WSU) shown in Fig. 1(A), which is the silica container, is 395 mm × 395 mm with white paint and extruded polystyrene foam insulation. Clear acrylic is used for the cover with a 0.3 cm thickness to easily allow the sun rays and heat to pass through and into the adsorption material. The acrylic opening, Fig. 1(B), is made as wide in dimensions as the adsorption material surface area and on the sides of the cover a reflective material (Tin) is installed to prevent the sun rays from entering in between the adsorption material container and the condenser. In other words, the sun rays will be directed towards the adsorption material only. The silica gel used in this study is the orange indicating silica gel beads with beads size about 2–4 mm. Beads will turn orange (active) to dark green (saturated) when they become 50–60% saturated with moisture.

The 3D final design of the harvester is shown in Fig. 1(C). Specific design details and the performance of the harvester are discussed in subsequent sections.

2.2. Performance of the harvester

The following analysis of the harvester is adapted from [13]. The energy that sorbent absorbs, q_H in units of kJ/mole is composed of three parts as follows:

- (a) latent heat to change the phase

$$q_{H,Latent} = \omega_{cap}q_{st} \quad (1)$$

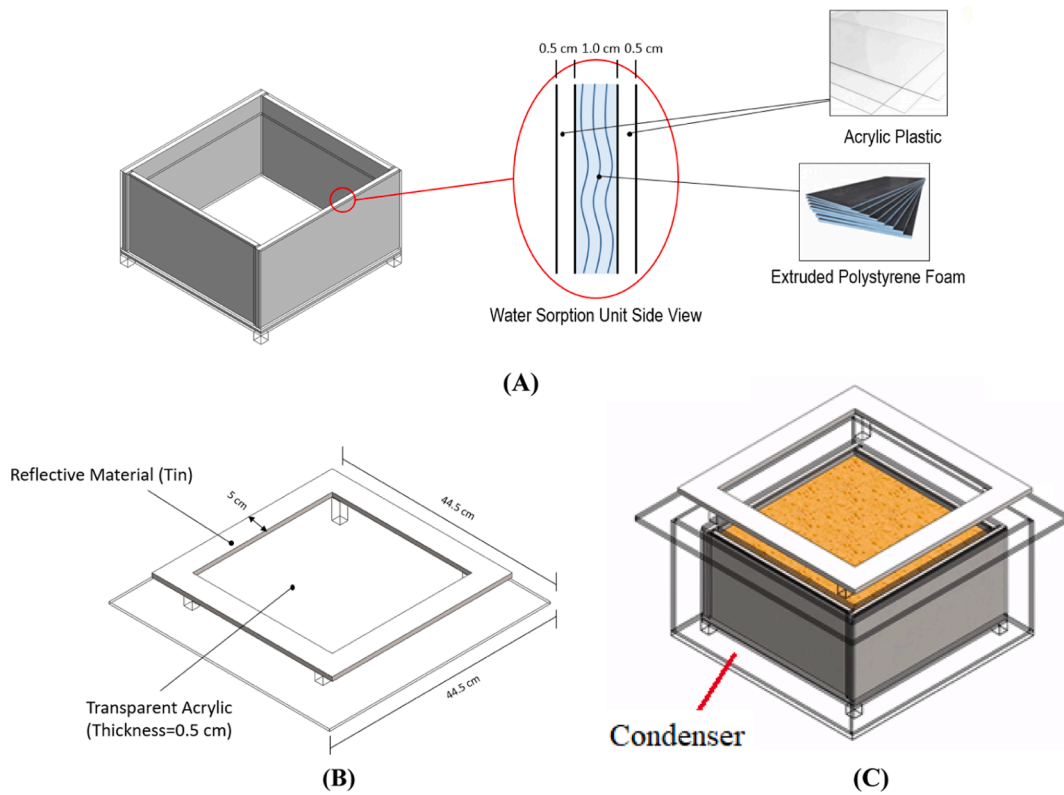


Fig. 1. (A) Water Sorbent Unit, (B) Cover and (C) Final Design.

where ω_{cap} (unitless) is the captured water per mass of the sorbent:

$$\omega_{cap} = \frac{\text{density of water} \times \text{Volume of water}}{\text{mass of sorbent}}$$

and q_{st} is the isosteric heat of adsorption in units of kJ/mole . For silica gel used in the present study, $q_{st} = 50 \text{ kJ/mole}$.

- (b) sensible heat to increase the temperature of the silica gel, ($q_{H,sensible}$) in units of kJ/mole , and
- (c) lost heat to the surroundings, ($q_{H,loss}$).

For the sorbent, the sensible heat is less than the latent heat and the lost heat is less than the sensible heat because the adsorbent container is thermally insulated. As a result, large portion of the absorbed energy, q_H will be taken by the sorbent and water (latent part) to release water. Therefore, the sorbent must have a low q_{st} to achieve this. For a water capture cycle to maximize the water release, the following condition must be satisfied:

$$(q_{H,min} > \omega_{cap} q_{st}) \quad (2)$$

where $(q_{H,min})$ is the minimum energy needed to release all captured water.

The water release efficiency (η_R) is defined as follows:

$$\eta_R = \frac{m_{rel}}{m_{cap}} = \frac{\omega_{rel}}{\omega_{cap}} \quad (3)$$

where m_{rel} and m_{cap} are the masses of the released and captured water, respectively and ω_{rel} is the mass of the released water per unit mass of sorbent (unitless). Notice that $\omega_{rel} \leq \omega_{cap}$ as sorbents capture more water than they release, or in other words, sorbents do not release all water that they capture.

From Equation (3), it can be concluded that for a fixed ω_{cap} , the release efficiency can be increased by using a sorbent that has the

following properties (1) relatively high thermal conductivity, k ($\text{W/m}\cdot\text{K}$) to conduct the heat fast, (2) low heat capacity, C_p ($\text{J/kg}\cdot\text{K}$) to not store the heat in itself, and (3) elevated energy absorptivity. Also, the sorbent containment must be designed to have large ratio of surface to volume. It can be argued that at high temperatures the sorbent is expected to release water at higher rate than capturing the water, given that the night hours are more than the sunlight hours.

To release the water vapor from the sorbent, a condensation (cooling) process is needed. The required energy for the condensation process consists of three components: sensible ($q_{C,sensible}$) that is used to decrease the air temperature and the released water temperature, (2) latent ($q_{C,latent}$) that is used to change the phase from gas to liquid, which is also equals to $\omega_{cap} h_{fg}$, and (3) heat loss ($q_{C,loss}$) to surrounding. As the enthalpy of condensation (h_{fg}) for water is very high at the range of the operating temperatures of the harvester, the latent part ($q_{C,latent}$) is much more than the sensible part ($q_{C,sensible}$). The minimum value of the cooling capacity of the harvester should be more $\omega_{cap} h_{fg}$ to insure that all the amount of the released water is condensed:

$$q_{C,min} > \omega_{cap} h_{fg} \quad (4)$$

In the present study, acrylic plastic is chosen as the material for the case (condenser) since it is available in abundance, easy to machine and not costly. A study conducted on two different thicknesses of acrylic plastic [21], revealed that a 6 mm thick acrylic gains heat (heats up) slower than the 3 mm thick acrylic and thus the 6 mm thickness is selected for the case. Also, [21] conducted a study on a white and a clear acrylic on how fast can each type of acrylic heat up and cool down. The study revealed that the white acrylic heats up slower than the clear acrylic and therefore, the white acrylic is selected.

The calculation procedure of the surface area of the case (A_c) is as follows:

The cooling energy needed to condense the water vapor, q_c is given as:

$$q_c = q_{C,sensible} + q_{C,latent} + q_{C,loss} \quad (5)$$

or

$$q_{C,sensible} + q_{C,latent} + q_{C,loss} = \omega_{rel} C_{p,wv} (T_{wv} - T_{dew}) + \omega_{rel} h_{fg} + q_{C,loss} \quad (6)$$

Assuming ($T_a = T_{wv}$) and thus neglecting the heat loss,

$$q_{C,sensible} + q_{C,latent} = (T_a - T_{dew}) \left(\omega_{rel} C_{p,wv} + \frac{m_{air}}{m_{MOF}} C_{p,a} \right) + \omega_{cap} h_{fg} \quad (7)$$

In the present study, the condensation process is assumed to occur solely due to natural cooling (no external cooling used) and hence for such process:

$$q_c = \int_{sunrise}^{sunset} \dot{q}_c(t) dt = A_c \int_{sunrise}^{sunset} \bar{h} (T_a - T_c) dt \quad (8)$$

where t is the time in seconds, h is the convection heat transfer coefficient in $W/m^2 \cdot K$ and T_c is the condenser temperature in Kelvin. This equation is rearranged to solve for the condenser surface area as follows:

$$A_c = \frac{m_{moj}}{\int_{sunrise}^{sunset} \bar{h} (T_a - T_c) dt} \left[(T_a - T_{dew}) (\omega_{cap} C_{p,w}) + \omega_{cap} h_{fg} \right] \quad (9)$$

Based on the above and assuming the water release occurs at 60 °C, condenser temperature is the same as the dew point temperature ($T_c = T_{dew}$), T of air is 45 °C and T of condenser is 35 °C, the desired for this study surface area of the condenser is estimated to be about 4539 cm^2 . The final dimensions of the case are given in Fig. 2A.

For the Water Sorption Unit (sorbent container), the size of the container is chosen based on the sorbent properties. Since the initial aim of this project is to harvest around 1 L of water per day, the needed mass of the sorbent is calculated accordingly. The thickness of the sorbent container layer was taken 1 in. (2.54 cm) from the code: National Institute of Standards and Technology (NIST) – Data Resources for Adsorption Science and Technology. The distance between the water sorption unit and the cover of the case, Fig. 2B, was taken to be 1 in (2.54 cm) from the same code.

The efficiency of the collecting cycle (η_c) is calculated as:

$$\eta_c = \frac{m_{col}}{\omega_{rel} m_{Sorb}} \quad (10)$$

where, m_{coll} and m_{sorb} are the masses of the collected water and the sorbent, respectively.

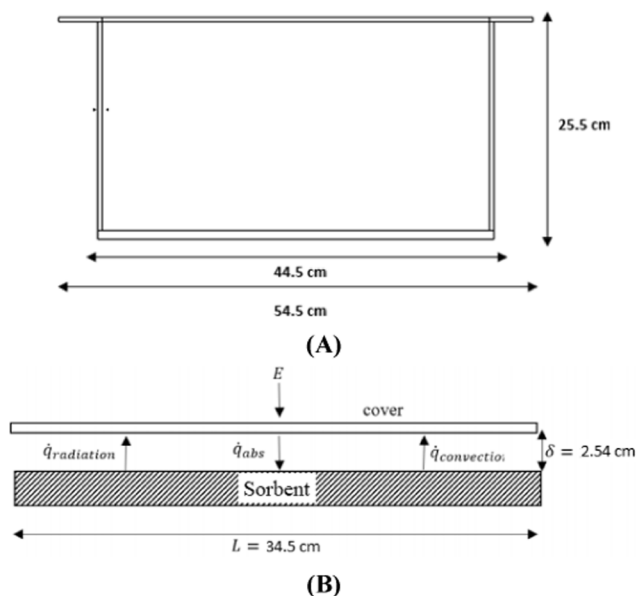


Fig. 2. (A) Front view of the case with dimensions, (B) Illustration of distance between sorbent surface and cover.

The condenser temperature must be kept below the dew point temperature for natural harvesters that operate using only ambient cooling. Therefore, an efficient condenser that meets this criteria must be designed by maximizing its surface area and by using augmented heat transfer techniques to boost the convection heat and mass transfer.

The overall efficiency of the Water Harvest Cycle (WHC), (η_{WHC}) is defined as:

$$\eta_{WHC} = \frac{m_{col}}{\omega_{cap} m_{Sorb}} = \eta_R \eta_c \quad (11)$$

Hence, to maximize the water production, the amount of the water released from the sorbent should be equal to the captured amount of water. This is not always the case and it depends on the sorbent properties, relative humidity and the operation temperatures as will be shown in the results section.

3. Water harvesting prototype with silica gel sorbent

Based on the above analysis of the harvester performance, the water harvesting prototype was built and is shown in Fig. 3. As shown in the Figure, the water sorption unit of the harvester holds the sorbent (silica) and the case (condenser) encloses it. Compared to devices available in open literature including the device built by [13], the harvester in the present study is characterized by its higher performance; durability; mobility; accuracy of measurements; compactness; easiness of assembly; ability to handle large range of tested parameters (temperatures, relative humidity, and radiant fluxes) and large range of sorbent thicknesses. All these aspects are discussed in more details in subsequent sections.

The sorbent used in this study is orange indicating silica gel beads from Dry & Dry [22] with the following specifications:

- Beads Size (granularity): 2–4 mm
- Specific surface area: 750–800 m^2/g
- Pore volume: 0.4–0.45 cm^3/g (0.43 average)
- Nominal pore size: 22 Angstroms
- Bulk density (average): 721 kg/m^3
- Beads will turn orange (active) to dark green (Saturated) when 50–60% absorbed with moisture. Still almost half more capacity left to adsorb moisture even after color change
- Free of Cobalt Chloride. The silica gel is doped with methyl violet moisture indicator formulated to change from orange to green
- Beads can be reactivated by placing in an oven for 0.5–2 h at 93–121 °C or in Microwave for about 10 min at DEFROST setting.

The moisture adsorption at 25 and 40 °C of the orange indicating silica gel as a function of relative humidity (RH) is shown in Fig. 1, (retrieved from [22;23]). Silica gel is a form of polymeric colloidal silicic acid that is partially dehydrated. It has an amorphous micro-porous structure with nominal pore size of 22 angstroms that are interconnected to form large surface area (the specific surface area is 750–800 m^2/g). This helps silica gel to attract and hold water by adsorption and capillary condensation allowing it to adsorb up to 50% of its weight in water [24]. As shown in Fig. 4, the moisture adsorption of silica gel at low RH values (below 30%) is very low (~16 g/100 g). However, the harvester is intended to be used in Qatar for which the average monthly RH ranges from 50% on May to 71% on January and December as shown in Fig. 5 (retrieved from [25]). This makes silica gel good choice as sorbent.

The prototype is equipped with heat lamp bulb, temperature measurement instrumentations and humidifier to reach the desired relative humidity. The heat lamp bulb setup is used to provide the required radiant flux (Fig. 3), it has the following specifications:

- 110–120 V, 150 W, E26 lamp base.
- Material: Ceramic, metal.

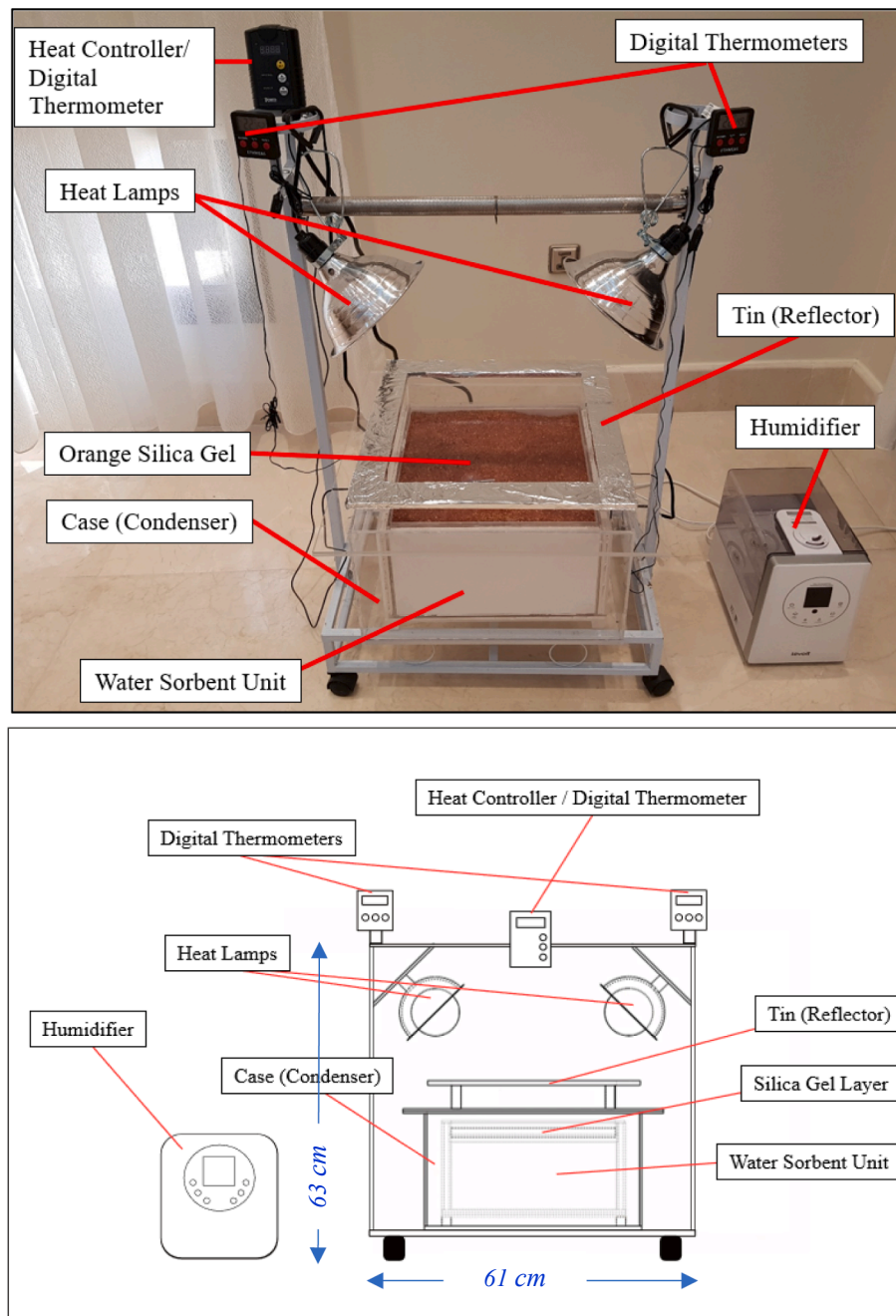


Fig. 3. Water harvester equipped with measurement instrumentations. The total size (L × W × H) is 66 × 61 × 63 cm.

- Multifunctional clamp light: scratch-resistant, adjustable ball joint and 8.5-inch aluminum reflector that can focus light.
- Temperature range: digital thermostat provides temperature control between 40 and 108°F (5–42 °C), with temperature display Range: 32–140 F (0–60 °C).

The digital thermometer and humidity gauge are precise within ± 1 ° temperature and $\pm 5\%$ relative humidity levels. The humidifier can provide a mist output of up to 500 mL/h.

4. Experimental results

The following procedures were followed in running the experiments:

1. The sorbent (silica gel) is saturated at the desired relative humidity and desired room temperature for 6 h. This is referred to as the water capture process.
2. After saturation, the case is sealed and exposed to artificial light for another 6 h. This is referred to as the water release process.
3. The data of temperatures and humidity are collected under low and high radiant fluxes roughly from 509 to 556 W/m², which represents worst case scenarios of average solar irradiance over the course of one day in Qatar.
4. After the second 6 h (after water release process), the liquid water is accumulated in the case and is collected using a needle. This is referred to as the water collection process.

Each experiment reported in the below sections was conducted three times in different days to insure repeatability. The experimental

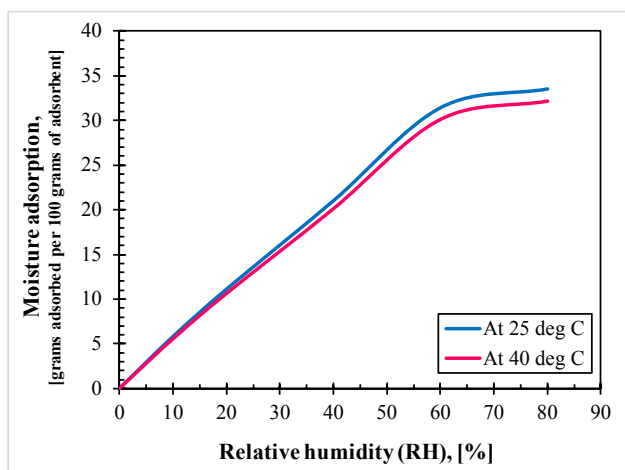


Fig. 4. Moisture adsorption of orange indicating silica gel as a function of relative humidity (RH).

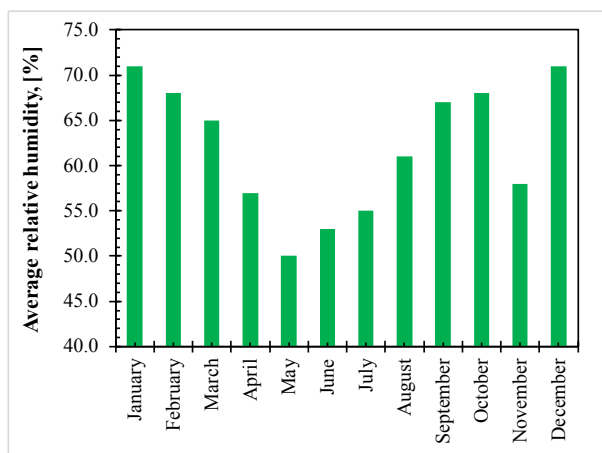


Fig. 5. Average monthly relative humidity (RH) in Doha, Qatar for 2019.

repeatability results showed that the differences in the results of the repeated experiments under the same conditions are less than 2%.

4.1. Comparison of experimental results

The results obtained in the present study are compared to those produced by Fathieh et al. [13] as shown in Table 1. In the reference experiment by [13], the authors used different sorbent under different

Table 1 Water harvester test conditions and performance compared to Fathieh et al. [13].

Test conditions and results	Reference experiment, Fathieh et al [13]				Present study experiment			
	558	792	558	792	509	529	556	529
Radiant Flux, W/m ²	MOF-801/G				Silica Gel			
Sorbent	MOF-801/G				Silica Gel			
Initial RH, %	30		30		40	30	40	40
Initial sorbent temperature, °C	18				20			
Capture time, hr	16.5		16.5		6			
Release time, hr	7.5		7.5		6			
Condenser temperature, °C	20				22			
Mass of sorbent, kg	1.650		0.825		2.549	2.552	2.542	1.186
Water production, g	25	56	37	78	59	285	159	286
P, Water production per kg of sorbent, g/kg	15	34	45	95	23	112	63	241
η _R , % (equation 3)	39	76	44	86	26	37.5	60	95.5
η _C , % (equation 10)	30	34	93	92	79	86.2	88	88.1
η _{WHC} , % (equation 11)	12	33	41	79	21	32.4	53	84.2

test conditions. So to make the comparison meaningful, the focus will be on comparing the performance of the harvester in terms of relative productivity (P) and efficiencies, where P (in g/kg) is defined as the ratio of the mass of the collected water in g to the mass of sorbent in kg:

$$P = \frac{m_{col}}{m_{sorb}} \tag{12}$$

As shown in Table 1, at comparable levels of radiant fluxes (558 W/m² in [13] versus 529 W/m² in present study) and higher mass of sorbent (1.65 kg in [13] versus 2.552 kg in present study), the harvester in this study produced more water than in the reference study (P = 112 g/kg in present study compared to 15 g/kg in [13], see the highlighted columns in blue in Table 1. The water release efficiencies (η_R) are comparable, while the water capture efficiency (η_C) is 86.2% in present study compared to 30% in [13] and the overall efficiency (η_{WHC}) is 32.4% compared to only 12% in [13].

The effect of reducing the mass of the sorbent on P and on the efficiencies (η_R, η_C and η_{WHC}) is significant as shown and highlighted in green color in Table 1. For the reference experiment, the decrease in the mass of MOF-801/G from 1.65 to 0.825 kg improved the water production by three folds (from 15 to 45 g/kg) due to the fact that sorbent surface area kept the same while the sorbent mass is reduced. The decrease in the mass of the MOF-801/G improved η_R slightly from 39 to 44%, while remarkable improvements are observed in η_C (from 30 to 93%) and in η_{WHC} (from 12 to 41%). This increase in all three efficiencies can be explained by looking carefully at the definitions of these efficiencies (Equations (3), (10) and (11)). The harvester in the present study still produced more water at higher release, capture and overall efficiencies compared to the reference study. It is observed that the release efficiency of the present study harvester has increased significantly to 95.5% and the overall efficiency to 84.2% when the mass of the sorbent was reduced from 2.552 kg to 1.186 kg, while the capture efficiency increased slightly to 88.1%. This is attributed to the properties of the sorbent (silica gel).

Fig. 6 shows a comparison between the sorbent used in the present study (silica gel) and different MOF materials from Fathieh et al. [13] in terms of capture efficiency (η_C), overall efficiency (η_{WHC}) and water productivity (P) under the same conditions. The water productive of silica gel at 1.186 kg is more than two times of that for MOF-303/G, 0.6 kg used in [13] at higher capture and overall efficiencies.

4.2. Effect of varying the radiant heat flux

In this section, the effect of varying the radiant heat flux is investigated under the following fixed conditions: Ambient Temperature = 22 (°C), Relative Humidity 40%, Silica Layer Thickness = 25 mm, Silica Surface Area = 1176.5 cm², Volume of Silica = 2941.2 cm³ and Mass of Silica = 2542 g. The radiant flux conservative range selected in the

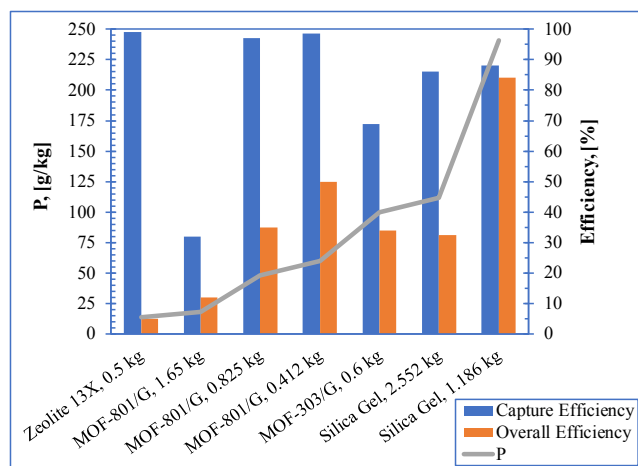


Fig. 6. Comparison of the efficiency and water productivity of sorbents.

current study is from 509 to 556 W/m². This is based on the fact that the average total annual radiant flux in the location of the study in Qatar (25.3773° N, 51.4912° E) is about 602 W/m² [26]. The data provided in Fig. 7 is retrieved from a study by the main author of the current paper [26] which shows the average radiant flux and the sunshine duration in Qatar for each month of the year. The highest average radiant flux is about 748 W/m² in March and the lowest is about 471 W/m² in November, while the average total annual radiant flux is 602 W/m² as mentioned above. Hence, the selected range from 509 to 556 W/m², while conservative, is considered reasonable representation of the actual radiant flux.

The captured water flow rate and the capture efficiency increase by increasing the radiant flux from 509 W/m² to 529 W/m², then slightly decrease as shown in Fig. 8a and 8b. The harvester's water capture flow rate is around 2.26 mL/min at about 89% efficiency for a cycle (12 h). The water flow rate release, the water release efficiency and the overall efficiency, however are increasing for the full range of the tested radiant flux, reaching up to 1.275 mL/min, 60% release efficiency and 53% overall efficiency, respectively, Fig. 8a and b.

The surface temperatures of all components of the harvester are important to observe and are shown in Fig. 8 (c to f). The surface temperatures of the acrylic cover, silica gel, WSU and condenser are all increasing with radiant flux. The difference, however between 3 h and 6 h cases of exposure to radiant flux is within 2 °C only. The maximum temperatures of the surface of the acrylic cover and the sorbent reached about 50.3 °C and 49.71 °C, respectively, indicating that most of the

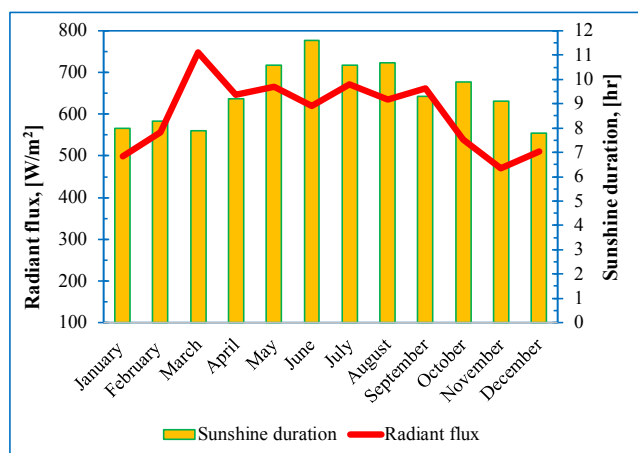


Fig. 7. The average radiant flux and the sunshine duration in Qatar (25.3773° N, 51.4912° E) for each month of the year, retrieved from [26].

radiant flux is being transferred to the sorbent, Fig. 8c and d. The maximum temperature of the condenser surface reached 35.29 °C, which is about 1.65 °C less than the WSU temperature indicating the effect of insulation. To summarize, increasing the radiant flux improves the water release and overall efficiencies, while raises the temperatures of the surfaces of the device by about 5 to 6 °C for the range of the studied parameters. To improve the performance of the harvester, future research should focus on lowering the condenser temperature to less levels than the achieved in this study by improving the insulation material and design.

4.3. Effect of varying the relative humidity

The effect of varying the relative humidity, Fig. 9, is investigated under the following fixed conditions: ambient temperature = 22 (°C), radiant flux = 530 W/m², silica layer thickness = 25 mm, silica surface area = 1176.5 cm², volume of silica = 2941.2 cm³ and mass of silica = 2558 g.

Water capture and release increase with relative humidity up to RH of 45%, then become almost steady as shown by Fig. 9a. The capture efficiency increases with RH, while the release efficiency remains almost steady, Fig. 9b. Increasing RH has minor effect on the surface temperature of the acrylic cover, Fig. 9c, sorbent, Fig. 9d and on WSU, Fig. 9e. It is observed that the surface temperature of the condenser for the 6 h operation case, Fig. 9f, increases by about 3.5 °C compared to the 3 h case, which suggests that the insulation needs to be improved for future use of the harvester.

4.4. Effect of silica layer thickness

The effect of varying the silica layer thickness, Fig. 10, is investigated under the following fixed conditions: ambient temperature = 22 (°C), radiant flux = 529 W/m², RH = 40% and silica surface area = 1176.5 cm². Changing the sorbent thickness for the same surface area, means that the mass of sorbent and the ratio of surface area to the volume of the sorbent will change. This is done to evaluate the effect on water collection when the mass of the sorbent is reduced. Increasing the silica thickness from 25 mm to 35 mm has almost no effect on the surface temperature of the components of the harvester, (Fig. 10a, b, c and d). For example, for the acrylic cover, about 1.5 °C difference is observed and for the sorbent surface temperature (Fig. 10c), about 1 °C decrease between the 25 mm and 35 mm thicknesses was observed. The captured water increases by increasing silica thickness from 25 to 35 mm as shown in Fig. 10e, while both the released and collected water decrease slightly suggesting that the lower thickness is better for higher amounts of collected water.

5. Discussion

Large number of experimental tests were conducted using the harvester prototype; nine of these experiments that best serve the following discussion are selected and shown in Table 2. On average, about 400 g of water was harvested or collected by the system within a cycle of 12 h as shown by experiment number 1 in the last column of Table 2. Running the experiment for 24 h, then 800 g of water can be collected per one day (24 h) at about 50% overall efficiency (η_{WHC}) for 25 mm silica layer thickness as shown by experiment number 1 of Table 2. This is considered acceptable since one of the goals of the study was to harvest one liter of water per day for this proof of concept study.

Referring to Table 2, by increasing the radiant flux in the desorption phase to 556 W/m² (experiment 1), the average water release increased to a maximum value of 458 g and the collected water increased to 405 g. Experiments 2 and 3 confirm that by reducing the radiant flux, less water is released and collected. At higher RH (60% in experiment 4 vs 40% in 2) the captured, released and collected water is higher by about 5%, while reducing RH to 30% (experiment 5 vs 6) resulted in about 40%

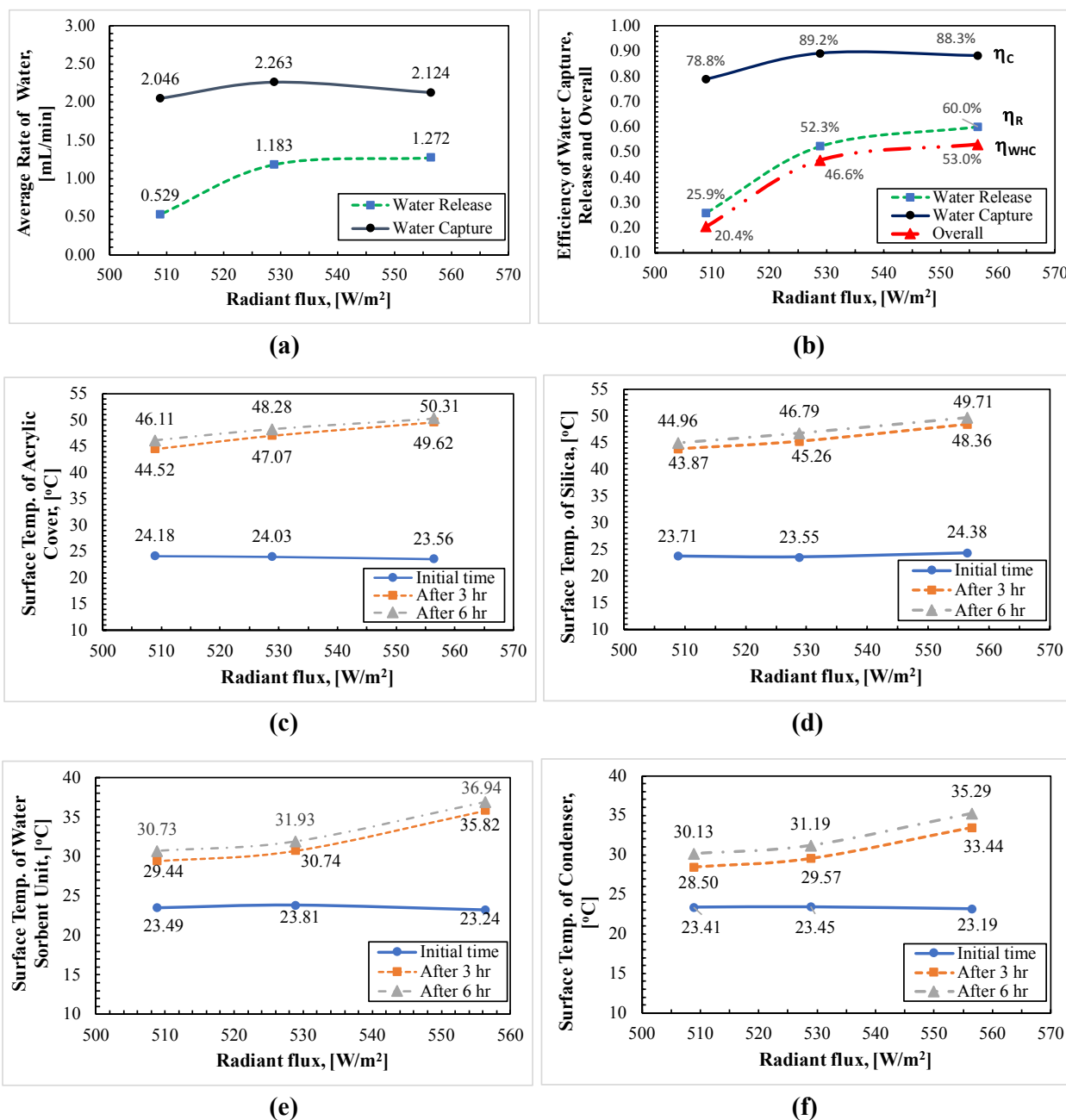


Fig. 8. Effect of the radiant heat flux on (a) the captured and released water flow rate, (b) efficiency, (c) surface temperature of the acrylic cover, (d) silica gel, (e) sorbent unit and (f) condenser.

reduction in the captured, released and collected water. Increasing the silica thickness from 25 mm (experiment 2) to 30 and 35 mm (experiments 6 and 7) results in decreasing the released and collected water as also confirmed in the results section above. Reducing the surface area of the silica (experiment 8) by half, although resulted in half of the captured water in experiment 2, the released and collected water are reduced only by 10% for 25 mm thickness of silica. For 30 mm thickness silica (experiment 9 vs 6), reducing the surface area by half resulted in reduction of water capture by 40% and reduction in water release and collection by 21%. Based on this, it is reasonable to conclude that the case presented by experiment 8 is the optimum case.

In general, the efficiency of the collection cycle, the efficiency of the water release from silica and the overall efficiency increase as the radiant flux increases to a peak point and then drop dramatically if the radiant flux kept increasing since the heat will start to damage the silica

gel. The measured surface temperatures of condenser, silica layer surface, water sorption unit and cover surface all increase as the heat source temperature increases. But the cover and silica surface temperatures accelerate faster than the water sorption unit and most importantly the condenser. This is due to the thermal insulation implemented in the water sorption unit.

Increasing the relative humidity using the humidifier in the adsorption phase, speeds up the adsorption cycle and hence increases the average water capture rate by silica. This will increase the water release and collection rates for a cycle since the silica becomes more saturated and can release water with less energy. The more saturated the silica is, the less energy it needs to release water, which results in higher overall efficiency.

Changing the silica layer thickness by using different silica containers does not affect the overall water collected significantly by the

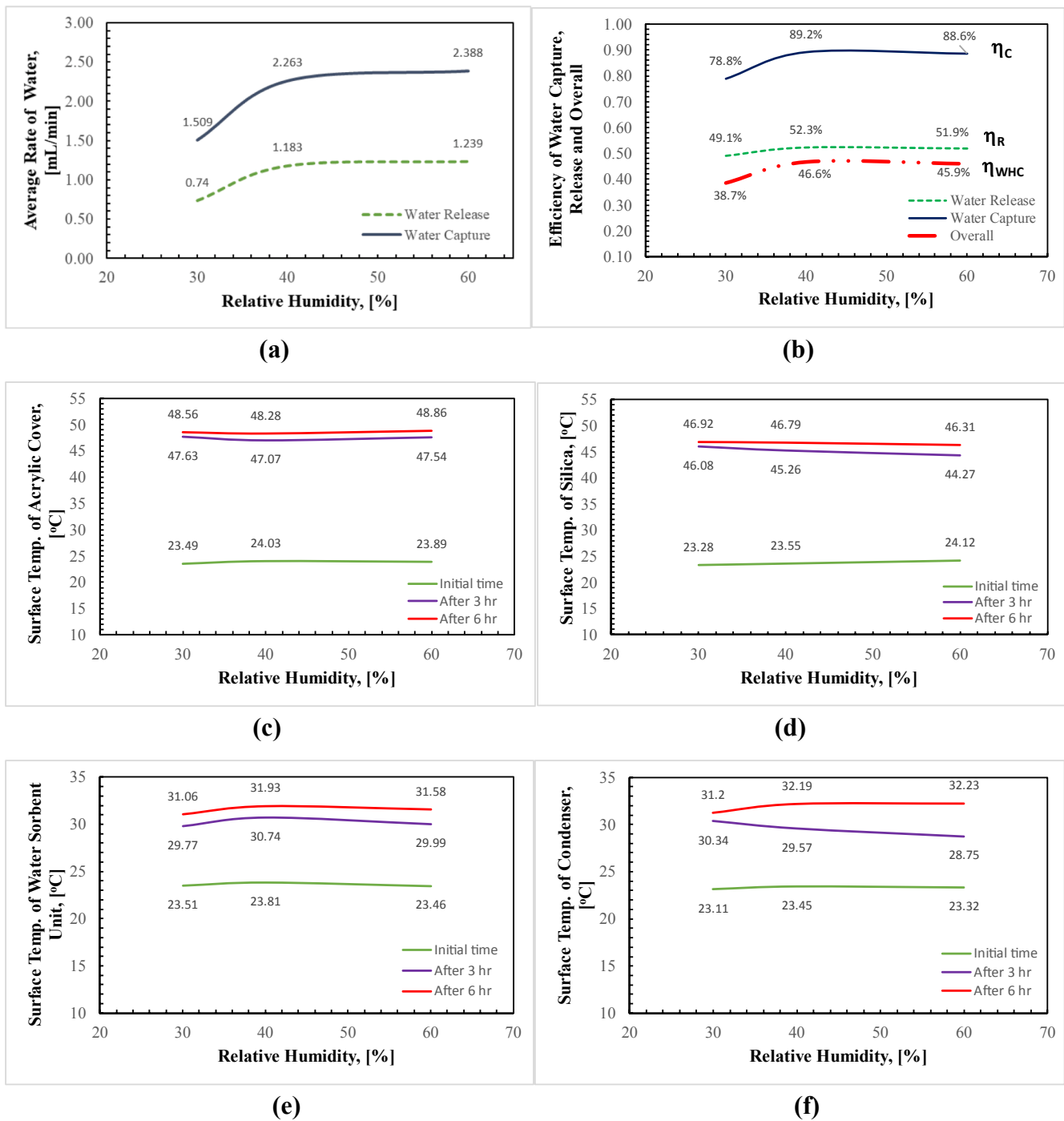


Fig. 9. Effect of varying the relative humidity on (a) the captured and released water flow rate, (b) efficiency, (c) surface temperature of the acrylic cover, (d) silica gel, (e) sorbent unit and (f) condenser.

end of each cycle for the same amount of time. However, it affects the water capture and release rates. The more the water is captured by the silica, the slower the capture rate will become. This is due to the fact that the first layer of silica adsorbs the water from the atmosphere first and then the next layer adsorbs the water from the first layer until it reaches the last layer. So, it takes more time to capture and then release water if the thickness is increased. For a given enough time, both thicknesses could become saturated since both had enough time for saturation. However, for a shorter time, the thin silica layer becomes saturated faster than the thick one and hence its overall efficiency is much higher compared to the one with more thickness.

The system can be improved by redesigning some of the components;

mainly the silica container where the capacity and efficiency of such system can be improved dramatically by having multiple layers of silica gel stacked on top of each other. In such case, the system will not change in size but will produce much more water per cycle. The system can also test different materials such as MOF-303 Aluminum based Metal Organic Framework [13]. This material is cheaper with high moisture adsorption capacity and needs less energy to release the water compared to other water adsorption materials.

6. Conclusions

A prototype is designed, built and tested for harvesting the water

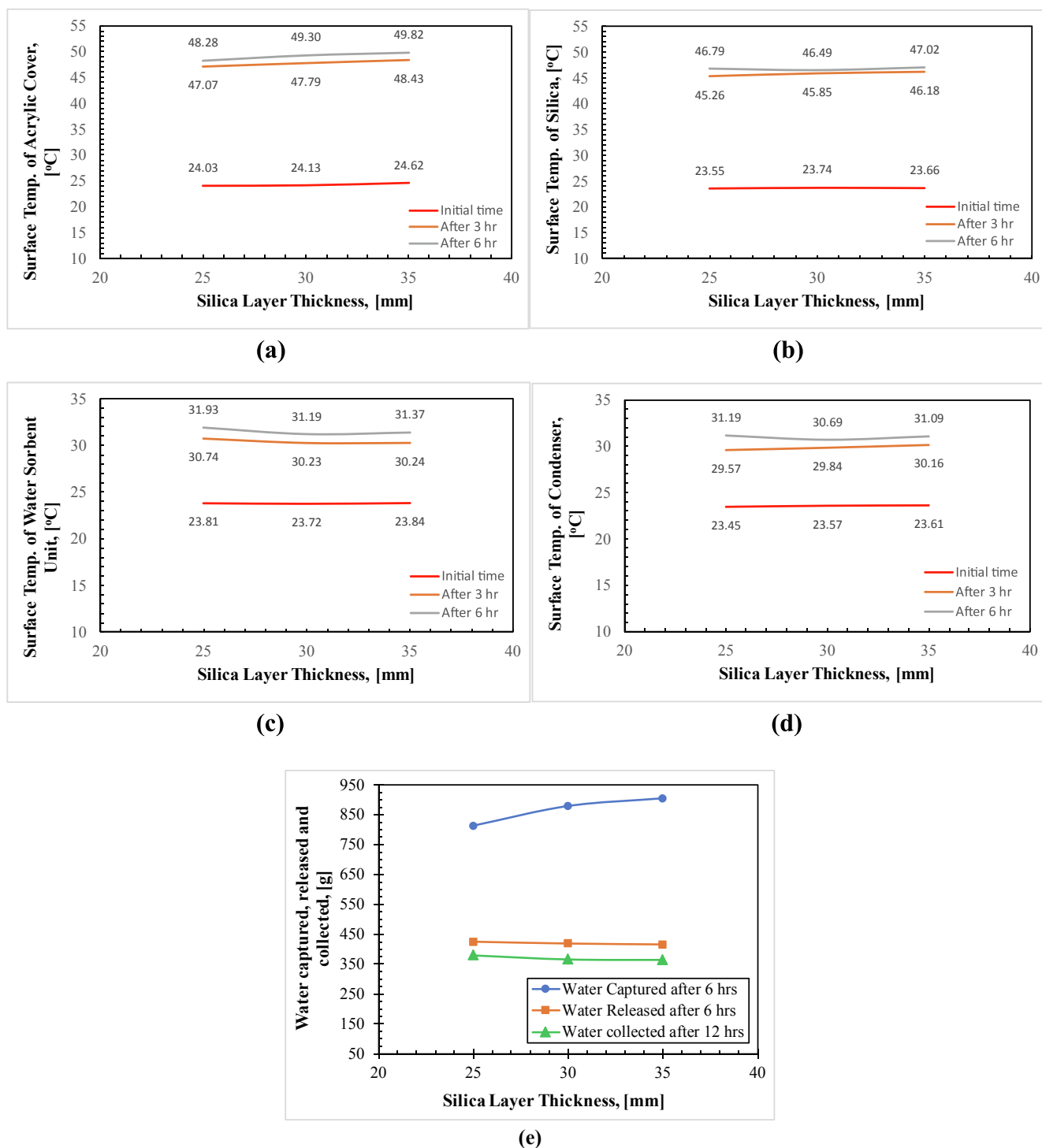


Fig. 10. Effect of varying the thickness of silica layer on (a) surface temperature of the acrylic cover, (b) silica gel, (c) sorbent unit and (d) condenser, (e) water captured, released and collected.

from air naturally under controlled conditions. The prototype consists of sorbent (silica gel in this study) exposed to radiant flux, water sorbent unit, condenser and reflector. Several experimental tests were conducted under the conditions of 22 °C ambient temperature, a range of relative humidity from 30 to 60%, a range of silica gel thickness from 25 to 35 mm, surface area to volume ratio from 0.29 to 0.4 and radiant heat flux range from 509 to 556 W/m². The prototype was able to produce up to 159 g of water per 1 kg of silica gel in a 12 h cycle when exposed to 556 W/m² radiant flux. Other findings and observations of the study are as follows:

- The harvester can produce 800 mL of water per one day (24 h) with an overall efficiency of 50% for 25 mm silica layer thickness.
- The water collection performance and overall efficiency have a peak point, after which they drop if the radiant flux is kept increasing.
- Increasing the relative humidity speeds up the adsorption cycle and hence increases the water capture, release rate and water collection rates.
- Changing the silica layer thickness does not affect the overall water collected by the end of each cycle for the same amount of time but affects the water capture and release rates.

Table 2
Selected experimental tests with variable RH, silica thickness, surface area and radiant flux.

Experiment Number	Ambient Temperature °C	Temp. of Heat Lamp °C	Relative Humidity, RH %	Thickness of Silica Layer mm	Silica Surface Area, A _s cm ²	Volume of Silica, V _{sil} cm ³	Mass of Silica after Adsorption g	Mass of Silica after Desorption g	Ratio, A _s /V _{sil}	Radiant flux W/m ²	Water captured after 6 h* g	Water released after 6 h** g	Water collected after one cycle (12 h)*** g
1	22	44	40	25	1177	2941	3305	2847	0.400	556	763	458	405
2	22	40	40	25	1177	2941	3371	2946	0.400	529	813	425	380
3	22	37	40	25	1177	2941	3284	3094	0.400	509	735	190	162
4	22	40	60	25	1177	2941	3459	3014	0.400	529	858	445	395
5	22	40	30	25	1177	2941	2552	3094	0.400	529	542	266	223
6	22	40	40	30	1177	3530	3911	3492	0.333	529	879	419	367
7	22	40	40	35	1177	4118	4375	3959	0.286	529	905	416	365
8	22	40	40	25	588.2	1471	1589	1204	0.400	529	403	385	340
9	22	40	40	30	588.2	1765	2128	1799	0.333	529	516	329	290

* Water captured after 6 h = Mass of Silica after Adsorption - Mass of silica.

** Water released after 6 h = Mass of Silica after Adsorption - Mass of Silica after Desorption.

*** Water collected after one cycle (12 h) is the actual water that was collected by the experimenter.

- The system can be improved by having multiple layers of sorbent stacked on top of each other and by using sorbents with higher moisture adsorption capacity and better thermal properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work presented in this publication was made possible by NPRP-S grant # [11S-1231-170155] from the Qatar National Research Fund (a member of Qatar Foundation). The findings herein reflect the work, and are solely the responsibility, of the authors.

The authors would like to acknowledge the financial support from the Department of Mechanical and Industrial Engineering (MIE) and College of Engineering (CENG) at Qatar University (QU).

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seppur.2020.117921>.

References

- [1] M. Shublaq, A.K. Sleiti, Experimental analysis of water evaporation losses in cooling towers using fi liters, Appl. Therm. Eng. 175 (April) (2020), <https://doi.org/10.1016/j.applthermaleng.2020.115418>.
- [2] M.A. Ahmed, S.M. Zubair, M.A. Abido, H.M. Bahaidarah, An innovative closed-circulated HDH system to extract water from the air: A case for zero-brine discharge system, Desalination 445 (July) (2018) 236–248, <https://doi.org/10.1016/j.desal.2018.07.024>.
- [3] Y. Tu, R. Wang, Y. Zhang, J. Wang, Progress and Expectation of Atmospheric Water Harvesting, Joule (2018), <https://doi.org/10.1016/j.joule.2018.07.015>.
- [4] R. Tu, Y. Hwang, Reviews of atmospheric water harvesting technologies, Energy 201 (2020), 117630, <https://doi.org/10.1016/j.energy.2020.117630>.
- [5] J.S. Solis-Chaves, C.M. Rocha-Osorio, A.L.L. Murari, V.M. Lira, A.J. Sguarez Filho, Extracting potable water from humid air plus electric wind generation: A possible application for a Brazilian prototype, Renew. Energy (2018), <https://doi.org/10.1016/j.renene.2017.12.039>.
- [6] B.A. Kashiwa, C.B. Kashiwa, The solar cyclone: A solar chimney for harvesting atmospheric water, Energy (2008), <https://doi.org/10.1016/j.energy.2007.06.003>.
- [7] M. Elashmawy, F. Alshammari, Atmospheric water harvesting from low humid regions using tubular solar still powered by a parabolic concentrator system, J. Clean. Prod. 256 (2020), 120329, <https://doi.org/10.1016/j.jclepro.2020.120329>.
- [8] Z. Pan, W.G. Pitt, Y. Zhang, N. Wu, Y. Tao, T.T. Truscott, The upside-down water collection system of *Syntrichia caninervis*, Nat. Plants 2 (7) (2016) 1–5, <https://doi.org/10.1038/NPLANTS.2016.76>.
- [9] B. Zhao, L.Y. Wang, T.S. Chung, Enhanced membrane systems to harvest water and provide comfortable air via dehumidification & moisture condensation, Sep. Purif. Technol. 220 (January) (2019) 136–144, <https://doi.org/10.1016/j.seppur.2019.03.034>.
- [10] B. Chaitanya, V. Bahadur, A.D. Thakur, R. Raj, Biomass-gasification-based atmospheric water harvesting in India, Energy (2018), <https://doi.org/10.1016/j.energy.2018.09.183>.
- [11] E.D. Wikramanayake, O. Ozkan, V. Bahadur, Landfill gas-powered atmospheric water harvesting for oilfield operations in the United States, Energy 138 (2017) 647–658, <https://doi.org/10.1016/j.energy.2017.07.062>.
- [12] M.P. Silva, et al., Water vapor harvesting by a (P)TSA process with MIL-125(Ti)₂NH₂ as adsorbent, Sep. Purif. Technol. 237 (November 2019) (2020) 116336, <https://doi.org/10.1016/j.seppur.2019.116336>.
- [13] F. Fathieh, M.J. Kalmutzki, E.A. Kapustin, P.J. Waller, J. Yang, O.M. Yaghi, Practical water production from desert air, Sci. Adv. (2018), <https://doi.org/10.1126/sciadv.aat3198>.
- [14] N. Hanikel, et al., Rapid cycling and exceptional yield in a metal-organic framework water harvester, ACS Cent. Sci. (2019), <https://doi.org/10.1021/acscentsci.9b00745>.
- [15] H. Furukawa, et al., Water adsorption in porous metal-organic frameworks and related materials, J. Am. Chem. Soc. (2014), <https://doi.org/10.1021/ja500330a>.
- [16] H. Kim, et al., Adsorption-based atmospheric water harvesting device for arid climates, Nat. Commun. (2018), <https://doi.org/10.1038/s41467-018-03162-7>.
- [17] F. Zhao, X. Zhou, Y. Liu, Y. Shi, Y. Dai, G. Yu, Super moisture-absorbent gels for all-weather atmospheric water harvesting, Adv. Mater. 31 (10) (2019) 1–7, <https://doi.org/10.1002/adma.201806446>.

- [18] E. Tsai, L. Vaz, A. Yeung, L.C. Klein, S. Jenkins, "Silica Gels for Atmospheric Water Harvesting" (2019).
- [19] H. Qi, et al., An interfacial solar-driven atmospheric water generator based on a liquid sorbent with simultaneous adsorption-desorption, *Adv. Mater.* 31 (43) (2019) 1–9, <https://doi.org/10.1002/adma.201903378>.
- [20] A. Entezari, M. Ejeian, R. Wang, Modifying water sorption properties with polymer additives for atmospheric water harvesting applications, *Appl. Therm. Eng.* 161 (April) (2019), <https://doi.org/10.1016/j.applthermaleng.2019.114109>.
- [21] L.W. McKeen, *Effect of Temperature and Other Factors on Plastics and Elastomers*, third ed., 2014.
- [22] Dry & Dry, "(5.5 LBS) 'DRY&DRY' PREMIUM ORANGE INDICATING SILICA GEL DESICCANT BEADS," 2020. [Online]. Available: <https://dryndry.com/collections/silica-gel-beads/products/5-lbs-dry-dry-premium-orange-indicating-silica-gel-desiccant-beads> [accessed: 10-Sep-2020].
- [23] Silica Gel Dessicant Products, "Indicating Silica Gel (Orange)," 2020. [Online]. Available: <http://www.silicagelco.com/silicagel.php?page=IndicatingSilicaGel%28Orange%29>.
- [24] Sorbent Systems, "Desiccant Chart Comparisons," 2020. [Online]. Available: https://www.sorbentsystems.com/desiccants_charts.html.
- [25] Planning and Statistics Authority, "Physical and Climate Features," 2020. [Online]. Available: <https://www.psa.gov.qa/en/statistics1/pages/topicslisting.aspx?parent=environmental&child=physicalclimate>.
- [26] Ahmad K. Sleiti, Motaz Elbeih, Analysis and optimization of concentrated solar power plant for application in arid climate, *Energy Sci. Eng.* ESE-2020-0 (2020), <https://doi.org/10.1002/ese3.742>. In press.