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Experimental Analysis of Atmospheric Water Harvester Using Ammonia Vapour Absorption System

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ABSTRACT

There are increasing concerns for the promising future of atmospheric water harvesters (AWH). AWH have been analysed theoretically and experimentally using different technologies such as Vapour Compression (VC) Thermoelectric (TE), Sorption (absorption, adsorption) and shape-based techniques. These techniques are suffering from low water harvesting or high energy consumption. The ammonia vapour absorption system (VAS) (which can be operated using renewable energy sources) has not yet been analysed experimentally. In this study, the AWH based on ammonia VAS has been studied experimentally, the effect of air flow velocity and ambient conditions have been analysed. The comparison between the existing techniques and VAS was performed to explore the possibility of implementing biomass, geothermal and solar energy in generating water from atmosphere, thus reducing the cost of the m^3 of water produced.

Keywords: atmospheric water harvester, vapour absorption system, velocity effect, AWH analysis, AWG applications.

INTRODUCTION

Atmospheric water condensation is an ancient phenomenon that can be observed on metal surfaces and windows nights and morning times [1]. Due to recent water scarcity worldwide; the areas of water harvesting start to appear [2]. Among old techniques of getting potable water in rural areas is distillers where water is allowed to evaporate by sun then collect the condensate [3, 4, 33]. Reverse Osmosis technique was also used to clean the contaminated water with single or multi-stage filtration [5]. Bani Khalid et al. [6], used a commercial atmospheric water removal device to reduce the humidity and to lower the air temperature in hot humid countries, in order to achieve comfortable outside conditions. The extracted water was used for irrigation and drinking at the same area. Recently, there has been a considerable interest in harvesting water from air directly. Various methods were used for harvesting water from atmosphere, including vapour compression refrigeration, thermoelectric, sorption, adsorption and desorption, ultrafiltration and expansion techniques. The machines available on the market use the vapour compression condensation (VCC), the (VCC) is characterized by high energy performance, its specific energy consumption (SEC) is about 220–300 Wh/kg, while 22–26 L/day can be produced [7]. The technology used in the AWH machines produces water with 0.03 JD/L cost, which is considered higher than tap (0.001JD/L) or bottle water (0.025JD/L). If AWH machine is to be competitive, then the produced water price must be reduced by reducing energy consumed per litre, energy cost, maximising water harvested or if water is to be transported long distances, where its cost may rise to 0.7 $/L [7, 8]. In order to maximise the harvested water amount, thus reducing SEC, research on enhancing heat transfer including fin natural/forced convection [9, 10] or different technique must be used.

LITERATURE SURVEY

Atmospheric water harvesting methods are wide and different in nature. The methods used in literature for atmospheric water collection can be divided into three main parts: 1 – methods using cooling to dew point, 2 – methods using sorption of water from the atmosphere by various water affinity materials, 3 – methods depending on shape properties such as special membrane technology, cobwebs, plants and animals [11].

The VCR consumes electrical power by the compressor and creates cooling effect at the evaporator; this cooling effect is used for AWH by passing air over the evaporator and collect condensate. AWH using solar powered VCR was reported by (Rang Tu, Yunho Hwang) [12], a 1.50 L/ h was produced with ambient temperature of 26.7 °C, wet bulb temperatures 19.4 °C, air flow rate 578 m^3/h and rated input power of 1035 W for the compressor. its SEC can be calculated as 0.69 kWh/L. Rang Tu and Yunho Hwang concluded that water productivity using VCR technologies lays in the range of 0.13–4.20 L/h and SEC is in the range of 0.18–2.08 kWh/L at air flow rate of 300–1000 m^3/h. Smaller value can be seen in literature, depending on the size of the device used and the cooling power, 250 mL have been achieved in 1.5 hours [13]. Kwan et al. in 2020 has experimented a hybrid system for AWH, this system depends on using a fuel cell to power a VCR machine for harvesting atmospheric water and add the fuel cell (FC) productivity to the VCR AWH productivity; up to 3 L/h of freshwater when RH = 75% with 2 kW FC, which is 50% higher than excluding the FC [14]. They reported SEC of 200 Wh/L. Ozkan et al. in 2017 has used the waste natural gas that is flared in the oilfield to generate water using AWG based on VCR driven by a gas turbine, they were able to condense 8.7 L–2.5 L per m^3 of natural gas, the SEC was about 1.2 kWh/L [15]. Another application of the AWH for maritime rescue was used; the best water productivity was 460 mL/h at 27 °C, 92% RH and 600 m^3/h air flow rate [16].

The vapour absorption refrigeration system such as Ammonia-Water, Lithium Bromide and Ammonia-Water- Hydrogen systems may be used to generate cooling load using any thermal energy input. Theoretical thermodynamic analyses have been done for VAR AWH system driven by solar energy [17]. Farhad et al. also analysed the VAR system using Parabolic Trough Solar Collector (PTSC) [18]. They found that maximum produced water is about 400 litre per month in tropical climates with specific energy consumption of 3 kWh/L. AWH by TEC Technology with water productivity and energy consumption were analysed in many studies; 1.6 L/day water capacity and 61 Wh power input was reported [19–23]. Xiaolong Xu et al. used the radiative cooling principle for a house cooling with storage tank and loop heat exchanger [24]. A 7 °C temperature difference with 52 W/m^2 have been achieved for water flow rate about 0.05 kg/s using convective-radiative cooling [25]. Moreover, expansion technique was used for AWH, Subiantoro [26] reached the dew point by reducing the pressure in a piston cylinder device with reciprocating motion.

Another method that is well analyzed in literature is sorption, which consists in collecting water vapor through use of different desiccants due to its affinity to water vapour. Many studies been done on AWH solar-thermal adsorption, Graphene Oxide-based aerogel has been used (CaCl2 50 wt% solution), at 70% RH night adsorption -day desorption was able to collect 2.89 L/m^2 per day [27]. Integrated hygroscopic photothermal organogel (POG) was proposed for AWH with solar power [28]. Black cotton saturated with calcium chloride and recycling the latent heat by using dual stage device were analyzed [29, 30]. Many other studies have been done on sorption technique with various desiccants and various ways of water collection including dual cycle with VCC for water collection [31, 32]. All of these methods are suffering from the high energy consumption, thus high cost of water productivity. As it can be seen from literature review; VCR, TEC, NRC and sorption techniques have got wide analyses both theoretically and experimentally in research. In literature, the theoretical analysis for the ammonia vapour absorption system is found in [17, 18] only. To the best of authors' knowledge, there is no real experimental investigation for the ammonia VAR system. VAR system can be driven by renewable energy sources such as solar and biomass energy; this can reduce the atmospheric water production cost, as the energy used is free. In this work, ammonia-water Electrolux machine is used as AWH. The machine is tested experimentally for harvesting water from atmosphere at different air flow velocities. The energy consumption, water production and system performance were analyzed. The achieved results were compared with the theoretical results from the VAR system and experimental results from other techniques for verification.

AMMONIA-WATER VAPOR ABSORPTION SYSTEM

The Electrolux ammonia-water vapour absorption system is shown in Figure 1. This system consists of absorber, generator, analyser, condenser and evaporator. The ammonia-water (AW) strong solution is passed through the generator which heats up AW solution evaporating the ammonia, ammonia is then passed through the analyser to remove and water vapour left with ammonia before the dry ammonia vapour passes through the condenser. Ammonia vapour condenses to liquid in the condenser and throttled to evaporator, where it is mixed with hydrogen reducing its pressure and thus temperature. The ammonia hydrogen mixture is then passed to the absorber where ammonia is separated from hydrogen and absorbed by water, see Figure 1.

EXPERIMENTAL SETUP

The experimental setup used in this work consists of VAR system (XK-XSZL1), with 250 V and 0.3 A power input, variable speed fan, circular insulated duct on the evaporator, Data Acquisition system, thermocouples and humidistat.

Working principle

The strong ammonia-water solution from the absorber flows to the generator where it is heated by external mean (electric, solar, gas or biomass), as a result of heating ammonia which is dissolved in water is vaporised. The vaporised ammonia passes from the generator to a rectifier or water separator before it enters the condenser where it is liquefied. Liquid ammonia then enters the evaporator where it meets with hydrogen that lowers its pressure and makes ammonia evaporate, absorbing heat from outside. The ammonia

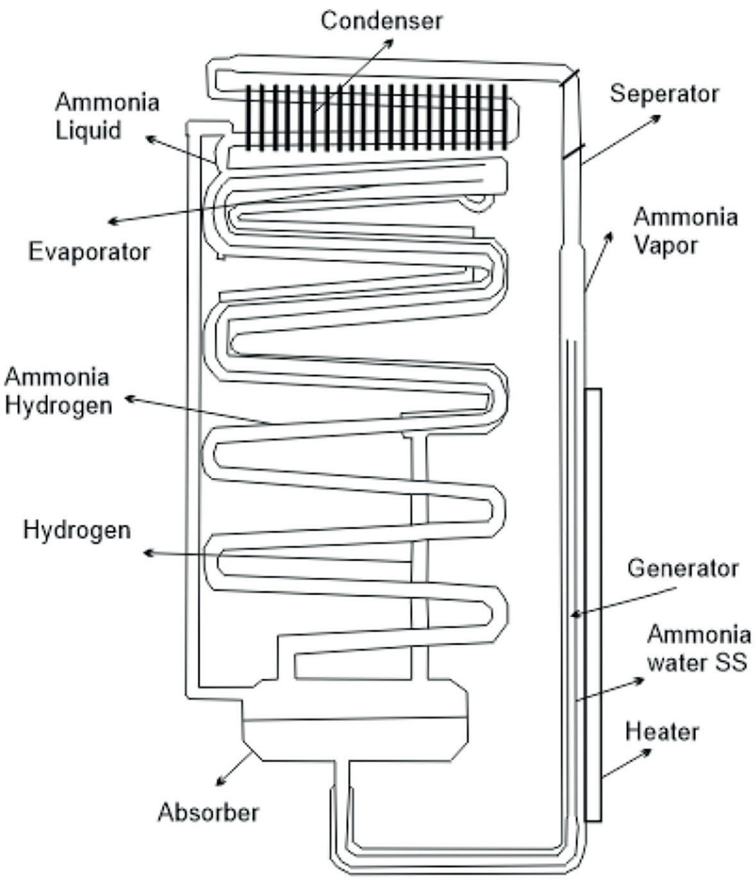

Figure 1. Schematic diagram of VAR system

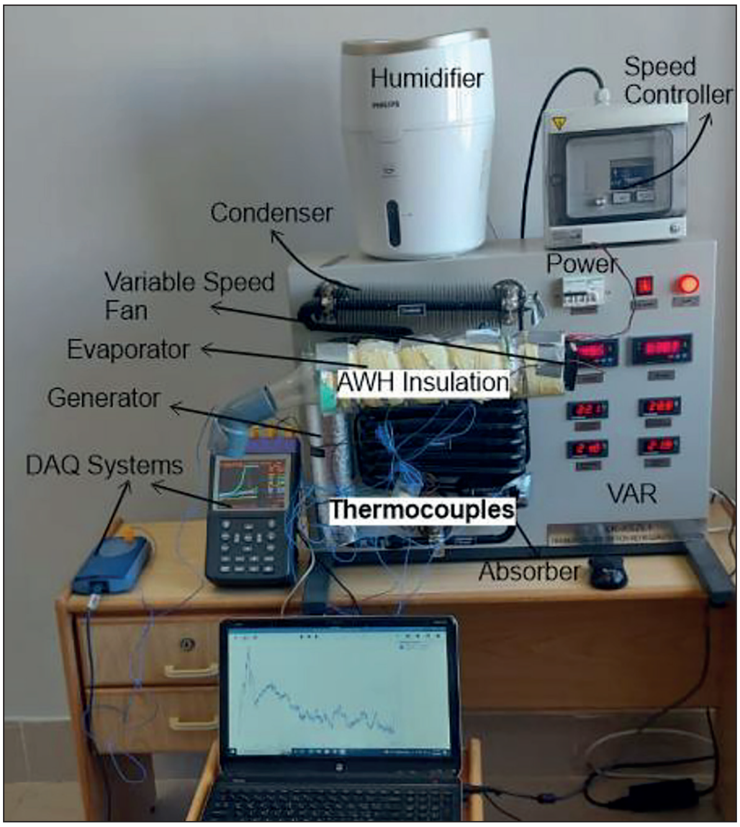

Figure 2. Experimental Setup of VAR system used as AWH

hydrogen mixture passes to the absorber, where water absorbs ammonia and releases hydrogen to flow back to evaporator.

Experimental procedures

The experimental set up Figure 2 was first switched on, then wait time to start up and reach steady state conditions, the temperatures and relative humidity for ambient conditions are recorded, after that the fan speed is set to a specific velocity (1, 2, 3, 4, 5). The device is left working for about 18 hours while the amount of water, inlet air temperature, outlet air temperature, evaporator, condenser, absorber and generator temperatures are recorded using the data acquisition.

RESULTS AND DISCUSSION

Experiments have been performed to test the workability of the VAR system. Different air flow rates from low to high have been used to investigate the effect of air volume flow rate on the AWH

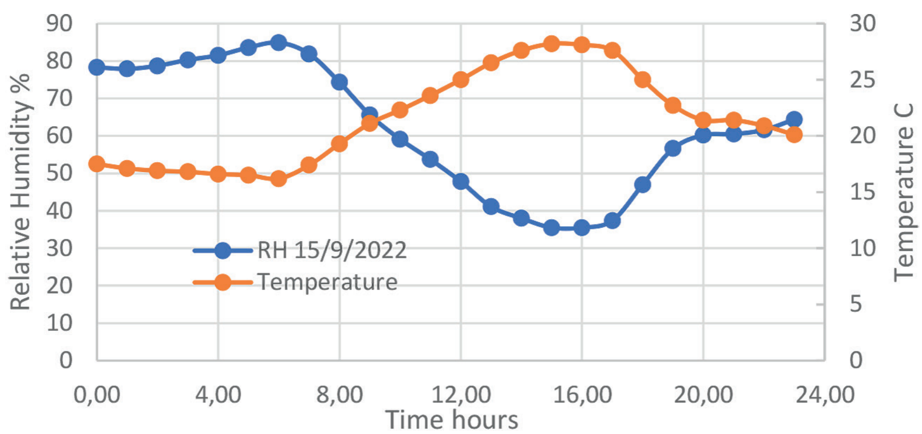

Figure 3. Temperature and relative humidity variation through the 24 hours

rate. As the temperature of the ambient air and its relative humidity are changing around the day's hours Figure 3. The average values for the ambient air and RH are considered. Figure 3 shows a sample variation of temperature and RH in 24 hours (on 15th September 2022 Amman-Jordan), the temperature of ambient air increases during the day and decreases during night time, where the RH has a high value during night and reduces dramatically during the day time.

This variation in RH and ambient temperature affect the amount of moisture in air that is targeted to be condensed. Figure 4 shows the humidity ratio variation during a day (24 hours), high chance of water per kg of dry air is available between 7 PM to 11 AM.

The experimental set up has been set and tested for steady state conditions as shown in Figure 5. The temperatures of all elements of the VAR are stable and working steadily for the 21 hours testing period.

The apparatus is then tested to water harvesting from atmosphere by applying air flow over the evaporator section with variable speed fan of 12 V and 1.65 A maximum power, the fan maximum flow rate is 64.9 CFM which is equivalent to 1.837 m^3/min. Five volume flow rates were tested (0.31, 0.62, 0.93, 1.24 and 1.55 m^3/min). The evaporator section consists of a tube with 2.25 cm diameter and 27 cm length (0.01908 m^2 surface area). Five tests were performed on five different days with five different flow rates, Figure 6 shows the amount of water harvested from atmosphere during the test periods. The relative humidity during the test periods was kept almost constant at about 70–75%, as can be seen in Figure 6. The increase in the water production using VAR is due to the increase in

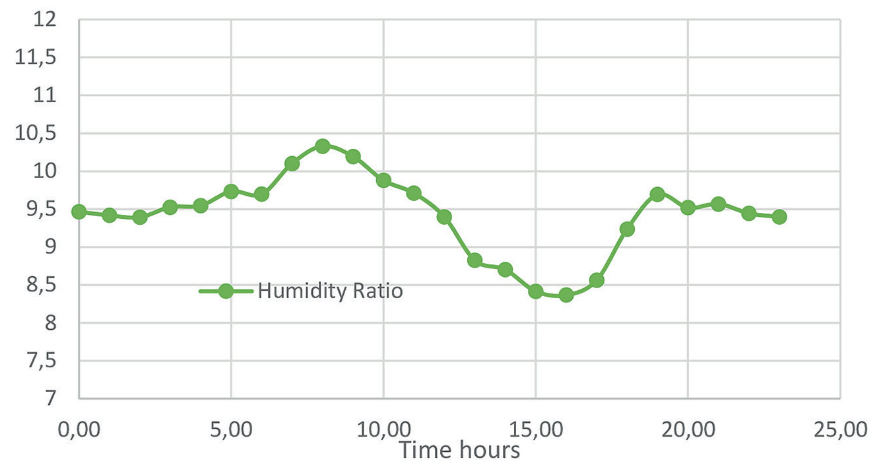

Figure 4. Humidity ratio variation through the 24 hours

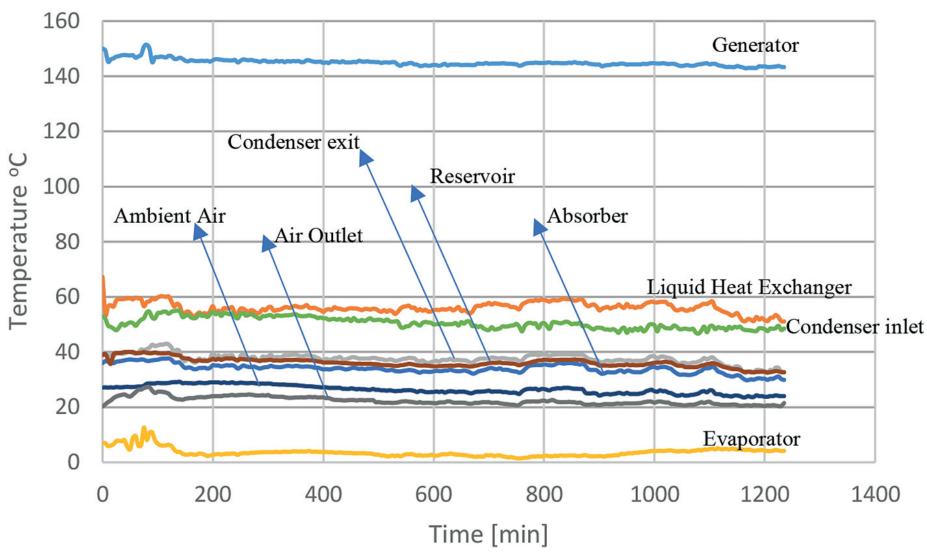

Figure 5. Temperatures on the VAR system

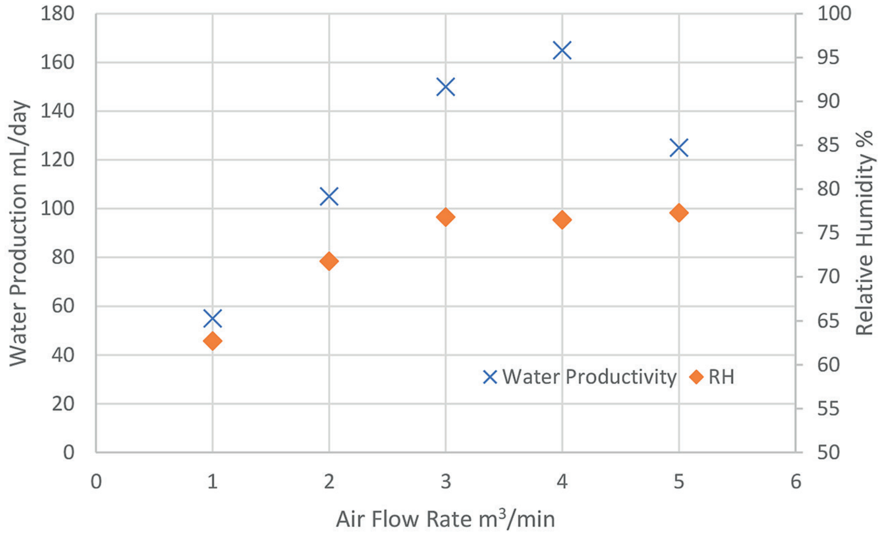

Figure 6. Relative humidity and water productivity (18 to 19-09-2022)

flow rate until it reaches 1.24 m^3/min, which is the optimum water production rate. Higher flow rates will decrease the condensation rate and use the cooling load into cooling air without efficient condensation.

The water production rate and specific energy consumption of the VAR are shown in Figure 7. The 8.2 mL/h water production rate is for a small load small surface area, it is equivalent to 0.43 L/h per m^2. This can collect more than 10 litres per day from a free energy like Sun, biomass or even geothermal energy. The specific energy consumption versus air flow rate is shown also in Figure 7, it is clear from the figure that the energy consumption is reduced by applying an appropriate air flow rate. This offers the need for more detailed investigation to reach the optimal heat transfer between the air and the surface of the VAR system.

To analyse the AWH using VAR system, a detailed analysis is performed to the ambient and the system data. As shown in Figure 8, the humidity and temperature of atmospheric air are variable and function of the day time. Upon the change of the ambient conditions humidity ratio and dew point temperature are changing as well. It is noted from Figure 8 that dew point temperatures and humidity ratios increase in the afternoon and decrease near the noon time. The ambient temperature is minimum between 8 PM to 11 AM, which is the same period for maximum humidity ratio. This period has almost no solar energy, but the highest potential for water collection from atmosphere.

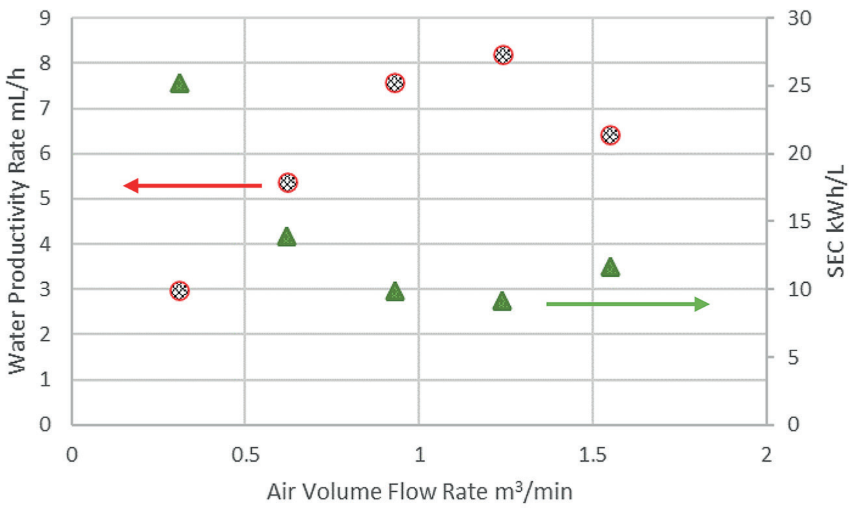

Figure 7. Specific energy consumption and water productivity rate (13 to 22-09-2022)

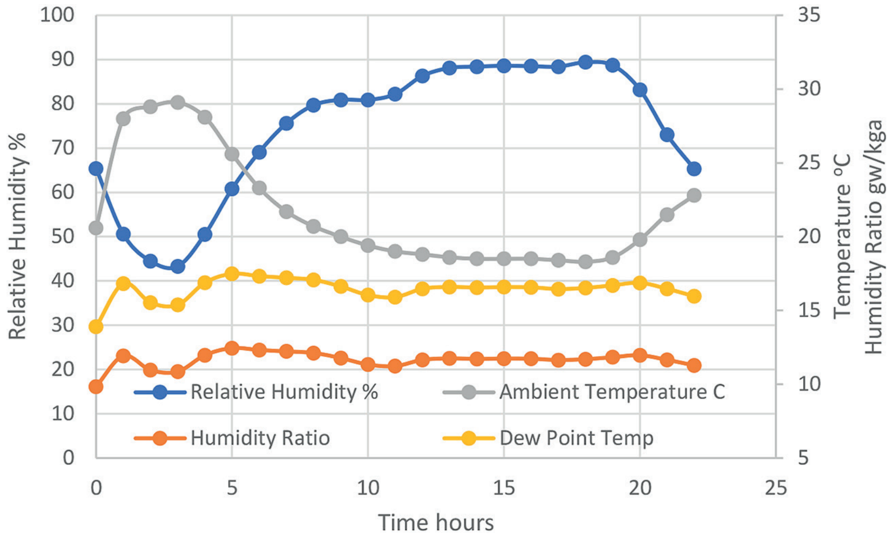

Figure 8. Humidity ratio and dew point temperatures for the ambient conditions on 18 to 19-09-2022

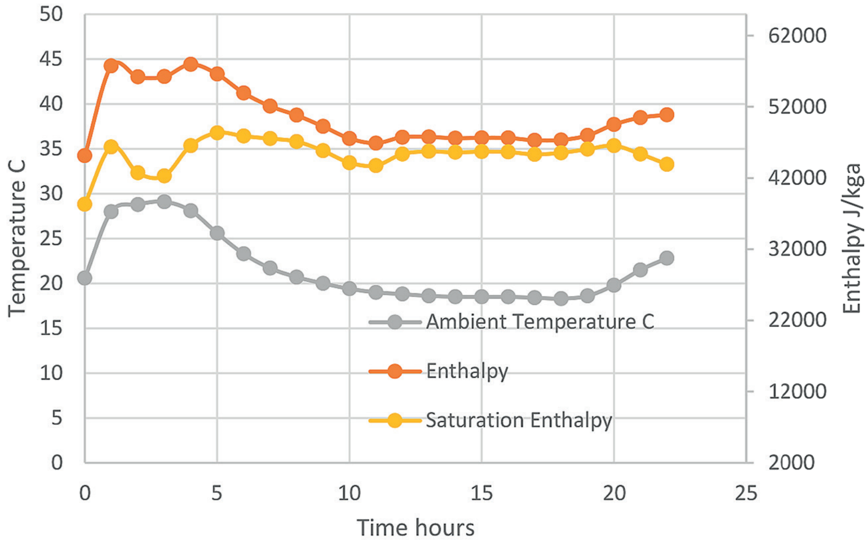

Figure 9. Enthalpy, saturation enthalpy and temperature for the ambient conditions on 18 to 19-09-2022

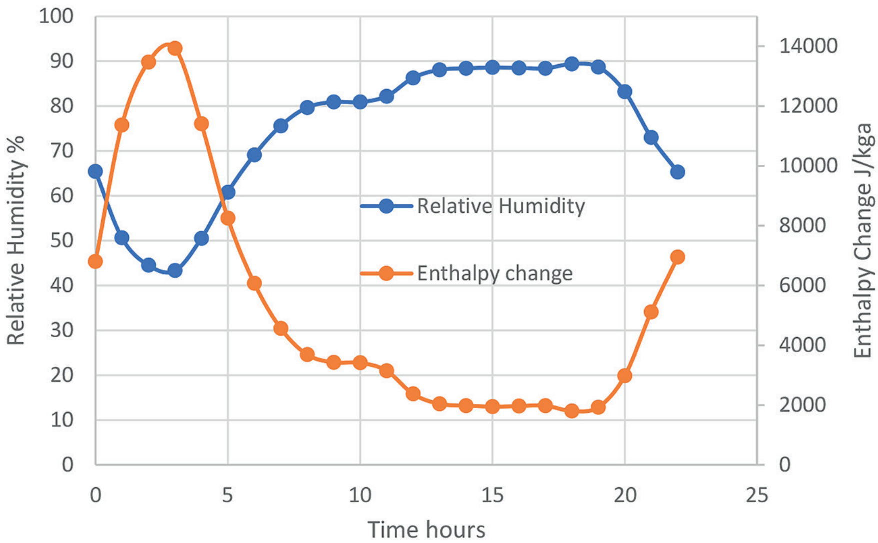

Figure 10. Relative humidity and enthalpy change for the ambient conditions on 18 to 19-09-2022

To further analyse the harvesting process, the enthalpy for the air in flow and saturation enthalpy are plotted in Figure 9. The graph shows that the air in flow enthalpy approaches the saturation enthalpy after the noon time (about 7–8 PM). Thus, the cooling load needed to make moist air condenses is minimum after noon, this suggest to collect energy within the day time from the Sun and utilise this energy afternoon to collect water from the atmospheric air (see Figure 10).

RESULTS

The results achieved in this work amounting to 10 L/day with about 9 kWh/L have been compared to the available results in literature [23] with 6.48 L/day and 5 kWh/L at 70% relative humidity. The findings were found to be fairly comparable with literature results even the SEC is higher than expected which indicates the need for more experimental investigation on the VAR system for best utilizing the cooling load from VAR system. This work is the first data achieved in a detailed experimental project aiming to include the VAR system within the AWH systems as it is characterized by the ability of being powered by renewable energy (No energy cost).

CONCLUSIONS

AWH systems are well established in literature and industry. AWH are suffering from the high energy consumption thus high production cost of water from atmosphere. This study experimentally tested a VAR system that can work by renewable energy (zero energy cost). As a result of the experiments, 10 L/m^2 per day water was produced from air, the SEC of the device was about 9 kWh/L. The findings were comparable to the available literature results with higher energy consumption. The high energy consumption is expected as the VAR system has a low COP. The results of this work suggest further experimental investigation on the VAR system for achieving maximum possible amount of water from atmosphere at the lowest energy consumption.

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REFERENCES

1. LEROY, C. 1751. Dissertation on the Elevation and Suspension of Water in the Air, and on Dew. (Dissertation on the Elevation and Suspension of Water in the Air, and on the Dew). Mémoires de l'Acad. Roy. des Sci., 481–518.
2. Ahmad, M., Rodríguez, A., Braslavskaya, A. 2005. Food and water insecurity: re-assessing the value of rainfed agriculture. Water Science and Technology: Water Supply, 5(1), 109–116. DOI: 10.2166/ws.2005.0014
3. Al-Qadami, E.H.H., Abdurrasheed, A.S., Mustaffa, Z., Amran, Y.H., Yusof, K.W., Ahsan, A. 2020. Productivity Enhancement of a Double Slope Solar Still Coupled with a Solar System. Journal of Ecological Engineering, 21(4).
4. Khalil, B., Adamowski, J., Shabbir, A., Jang, C., Rojas, M., Reilly, K., Ozga-Zielinski, B. 2016. A review: dew water collection from radiative passive collectors to recent developments of active collectors. Sustainable Water Resources Management, *2*(1), 71–86.
5. Peng, N., Teoh, M.M., Chung, T.S., Koo, L.L. 2011. Novel rectangular membranes with multiple hollow holes for ultrafiltration. Journal of membrane science, 372(1–2), 20–28.
6. Bani Khalid, M., Beithou, N., Al-Taani, M., Andruszkiewicz, A., Alahmer, A., Borowski, G., Alsaqoor, S. 2022. Integrated Eco-Friendly Outdoor Cooling System – Case Study of Hot-Humid Climate Countries. Journal of Ecological Engineering, 23(1), 64–72. https://doi.org/10.12911/22998993/143785
7. Kwan, T.H., Yuan, S., Shen, Y., Pei, G. 2022. Comparative meta-analysis of desalination and atmospheric water harvesting technologies based on the minimum energy of separation. Energy Reports, 8, 10072–10087.
8. http://www.genaq.com/water/.
9. Vián, J.G., Astrain, D., Domınguez, M. 2002. Numerical modelling and a design of a thermoelectric dehumidifier. Applied Thermal Engineering, 22(4), 407–422.
10. Alahmer, A., Khalid, M.B., Beithou, N., Borowski, G., Alsaqoor, S., Alhendi, H. 2022. An Experimental Investigation into Improving the Performance of Thermoelectric Generators. Journal of Ecological Engineering, 23(3).
11. Bhushan B. 2020 Design of water harvesting towers and projections for water collection from fog and condensation. Phil. Trans. R. Soc. A, 378, 20190440. http://dx.doi.org/10.1098/rsta.2019.0440
12. Tu, R., Hwang, Y. 2020. Reviews of atmospheric water harvesting technologies. Energy, 201, 117630.
13. Wang, Y., Danook, S.H., Al-Bonsrulah, H.A., Veeman, D., Wang, F. 2022. A Recent and Systematic

Review on Water Extraction from the Atmosphere for Arid Zones. Energies, 15(2), 421.

14. Kwan, T.H., Shen, Y., Hu, T., Pei, G. 2020. The fuel cell and atmospheric water generator hybrid system for supplying grid-independent power and freshwater. Applied Energy, 279, 115780. DOI: 10.1016/j.apenergy.2020.115780
15. Ozkan, O., Wikramanayake, E.D., Bahadur, V. 2017 Modeling humid air condensation in waste natural gas-powered atmospheric water harvesting systems. Applied Thermal Engineering, 118, 224–232.
16. Runze, D., Qingfen, M., Hui, L., Gaoping, W., Wei, Y., Guangfu, C., Yifan, C. 2020. Experimental investigations on a portable atmospheric water generator for maritime rescue. Journal of Water Reuse and Desalination, 10(1), 30–44.
17. Salek, F., Moghaddam, A.N., Naserian, M.M. 2018. Thermodynamic analysis and improvement of a novel solar driven atmospheric water generator. Energy Conversion and Management, 161, 104–111.
18. Salek, F., Eshghi, H., Zamen, M., Ahmadi, M.H. 2022. Energy and exergy analysis of an atmospheric water generator integrated with the compound parabolic collector with storage tank in various climates. Energy Reports, 8, 2401–2412.
19. Eslami, M., Tajeddini, F., Etaati, N. 2018. Thermal analysis and optimization of a system for water harvesting from humid air using thermoelectric coolers. Energy Conversion and Management, 174, 417–429.
20. Yao, Y., Sun, Y., Sun, D., Sang, C., Sun, M., Shen, L., Chen, H. 2017. Optimization design and experimental study of thermoelectric dehumidifier. Applied Thermal Engineering, 123, 820–829.
21. Udomsakdigool, C., Hirunlabh, J., Khedari, J., Zeghmati, B. 2007. Design Optimization of a New Hot Heat Sink with a Rectangular Fin Array for Thermoelectric Dehumidifiers. Heat Transfer Engineering, 28(7), 645–655. DOI: 10.1080/01457630701266470
22. Shourideh, A.H., Ajram, W.B., Al Lami, J., Haggag, S., Mansouri, A. 2018. A comprehensive study of an atmospheric water generator using Peltier effect. Thermal Science and Engineering Progress, 6, 14–26.
23. Liu, S., He, W., Hu, D., Lv, S., Chen, D., Wu, X., Li, S. 2017. Experimental analysis of a portable atmospheric water generator by thermoelectric cooling method. Energy Procedia, 142, 1609–1614. DOI: 10.1016/j.egypro.2017.12.538
24. Xu, X., Niu, R., Feng, G. 2015. An Experimental and Analytical Study of a Radiative Cooling System with Flat Plate Collectors. Procedia Engineering, 121, 1574–1581. DOI: 10.1016/j.proeng.2015.09.180
25. Hosseinzadeh, E., Taherian, H. 2012. An Experimental and Analytical Study of a Radiative Cooling System with Unglazed Flat Plate Collectors. International Journal of Green Energy, 9(8), 766–779. DOI: 10.1080/15435075.2011.641189
26. Subiantoro, A. 2017. Expander-based Atmospheric Water Harvesting in the Tropics. Asian Journal of Water, Environment and Pollution, 14(3), 1–8. doi:10.3233/ajw-170020.
27. Wang, X., Li, X., Liu, G., Li, J., Hu, X., Xu, N., Zhu, J. 2019. An interfacial solar heating assisted liquid sorbent atmospheric water generator. Angewandte Chemie, 131(35), 12182–12186.
28. Ni, F., Qiu, N., Xiao, P., Zhang, C., Jian, Y., Liang, Y., Chen, T. 2020. Tillandsia-inspired hygroscopic photothermal organogels for efficient atmospheric water harvesting. Angewandte Chemie International Edition, 59(43), 19237–19246.
29. Elashmawy, M., Alatawi, I. 2020. Atmospheric water harvesting from low-humid regions of Hail City in Saudi Arabia. Natural Resources Research, 29(6), 3689–3700.
30. LaPotin, A., Zhong, Y., Zhang, L., Zhao, L., Leroy, A., Kim, H., Wang, E. N. 2021. Dual-stage atmospheric water harvesting device for scalable solar-driven water production. Joule, 5(1), 166–182.
31. Wang, Y., Danook, S.H., AL-bonsrulah, H.A., Veeman, D., Wang, F. 2022. A Recent and Systematic Review on Water Extraction from the Atmosphere for Arid Zones. Energies, 15(2), 421.
32. Zhao, F., Zhou, X., Liu, Y., Shi, Y., Dai, Y., Yu, G. 2019. Super moisture-absorbent gels for all-weather atmospheric water harvesting. Advanced Materials, 31(10), 1806446.
33. Ahmad, A., Hamdan, M., Abdelhafez, E., Esra'a Turk, E., Ibbini, J., Abu Shaban, N. 2019 Water disinfection by solar energy. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 17(43), (2088–2098).