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A novel method to convert an air conditioner into an atmospheric water generator

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ABSTRACT

Clean water is a very important, basic need of life; therefore, its sources must be researched and developed. The vast amount of water vapor present in a warm and humid atmosphere could be a potential water source. In this study, a new atmospheric water generator (AWG) was designed and tested. The system consists of a window air conditioner and an attachment. It was made at a local workshop from food grade 304 stainless steel This attachment completely converted the air conditioner to an AWG. The system was tested under warm and humid climatic conditions in the coastal town of Rayyis, Saudi Arabia. The performance of the system was compared with the performance of three commercial units. The best water harvesting rate and the energy consumption rate, at an 81-86 % relative humidity and 30-29 °C, were 0.7 L/h and 1.02 kWh/L, respectively. This comparison shows that the developed system has potential as a commercial product.

INTRODUCTION

The global population in the 20th and 21st century has increased rapidly. As a result, the water consumption by irrigation increased dramatically because agriculture uses 70% of water worldwide, and this figure increases to 95% in developing countries [1]. Rapid industrial development leads to the pollution of ground water and rivers, and climate change of the earth causes desertification in some areas [2]. The percentage of the global population that will experience water scarcity is projected to increase with increasing levels of warming in the 21st century [3].

According to an optimistic study, desalination in Saudi Arabia will produce approximately 2.0 billion m^3 domestic fresh water/year in the year 2040 [4]. The earth's atmosphere contains approximately 12900 km^3 of moisture [5]. This is a huge resource of water and could be considered a sustainable and innovative solution needed to help the future global crisis of freshwater shortages.

A system that converts water vapor to liquid water is called either an atmospheric water generator (AWG) or atmospheric water harvesting (AWH) system. This system depends on either condensation or sorption [6,7] methods. Condensation methods include active cooling condensation [8], a refrigeration technology, such as vapor compression cycle (VCC or VCR) [9,10], adsorption/absorption chiller [11,12] and thermoelectric cooling (TEC) systems [13-15]. VCC can be used either for just water harvesting or for both air conditioning and water harvesting. For air conditioning and water harvesting, normally central cooling systems are used and the condensed water is considered the by-product of air cooling [16].

Generally, condensation methods are used to condense water from atmospheric air by cooling some surfaces below the water's dew point temperature. Then, the water condenses on these surfaces.

This study is an experimental investigation of producing water using a commercial window air conditioner as a source of refrigeration. At different humidity levels, the production of water will be measured by the system, which consists of a window air conditioner and a specially designed stainless steel attachment. This attachment completely converts the air conditioner to an atmospheric water harvesting system.

System Design and the experimental set-up

The attachment was made at a local workshop from food grade 304 stainless steel. A schematic of the attachment is shown in Figure 1. Pictures of the top and interior of the attachment are shown in Figure 2. The cold air comes from the air conditioner to zone A and went to zone B through some of the closed slide paths. Then, the air returns from zone B to zone C through another closed slide paths. In zone C, the air returns to the air conditioner to cool down. The attachment consists of 16 slides with widths of approximately 1 cm, and the space between them is approximately 1.5 cm. The system components and the experimental setup are shown in Figure 3. The air conditioner is a 24000 BTU window air conditioner (Gree). The air conditioner thermostat sensor is covered with an insulator to obtain the lowest temperature the air conditioner achieve give. Figure 4 shows a photo of the complete system during the measurements. The electricity power line of the air conditioner is connected to a single-phase power meter. The interface is a CASSY module (LD Didactic, Leybold). The weather is measured by a Pasco sensor (Pasport 6-in-1 weather sensor). The measurements were taken in Rayyis, which is a small coastal town in Al Madinah Province (23°35'04.9"N, 38°35'59.3" E).

Three thermocouples were used to monitor the system. The first one is for measuring the temperature of air, which is coming from the air conditioner. This thermocouple is inside the attachment in zone A, directed towards the front of the air conditioner output. The second thermocouple was placed at the middle top of zone B. The third thermocouple was placed away from the system to measure the ambient air.

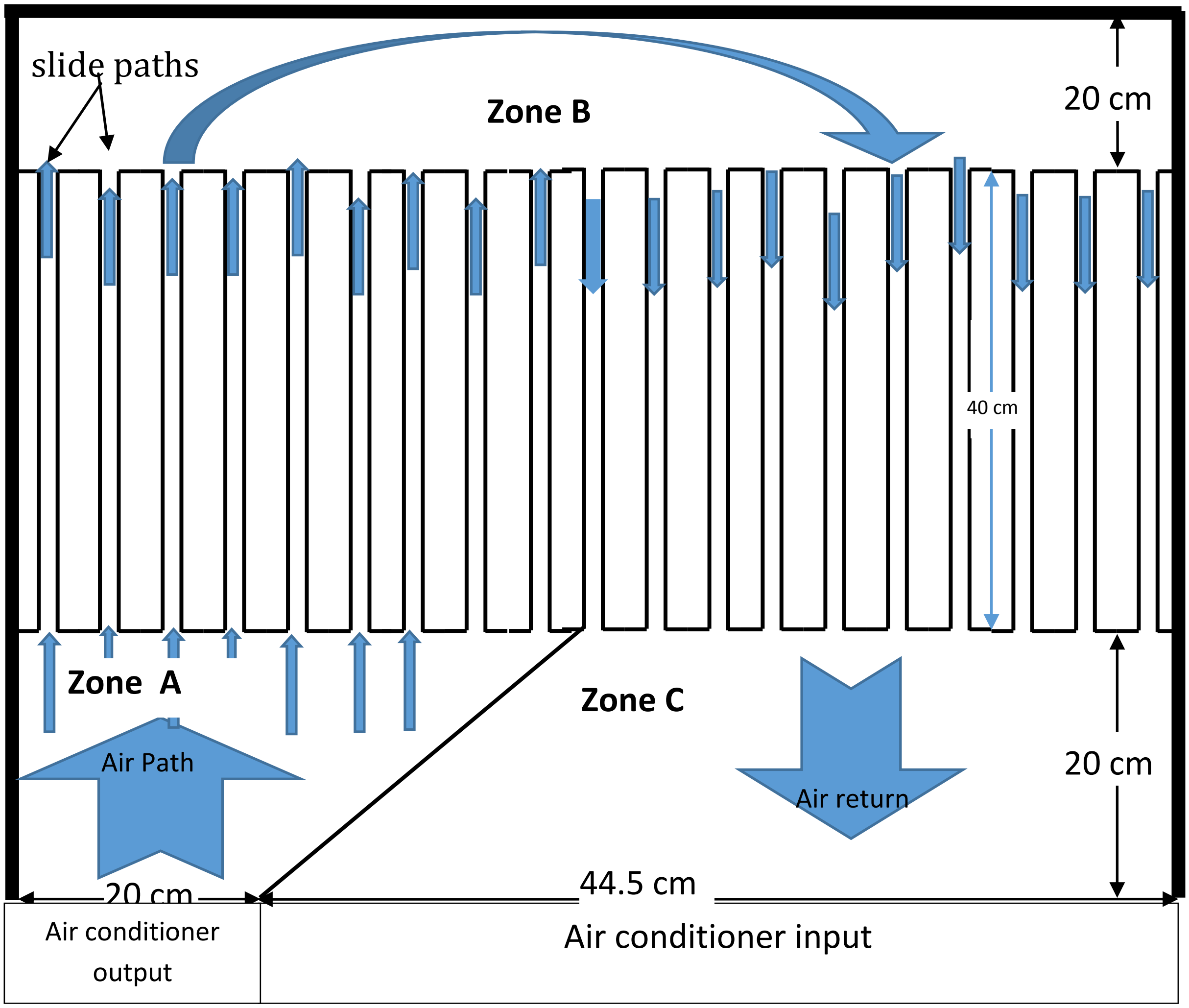

Figure 1. Schematic diagram of the attachment.

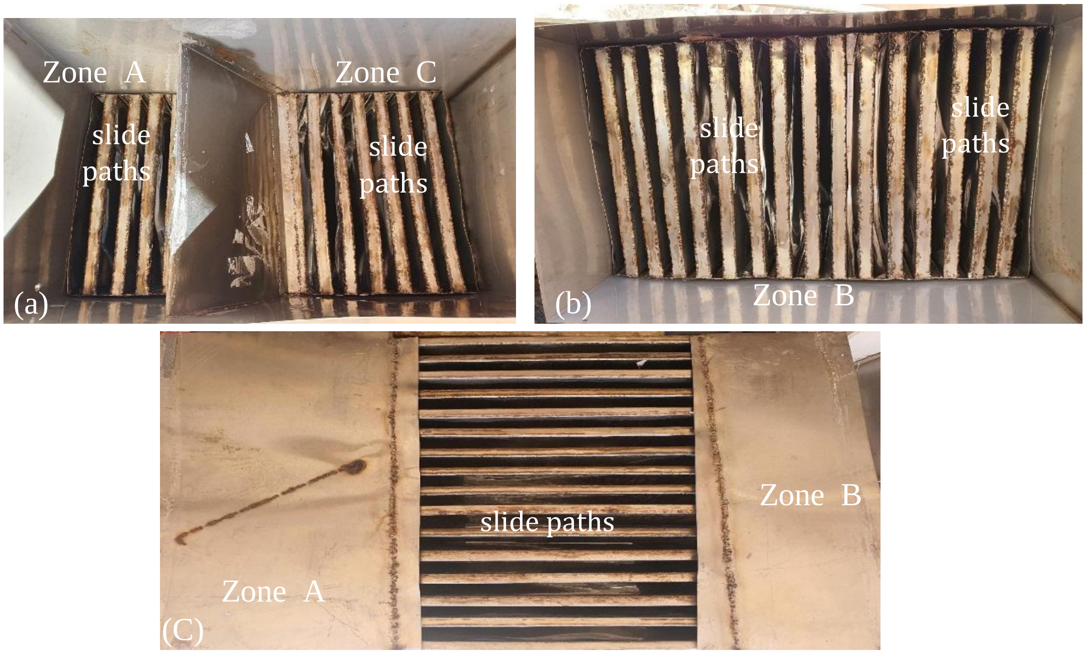

Figure 2. Photos from the inside of the attachment (a) zone A and C, (b) zone B and (C) and from above.

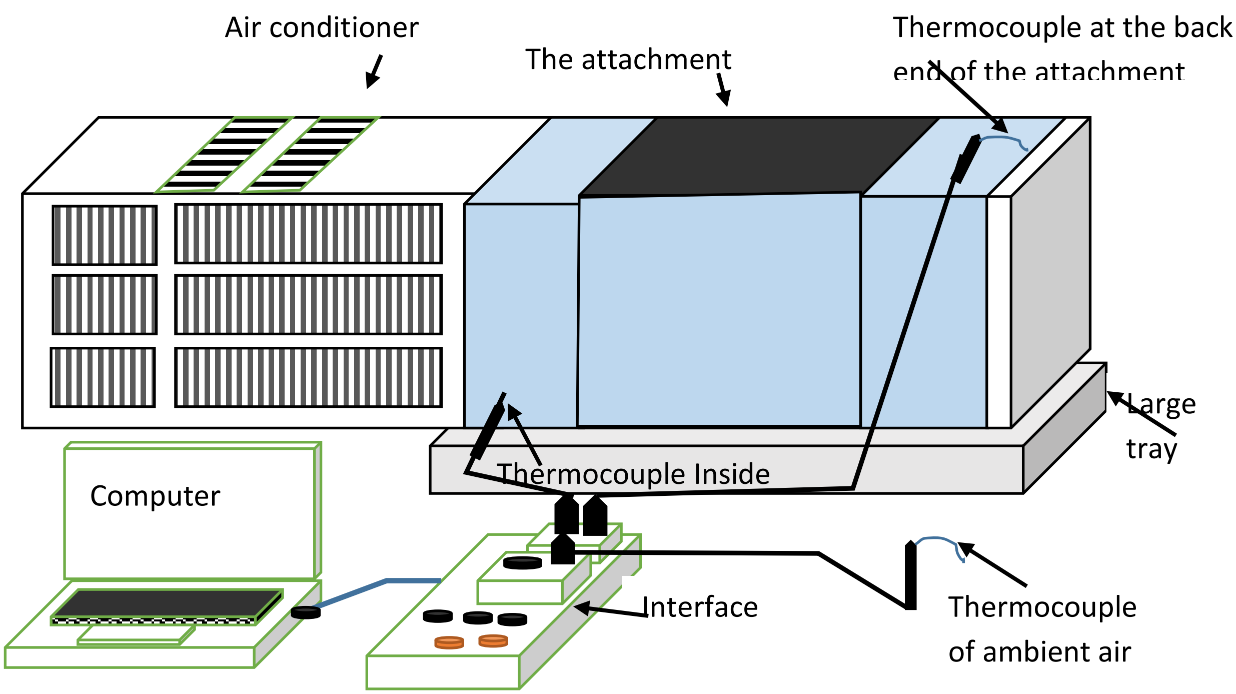

Figure 3. Schematic diagram of the system components and the experimental setup.

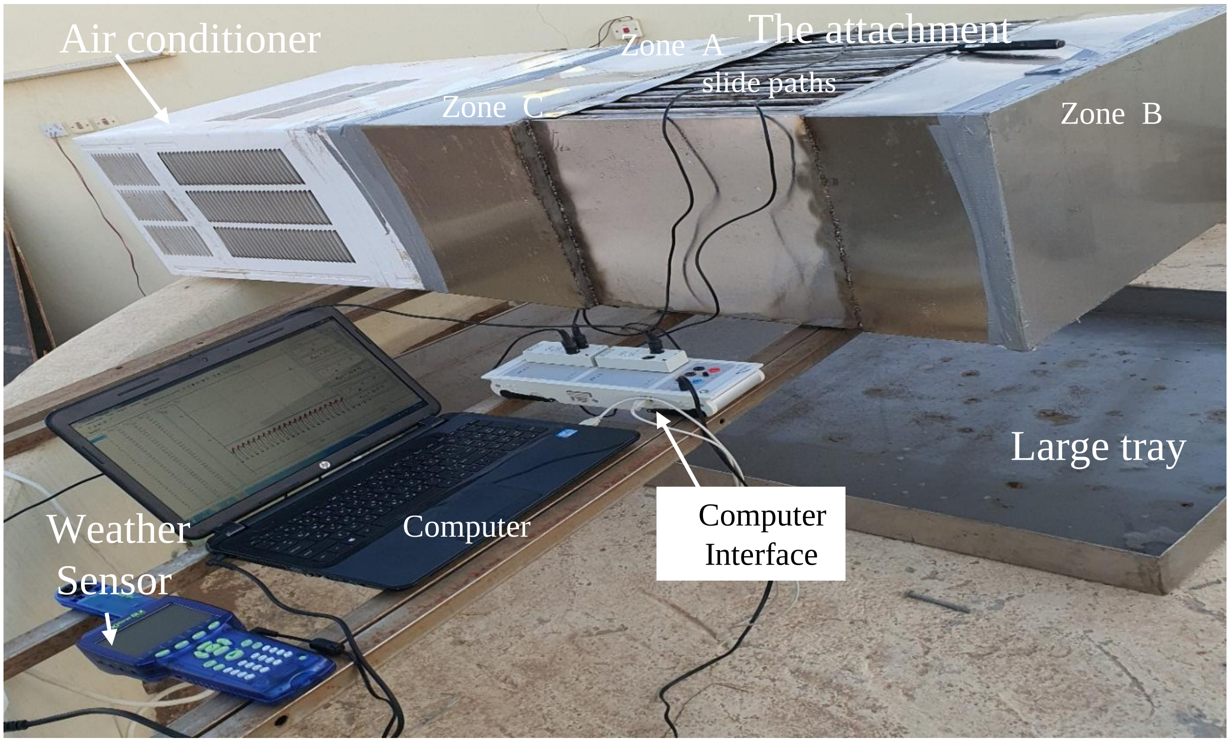

Figure 4. Photo of the complete system during the measurements.

EXPERIMENTAL RESULTS

1. Production of water at 30% relative humidity.

The first measurement was performed on 11th Aug 2020 at 20:20 for 238 min. The relative humidity was 30%. The temperature was measured with time in zone A and zone B, and the temperature was ambient air was also measured, as shown in Figure 5. In zone A, the temperature decreased to approximately -3±1.5 °C as the compressor of the air conditioner started running; after it stopped, the temperature increased until it reached approximately 23±1.5 °C. The temperature at the rear of the attachment in zone B was between 26±2 °C and 16±3 °C, which depends on the compressor's running time. In addition, both the temperatures of zones A and B take the shape of a saw tooth wave due the running time of the compressor. The average time that the actual compressor worked was approximately 5 min., whereas the stop time was approximately 10.58±1.4 min. The temperature of the ambient air decreased gradually from 36 °C to 32°C. The power consumption was 2.8 kWh. No water was produced because the relative humidity and the dew point were very low, approximately 30% and 15.4 °C, respectively.

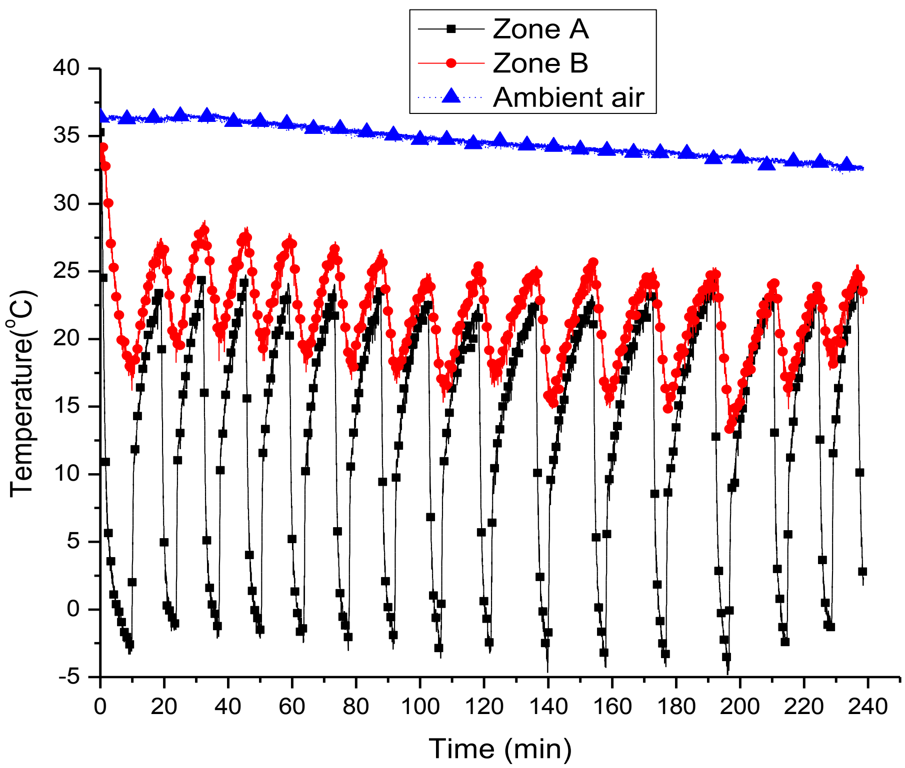

Figure 5. The variation in the temperatures of zone A, zone B and ambient air with time at 30% relative humidity.

2. Production of water at 66-72% relative humidity

The measurements were performed at 00:20 on 12^{th} Aug 2020 after midnight for 338 min. The relative humidity was between 66 and 72%. The temperatures inside the attachment at zone A, at the end of the attachment at zone B, and the ambient air are shown in Figure 6. The lowest temperature in zone A was approximately -3 °C, and the maximum was approximately 26 °C, which is the same maximum temperature in zone B. The lowest temperature was approximately 16 °C in zone B, whereas the dew point was approximately 23.7 °C at 66% R.H. and 24.3 °C at 72% R.H. The power consumption was 4.3 kWh when the temperature of the atmosphere was between 32 and 30 °C. The volume of water produced was approximately 3.5 L. Then, the power cost was approximately 1.23 kWh/L, and the water harvesting rate was 0.62 L/h. Figure 7 shows the image of condensation on the outer surfaces of the attachment.

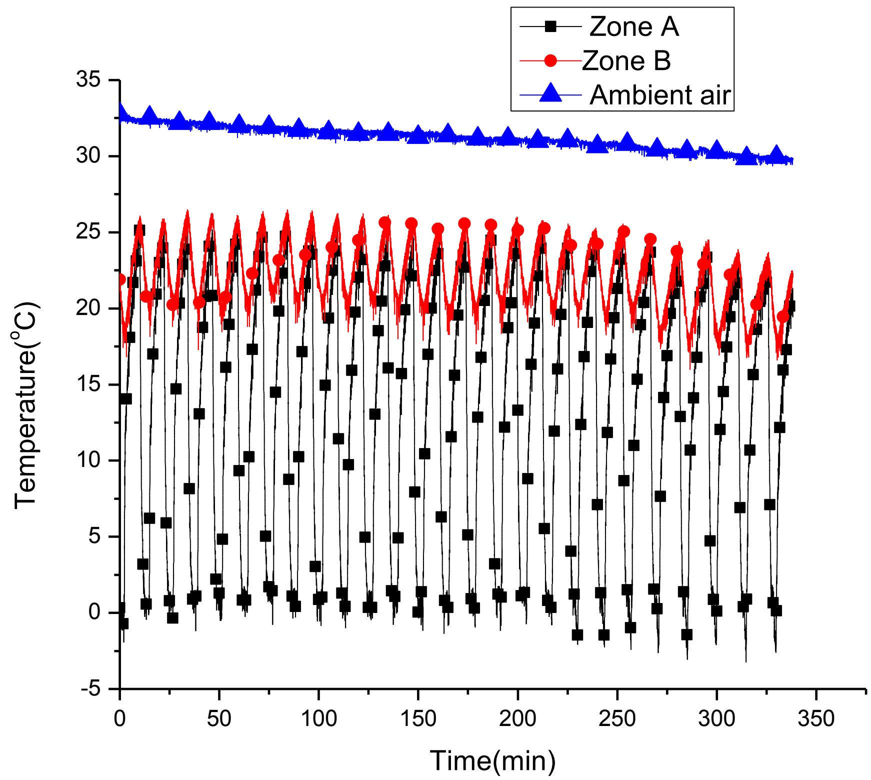

Figure 6 . The variation in temperatures with time for zone A, zone B and ambient air at 66-72% relative humidity.

Figure 7. Photo of condensation of water on the surface of the attachment.

3. Production of water at 81-100% relative humidity

The measurements started at 18:35 on 12th Aug 2020 and proceeded until 06:35 on 13th Aug 2020, and the total run-time of approximately 12 h. The relative humidity was between 81 and 100%. The temperatures inside the attachment at zone A, at the end of the attachment at zone B, and of the ambient air are shown in Figure 8. The lowest temperature in zone A was approximately -3 °C, and the maximum was approximately 25 °C, which is the same as the maximum temperature in zone B. The lowest temperature was approximately 16 °C in zone B, whereas the dew point was approximately 28.8 °C at 81% R.H. and 29.3 °C at 97% R.H. The total power consumption was 8.5 kWh. The fit of power with respect to time gave a rate of 0.011 kWh/min, as shown in Figure 9. This rate corresponds to a total consumption of power of approximately 7.992 kWh, which is different than the real power consumption, 8.5 kWh, because the temperature of ambient air was not constant all the time. The ambient air temperature was between 32.7 and 29 °C for 367 min and from 30 °C to 28.7 °C for the remaining time. The volume of water produced was approximately 6.6 L. Then, the power consumption rate was approximately 1.28 kWh/L, and the water harvesting rate was 0.55 L/h.

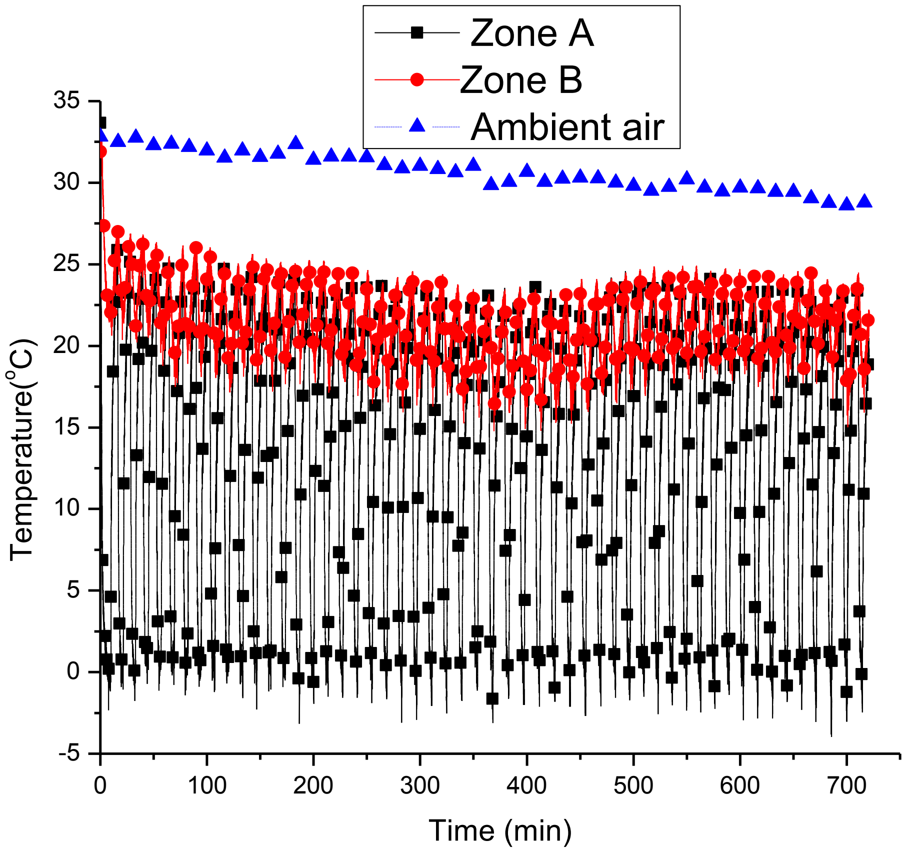

Figure 8. The variation in temperatures with time for zone A, zone B and ambient air at 81-100% relative humidity.

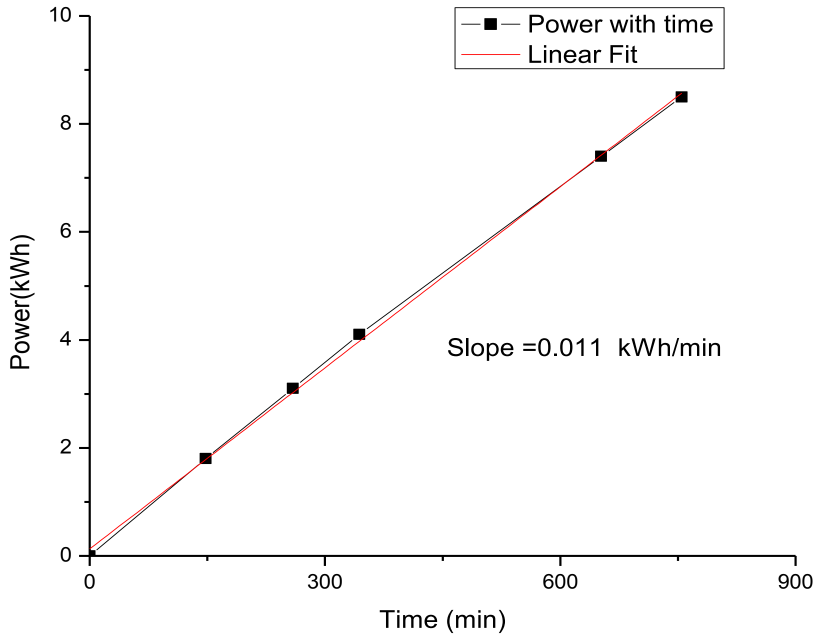

Figure 9. Relation between the power consumption and time.

4. Production of water at 79-100% relative humidity

Additional measurements were recorded from 00:08 to 06:08 on 15th Aug. The relative humidity was between 79 and 100%. The temperatures inside the attachment at zone A, at the end of the attachment at zone B, and of ambient air are shown in Figure 10. It is clear that, there are two different periods. In period 1, the temperature of ambient air decreased from 32°C to 30°C due to a breeze that occurred for approximately 146 min. The system was affected by the breeze, and therefore, the temperatures in zones A and B measured during period 1 were lower than the temperatures measured during period 2. The dew point was approximately 24.7 °C at 79% R.H. and 29.2 °C at 100% R.H. The total power consumption was 3.1 kWh, and the produced volume was approximately 3 L, resulting in a 1.03 kWh/L power consumption rate and a 0.5 L/h water harvesting rate. Although the relative humidity was 79% at the beginning, the absolute humidity was as low as 23.4 g/m^3, which should normally be over 25 g/m^3. Therefore, the water harvesting rate was less than 0.6 L/h.

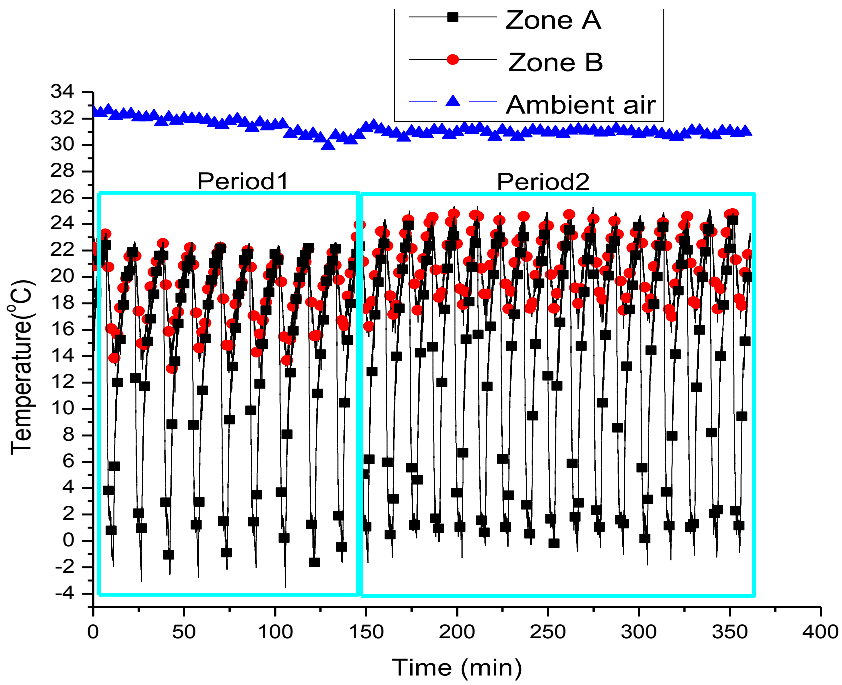

Figure 10. The variation in the temperatures with time for zone A, zone B and ambient air at 79-100% relative humidity.

5. Production of water at 81-86% relative humidity

Measurements were taken between 00:37 and 07:00 on 14th Aug. 2020. The relative humidity was between 81 and 86%. The temperatures inside the attachment at zone A, at the end of the attachment at zone B, and of the ambient air are shown in Figure 11. The lowest temperature in zone A was approximately -2.4 °C, and the maximum was approximately 26 °C, which is approximately the same as the maximum temperature in zone B. The lowest temperature was approximately 16 °C in zone B, whereas the dew point was approximately 25.8 °C at 81% R.H. and 26.3 °C at 86% R.H. The total power consumption was 4.7 kWh. The variation in the ambient air temperature was small, between 29 °C and 30.5 °C. The volume of water produced was approximately 4.6 L. Then, the power consumption rate was approximately 1.02 kWh/L, and the water harvesting rate was 0.7 L/h.

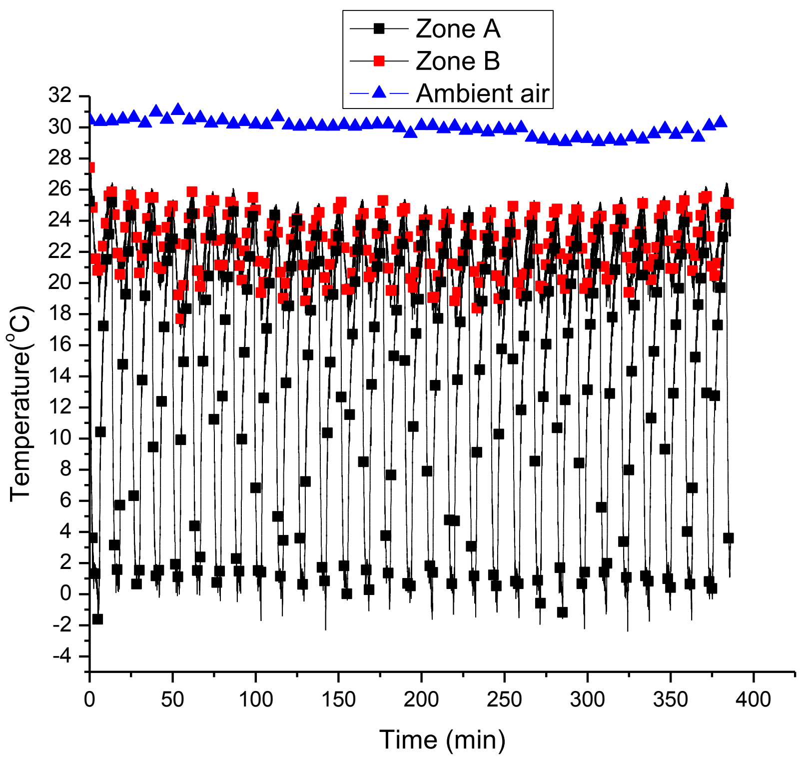

Figure 11. The variation in the temperatures with time for zone A, zone B and ambient air at 81-86% relative humidity.

6. Production of water at 72-92-82% relative humidity

The measurements started at 23:40 on 10th Sept. and proceeded until 06:58 on 11th Sept. 2020. The temperatures inside the attachment at zone A, at the end of the attachment at zone B, and of the atmosphere are shown in Figure 12. The measurements can be divided into two periods according to the temperature difference, as shown in Fig. 10. In period 1, there is a variation in temperature due to a slight breeze that occurred, while in period 2, the temperatures are almost constant because the wind was almost constant. Ambient airflow brings more inlet moisture [17] but reduces the cooling capacity [18] of the surface of the attachment. The variation in the relative humidity with time is shown in Figure 13. The relative humidity that night started at 76% and decreased to 72% in a short time of 82 min. Then, it increased to approximately 92% in 249 min, and after that, it decreased to 81%. The total power consumption was 5.7 kWh. The variation in the ambient air temperature was almost constant, between 32.5 and 33.5 °C. The volume of water produced was approximately 4.3 L. Then, the power consumption rate was 1.3 kWh/L, and the water harvesting rate was 0.61 L/h.

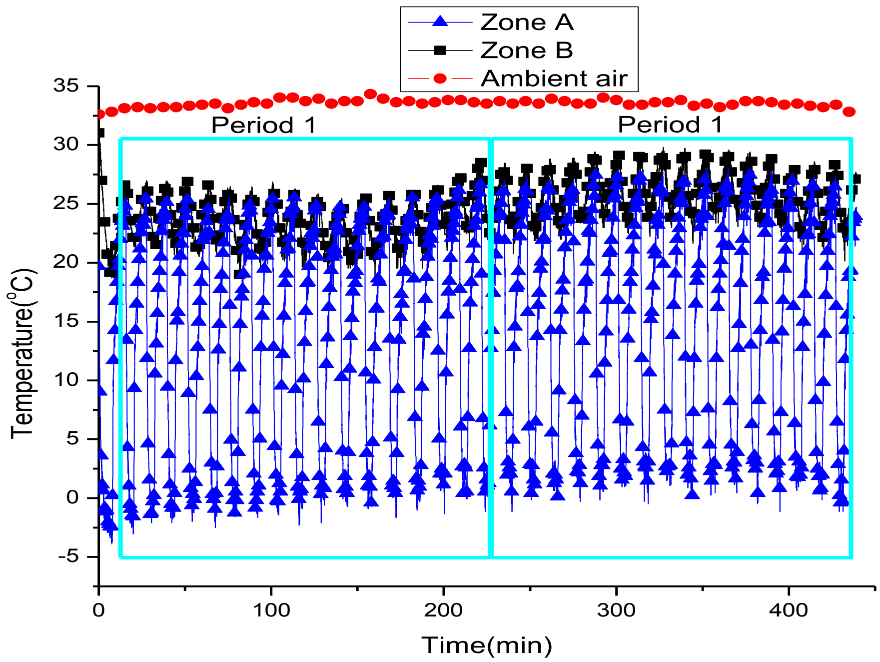

Figure 12. The variation in temperatures with time for zone A, zone B and ambient air at 72-92-82% relative humidity.

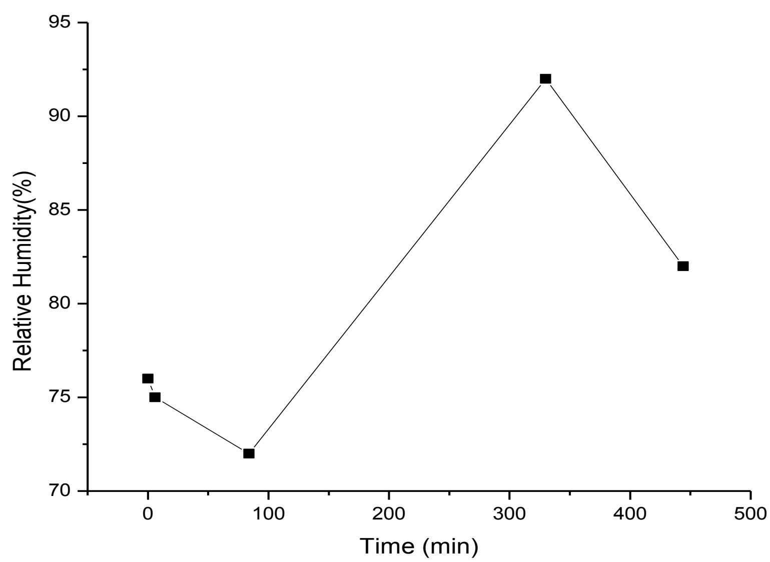

Figure 13. The variation in relative humidity from 23:40 on 10th September until 06:58 on 11th September 2020.

7. Production of water at 65-97% relative humidity

The measurements started at 18:13 on 11th Sept. and proceeded until 05:48 on 12th Sept. 2020. The temperatures inside the attachment at zone A, the end of the attachment at zone B, and of the ambient air are shown in Figure 14. Even though the time of the measurements was long, approximately 696 min., the wind was stable during the entire time, and the air temperature reduced from approximately 33 °C to 29 °C. The relative and absolute humidity increased from 65% to 97% and from 25.4 to 30.9 g/m^3, respectively, as shown in Figure 15. Both the relative and absolute humidity values had the same increasing behaviour. The total power was 9.5 kWh. The volume of water produced was approximately 8.3 L. Then, the power consumption rate was approximately 1.14 kWh/L, and the water harvesting rate was 0.72 L/h. The high water harvesting rate indicates a typical and desired relationship between the relative and absolute humidity values.

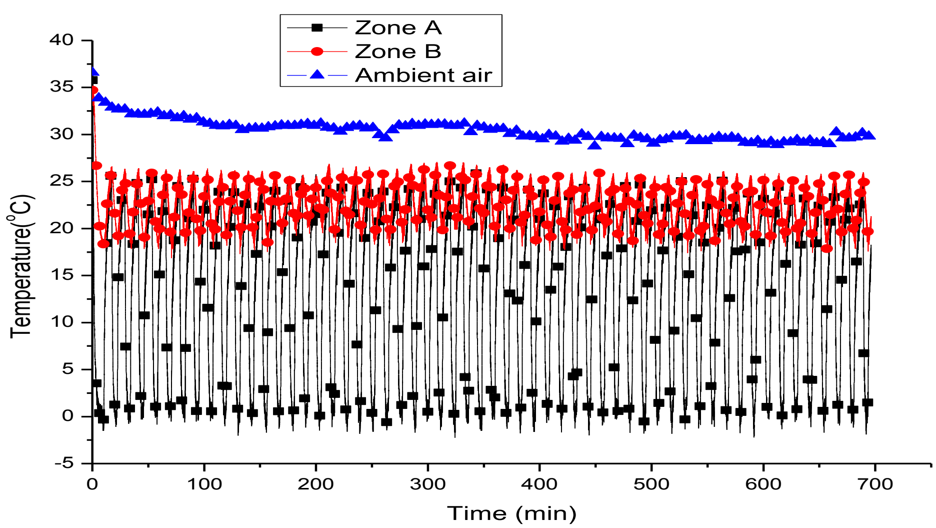

Figure 14. The variation in temperatures with time for zone A, zone B and ambient air temperature at 65-97% relative humidity.

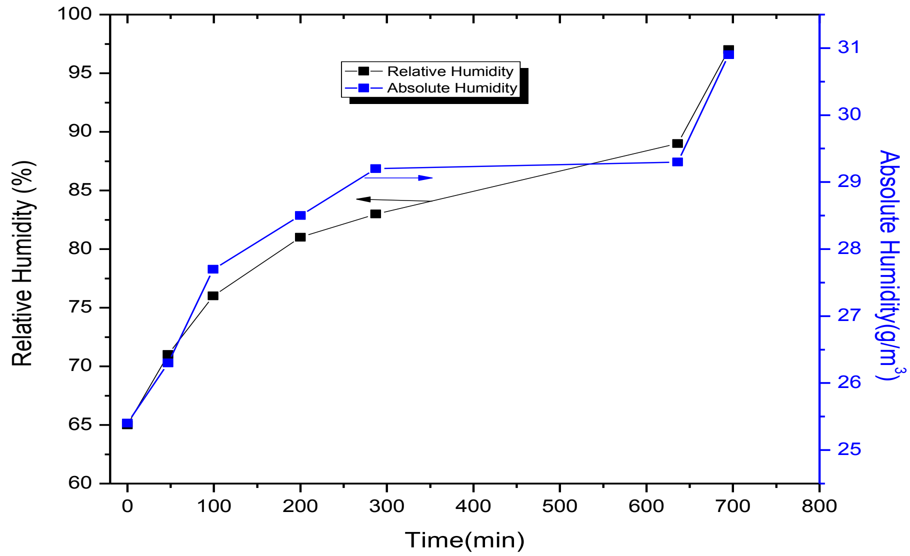

Figure 15. The typical variation in relative and absolute humidity with time from 18:13 on 11th Sept. until 05:48 on 12th Sept. 2020.

DISCUSSION

The performance and limitations of three commercial atmospheric water harvesting systems were investigated experimentally by Farshid Bagheri [19]. He found that the average rate of water harvesting and the energy consumption rate in warm, humid ambient air at 30 °C and a R.H. of 60% are 0.65 L/h and 1.02 kWh/L, respectively. Hot and humid climates are best suited for extracting water from air [20]. A comparison between the performance of our system and these three systems [19] according to the water harvesting rate (L/h) and energy consumption rate (kWh/L) is illustrated in Table 1. The measurements were taken outdoors for our system, and hence, the humidity and ambient air were uncontrollable. Therefore, we did not have exactly the same conditions of temperature and humidity as the three commercial systems. However, since we performed many measurements in different conditions, we can predict the performance of the system. The performance of our system at 66 -72% humidity and a 32-30 °C temperature is close to that of system 1. The best performance was obtained when the ambient air temperature was between 30 and 29 °C and the humidity was between 81 and 86%, because the water harvesting and power consumption rates were 0.7 L/h and 1.02 kWh/L, respectively. The system produced more water, 0.72 L/h, at a higher relative humidity, 65-97%, but it consumed more power, 1.14 kW/h, because the ambient air temperature was higher, 32-29 °C. The consumption of the system, 1.3 kW/h, was the highest due to the high air temperature, 33-32 °C. The production of water depends not only on relative humidity but also on the absolute humidity [21], which should be more than 25 g/m^3. Therefore, the production rate was 5 L/h, whereas the relative humidity was high, > 79%.

Table 1. Comparison between the performance of our system and that of three commercial systems[19].

The systems	Relative Humidity (%)	Temperature °C	Water harvesting rate (L/h)	Energy consumption rate (kWh/L)
Commercial system 1	60	30	0.65	1.21
Commercial system 2	60	30	0.66	0.82
Commercial system 3	60	30	0.64	1.02
Our system	30	36 - 32	0	α
Our system	65-97	32-29	0.72	1.14
Our system	66-72	32 - 30	0.62	1.23
Our system	72-92-82	33-32	0.61	1.3
Our system	79-100	32-30	0.5	1.04
Our system	81-86	30-29	0.7	1.02
Our system	81-100	32-30	0.55	1.28

CONCLUSION

A new AWG system was designed using a window air conditioner and an attachment made of stainless steel grade 304. It was tested in the outdoors in different warm and humid climates. It yielded an average water harvesting rate of approximately 0.62 L/h for relative and absolute humidity values above 65% and 25 g/m^3, respectively. The energy consumption rate increased to 1.02 kW/h as the ambient air temperature increased to 30 - 29 °C and 1.3 kW/h as the ambient air temperature increased to 33-30 °C. Then, the system performance was acceptable and compared to that of some commercial systems. Moreover, the yield and the energy consumption can be improved through additional research and development of the ambient airflow velocity, the material and the surface area of the attachment.

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