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Atmospheric Water Harvesting Technology: Review and Future Prospects

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ABSTRACT

Atmospheric water harvesting (AWH) devices represent a fruitful hope to cope with the water shortage problem throughout the world. The vast development in AWH technology and the wide spread of various AWH techniques will largely contribute to the implementation of AWH machines in different household, agricultural and industrial applications. In the last decades, a huge amount of research has been done on AWH methods with amazing differences in results that mislead readers and even researchers. In this study, the AWH theoretical technology developments, various AWH methods and various AWH machines in the market were reviewed. A comparison between the different theoretical methods was presented, concentration on unifying results based on area and energy consumption per harvested amount was performed for clear judgment on the different published data. The gaps between theory and market available devices were stated with recommendations for further development in AWH technology.

Keywords: atmospheric water harvesting, adsorption, absorption, vapor compression, expansion cooling.

INTRODUCTION

Nowadays, atmospheric water harvesting (AWH) or atmospheric water generator (AWG) are well known machines available on many markets based on vapor compression refrigeration or absorption concepts. These machines are not widespread in households or commercially worldwide for different reasons, including their energy efficiency, uncertainty of the generated water quality, advertising, and marketing problems. Schematic of different water harvesting techniques are shown in Figure 1.

It is anticipated that AWH machines will have a valuable contribution in covering the essential portable water needs in arid regions and may contribute to world food security if used in hydroponic agriculture (Aurangzaib, 2023). The condition that must be met to make AWH widely spread is the favorable payback period. This can be achieved if the payback period is reduced to at least one third of its expected life or when highly refundable applications are ascertained, such as planting in desert areas or greening the barren mountains.

Water vapor condensation from atmosphere is a well-established phenomenon, researchers well defined the universal interpretation of dew temperature in mid-20th century. Research has been accelerated as water scarce areas started to appear; thus, water and food insecurities come to be a real problem in the modern world (Ahmad et al., 2005). One of the oldest ways of obtaining potable water in rural areas, deserts or even sea is by using water distiller to evaporate water by sun and collect the condensate (Khalil et al., 2016; Al-Qadami et

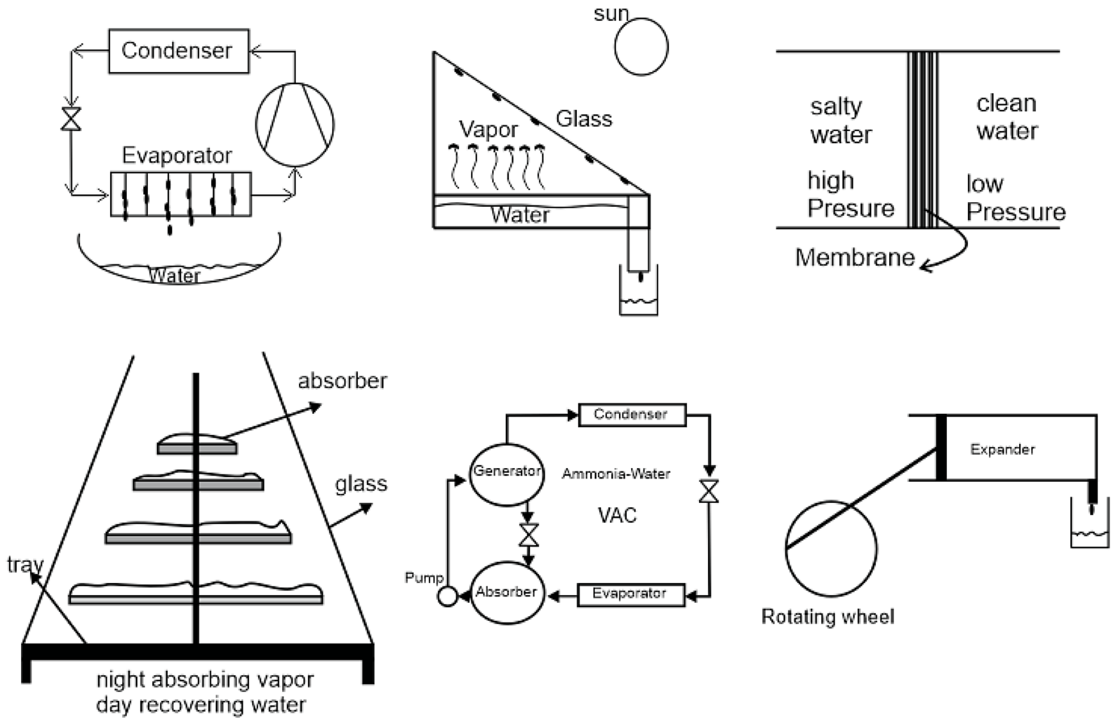

Figure 1. Schematic diagrams of various water harvesting systems

al., 2020). Different water distillers were proposed, tested and implemented in rural areas where contaminated water is available, but potable is not. In a later step, the usage of the Reverse Osmosis phenomenon was used to clean the contaminated and/ or sea water using different membrane types and multi-stage filtration (Peng et al., 2011).

Special type membranes were used to harvest water from air and remove air humidity as an air conditioning process (Liang et al., 2018). Humidity removal in hot humid climate is also used to control the outside environment relative humidity; Bani Khalid et al. (2022) used water removal from atmosphere to reduce the humidity and to lower the air temperature, reaching comfortable outside conditions, as well as use water for irrigation and drinking at the same time.

This work aimed to develop a deep understanding of the AWHs, both the ones available in the market and those proposed by the theoretical and experimental research. AWH characteristics, capacity and energy consumptions were analyzed and compared. The weaknesses in the different methods used were highlighted and the promising techniques were addressed for further research.

Machines available on the market

Various methods were used for harvesting water from atmosphere including the use of vapor compression refrigeration, vapor absorption, sorption, adsorption and desorption, as well as ultrafiltration and expansion methods (Figure 1). Most of the machines already available on the market adopt the vapor compression condensation (VCC), because this method is considered due its high energy performance. The specific energy consumption (SEC) of VCC systems is in the range of 220–300 Wh/kg, while 22–26 L/day can be produced (Kwan et al., 2022). Table 1 shows a list of the machines available on the world market with their water productivity per day, used refrigerant type, its energy efficiency, company website and working conditions.

In order to give a scientific opinion on the available machines, assign its weak points and address the researchers to perform valuable research that can serve this important promising sector; the machines available on the market have been searched, studied and compared.

Water status on the market

The technology used in the AWH machines on the market is based on VCC. The AWG machine water comes to be competitive when water needs to be transported over long distances where its cost may rise to 0.7 $/L (http://www.genaq.com/water/). From the previous discussion, it is clear that AWH machines will not be

Table 1. List of companies producing AWH machines, specifications and addresses

Company name	Water capacity [L/day]	Refriger-ant gas	Power required [W]	Energy efficiency [Wh/L]	Web address	Ambient conditions
Airowater	25, 500	R-134a	500, 7000	480	https://www.airowater.com/	in 24 hours at 70% RH
Watergen	550, 900, 3300–6000	R-410a	5600, 10000, 60–90 kW	350	https://www.watergen.com/	26.6 °C, 60% RH
Genaq	20, 50, 200 500, 4500	R134a	250, 700, 2500, 4700, 40000	420	http://www.genaq.com/	30.0 °C, 80% RH
Tsunamiproducts	36–700	R-410a	580, 7500	386, 267	https://www.tsunami-products.com/	16–38 °C 60–90% RH
Amoybrand	3000	R-407c	11–62 kW	584	https://www.amoybrand.com/	30.0 °C, 80% RH
Suntowater	30	desiccant/ ACS salt	1 kW	800	https://suntowater.com/	0–55 °C 15–90% RH
Atwtec	1000	R-410a	12 kW	288	http://atwtec.com/	15-40 °C 40–90% RH
Acquarias	20, 36, 50, 100	R-410a	400, 680, 800, 1250	480, 300	http://www.acquarias.com/	15–43 °C >25% RH
Innovaqua	9–30	R-134a	–	350	https://www.innovaqua.shop/	35–95% RH
PW HR-10000	10000	R-407c	–	–	https://powersolution-saustralia.com.au/	30.0 °C, 80% RH
Skywater-AKVO	500	R-407c, R-22	4400	211	https://www.skywater.com/	30.0 °C, 80% RH
Esharawater	1200	R-417	14 kW	280	https://esharawater.com/	
Waterfromairmachine	15, 30, 60		4 kW	960	https://waterfromair-machine.com.au/	30.0 °C, 80% RH
ECOLOBLUE	25, 100, 1000	R134a, R410a	0.5, 1.33, 8.7 kW	208	https://planetswater.co.uk/	30.0 °C, 80% RH
Recor-AIROWATER	100, 500, 1000	–	1.1, 5, 10 kW_{nomin}	240	https://www.recor.co.za/ www.airowater.co.za	23,0 °C, 40% RH
Watairuk	16	R-134a	900	1350	https://www.watairuk.uk	30.0 °C, 80% RH
Rayagua	30, 250, 5000	R-407c	2.2 kW	170	https://www.rayagua.com/	30.0 °C, 80% RH

able to penetrate the market in the cities and their role will be limited to desert areas where water is not available, and its delivery will cost much money. To make AWGs competitive on the market, the energy efficiency and/or water harvesting technology should be improved. Referring to Table 1, about eighteen different companies worldwide produce AWH machines with variable water capacities (8 to 10000 L/day) and variable energy efficiencies ranging from 0.211 to 1.3 kWh/L. Almost all companies depend on the vapor compression refrigeration with R-134a for small units, R-410a and R-407c for medium and large units. The large numbers of water harvested usually belongs to artificially created ambient conditions with 80–95% relative humidity (RH) which are not usually available in real life locations. As noted from the companies' review (Table 1), the SEC values of all AWH manufacturers are fluctuating between 0.211 kWh/L or above, depending on the specific heat exchanger design and the cooling capacity which depend on the used refrigerant. The commercially-available AWH machines have been tested in laboratory to measure the water productivity and SEC from different AWH manufacturers. The average water productivity ranges between 0.05 L/h for cold and humid to 0.65 L/h for warm and humid climates. The average SEC range is from 1.02 kWh/L for warm and humid to 6.23 kWh/L for cold and humid climates (Bagheri, 2018).

THEORETICAL AND EXPERIMENTAL RESEARCH ON AWH

To maximize the harvested water amount, thus reducing the SEC, various studies have been conducted, researching the heat transfer from the evaporator through fin characteristics (length, spacing, and height) (Vián et al., 2002), free and forced convection (Alahmer et al., 2022); forced convection allows for lower surface temperature, thus higher cooling rate is achieved, resulting in a

Figure 2. Thermoelectric water harvester with enhanced heat transfer rate

higher power generation from the TEG or higher AWH from thermoelectric cooler (TEC) is shown in Figure 2.

AWH methods

The AWH methods are wide and different in nature, the methods used for atmospheric water collection may be divided into (1) the methods using cooling to dew point, such as VCC, VAC, TEC, expander and radiative cooling, (2) the methods using sorption of water from the atmosphere by different water affinity materials ($CaCl_2$, LiCL, COFs, and MOFs), then collecting this water by different techniques such as the heating and condensation, pressure difference and desorption technique, (3) the methods using shape properties in extracting vapor from atmosphere, such as what happens with special membrane technology, cobwebs, plants and animals (Bhushan, 2020).

Cooling of atmospheric air contents to a temperature where water vapor in air converts to liquid water at the specific pressure can be carried out using different methods, such as:

- vapor compression refrigeration (VCR) technique,
- vapor absorption refrigeration (VAR) technique,
- thermoelectric cooling (TEC) technique,
- natural radiative cooling (NRC) technique,
- atmospheric air expander (AAE) technique.

AWH by VCR technique

This is the most well-known refrigeration machine that consists of a compressor, condenser, expansion valve and evaporator. VCR consumes electrical power by the compressor and creates a cooling effect at the evaporator; this cooling effect is used for AWH by passing air over the evaporator (Fig. 3).

The energy input to the cycle is the power consumed by the compressor , this power is given by:

$$\dot{W}_c = \left(\frac{n}{n-1}\right) \dot{m}\, R\, T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1 \right] \quad (1)$$

where: $\dot{m}$ – air mass flow rate, R – gas constant, T_1 – compressor inlet temperature, P_1 – compressor inlet pressure, P_2 – compressor exit pressure, n – is the polytropic index.

The cooling load is found from:

$$\dot{Q}_c = \dot{m}_R (h_4 - h_1) \quad (2)$$

$$COP = \dot{Q}_c / \dot{W}_c \quad (3)$$

where: $\dot{m}_R$ – refrigerant mass flow rate, h_1 – evaporator exit enthalpy, h_4 – evaporator inlet enthalpy, COP – is the coefficient of performance.

The working principle of the VCR is well known, the factor affects the water harvesting to transfer this cooling load uniformly to the vapor particles to achieve maximum condensation.

AWH using the solar powered VCR was reported by Tu and Hwang (2020), 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

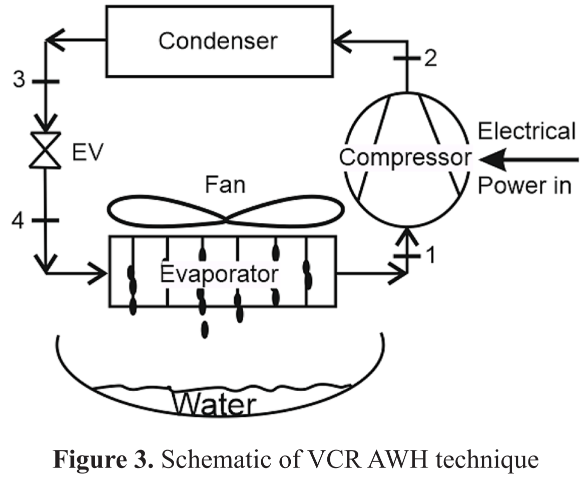

Figure 3. Schematic of VCR AWH technique

compressor. Its SEC can be calculated as 0.69 kWh/L. They 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 h (Wang et al., 2022). Kwan et al. (2020) has experimented with 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 can be obtained when RH = 75% with 2 kW FC, which is 50% higher than excluding the FC. They reported SEC of 200 Wh/L.

In an attempt to solve the problem of polluted water in a mining region of Mexico, Mendoza-Escamilla et al. (2019) have used 1, ½ and ¼ ton of refrigeration in order to detect the feasibility of supplying the site with AWH. They used a photovoltaic power supply to drive the AWH system and achieved 0.89–3.6 L/day in January as minimum amount, while 3.9–18 L/day in August as a maximum. They found that the water production costs ranged between 0.0093–0.038 USD/L. Ozkan et al. (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 8.7–2.5 L/m^3 of natural gas, SEC was about 1.2 kWh/L. Another application of the AWH was maritime rescue; the best water productivity was 460 mL/h at 27°C, 92% RH and 600 m^3/h air flow rate (Runze et al., 2020). To use the wasted energy from the vented/flared land fill gas (LFG), an average of 4.6 L/m^3 of the LFG were achieved (Wikramanayake, 2017) (note methane heating value is 33906 kJ/m^3, 31670 kJ/m^3 for natural gas). The variation in SEC belongs to the variation in the working principle, design and refrigerant used. Various climatic conditions were used to test the AWH in laboratory. The minimum SEC was found as 0.75 kWh/L, with water productivity of 1.78 L/h for warm-humid climate and maximum SEC was 4.71 kWh/L with 0.28 L/h water for mild and dry climate (Patel et al., 2020).

AWH by VAR technique

The vapor absorption refrigeration system does not require a compressor, it is replaced by the absorber-generator pair for pressurizing the system; VAR such as ammonia-water, lithium bromide and ammonia-water-hydrogen systems may be used to generate cooling load using any thermal energy input (Fig. 4).

$$Energy\ in = Energy\ out$$

$$\dot{Q}_g + \dot{m}_4 h_4 = \dot{m}_5 h_5 + \dot{m}_7 h_7 \tag{4}$$

where: $\dot{m}$ – is the mass flow rate, h – enthalpy at the given point, $\dot{Q}_g$ – generator heat, could be from any thermal source of energy, including solar, biomass or geothermal.

The mass conservation equations are:

$$\dot{m}_4 = \dot{m}_5 + \dot{m}_7 \tag{5}$$

The cooling load of the evaporator can be found by applying the conservation of energy and conservation of mass equations as:

$$\dot{m}_1 = \dot{m}_2 \tag{6}$$

$$\dot{m}_w = \dot{m}_a (w_{a1} + w_{a2}) \tag{7}$$

$$\dot{Q}_{ev} + \dot{m}_2 h_2 = \dot{m}_1 h_1 \tag{8}$$

$$\dot{Q}_{ev} = \dot{Q}_{ev,sen1} + \dot{Q}_{ev,lat} + \dot{Q}_{ev,sen2} \tag{9}$$

where: $\dot{Q}_{ev}$ – evaporator heat absorption, $\dot{Q}_{ev,sen1}$ – sensible heat entering the evaporator, $\dot{Q}_{ev,sen2}$ – sensible heat leaving evaporator, $\dot{Q}_{ev,lat}$ – latent heat change, $\dot{m}_a$ – air mass flow rate, $\dot{m}_w$ – water mass flow rate (condensed water on the evaporator), w_{a1} – air humidity ratio before evaporator, w_{a2} – air humidity ratio after evaporator.

Almost no experimental work has been done on analyzing the VAR machine in AWH technology, this may be due to the high initial cost of the VAR system or its low COP. Nevertheless, such a system can be driven by solar, biomass, nuclear

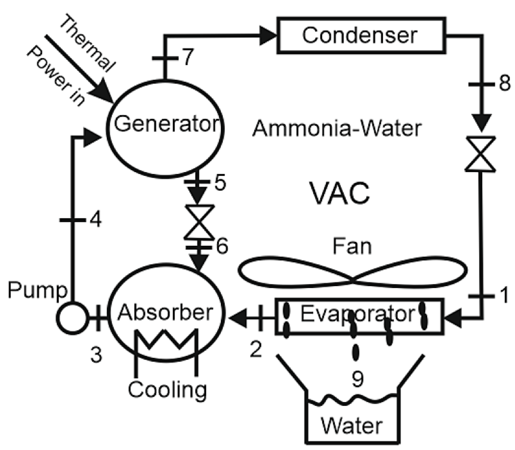

Figure 4. Schematic of VAR AWH technique

or even geothermal renewable energies. Theoretical thermodynamic analyses have been done for the VAR AWH system driven by solar energy; the equations governing the system have been stated and modeled (Okour et al., 2022). The proposed system consists of three parts: (1) solar driven ammonia absorption refrigeration cycle, (2) saline water desalination cycle, and (3) air dehumidification cycle. It produces water from two sources simultaneously with a single power input (Salek, 2018). The VAR system using parabolic trough solar collector was also analyzed (PTSC) (Salek, 2022). It was found that the maximum rate of water generation is nearly 400 L/month in tropical climates with specific energy consumption of 3 kWh/L. They also performed an exergy analysis of the whole system and found that the highest exergy destruction rate was due PTSC component.

AWH by TEC technique

The thermoelectric module shown in Figure 2, is a direct energy conversion device used to convert electrical energy directly to a cooling effect. TEC consists of N and P type semi electric materials, with current flow through TEC hot side and cold side initiated from what is called Peltier cooler, as shown in Figure 5.

The thermoelectric materials (properties of semiconductors) and temperature differences as displayed in Eq. 10 & 11 are primarily responsible for the power generated by TEG:

$$\dot{Q}_h = \alpha\, T_h\, I - \frac{1}{2}\, I^2\, R + K\,(T_h - T_c) \quad (10)$$

$$\dot{Q}_c = \alpha\, T_c\, I + \frac{1}{2}\, I^2\, R + K\,(T_h - T_c) \quad (11)$$

where: α – is the Seebeck coefficient, R – is the internal electrical resistance, K – is the thermal conductance, I – is current, T_h – is the hot junction temperature, T_c – is the cold junction temperature.

TEC has been tested for AWH purposes for its advantages in direct energy conversion low weight and minimum maintenance requirements. Table 2 shows some research done on TEC with its water productivity and energy consumption.

It was reported before that the energy consumption ranges between 0.118 to 4.7 kWh/L of water. To minimize the energy consumption, (Udomsakdigool et al., 2007) analyzed the fin spacing efficiency to maximizing convection heat transfer. The effect of fin length, fin material and air velocity were studied by (Shourideh et al., 2018); the authors tested the variable fin length (8 cm optimal), air velocity (2 m/s max production) and found that copper fins are better than aluminum fins. The TEC efficiency depends on the power supplied:

$$\dot{W}_{net} = V \cdot I \quad (12)$$

where: $\dot{W}_{net}$ – net electrical power (W), V – voltage (V), I – current (A).

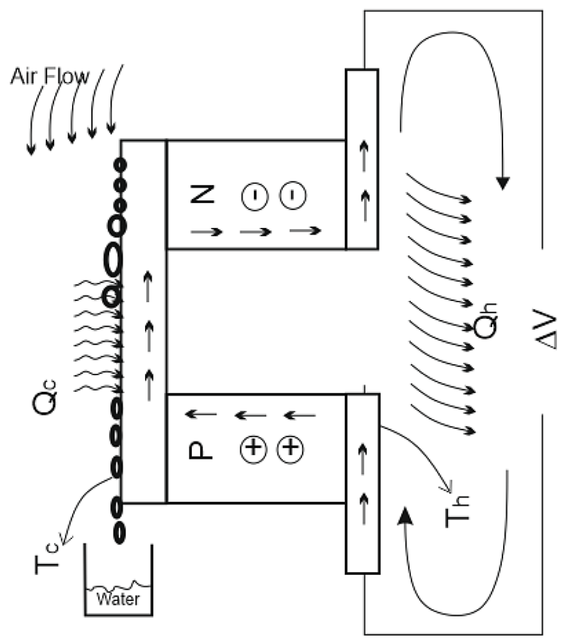

Figure 5. Schematic of the VAR AWH technique

Table 2. AWH by TEC technology with water productivity and energy consumption

Reference	Water capacity [L/day]	Power required [Wh]	SEC [kWh/L]	Notes
Eslami et al., 2018	1.6	60	0.9	–
Inbar et al., 2020	0.624	20	0.833	–
Yao et al., 2017	0.7944	90	2.719	with 3 fans
Shourideh et al., 2018	1.58	61	0.926	80% RH
Kabeel et al., 2014	3.9	236	1.45	80% RH
Liu et al., 2017	0.27	53	4.8	70% RH
He et al., 2019	0.6	–	–	80% RH

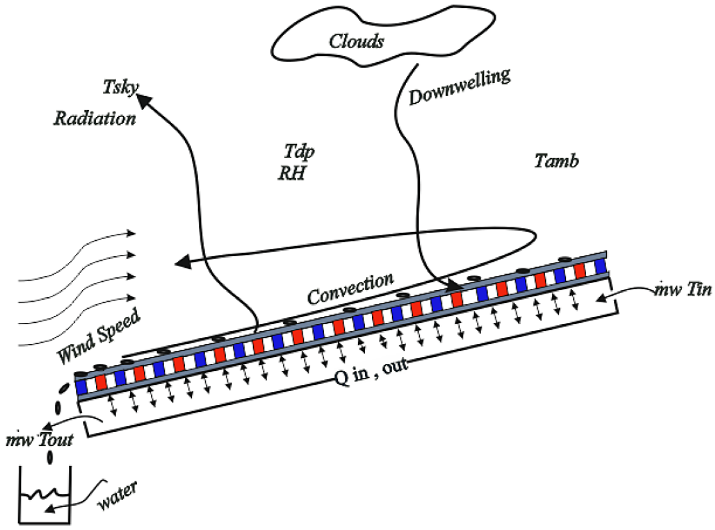

Figure 6. Schematic of VAR natural radiative cooling AWH technique

and has a thermal efficiency:

$$\eta_{th} = \frac{\dot{Q}_c}{\dot{W}_{net}} \tag{13}$$

AWH by NRC technique

One of the most ancient techniques in passive cooling is the radiative cooling (Fig. 6). Xu et al. (2015) has analyzed the radiative cooling for a house with storage tank and loop heat exchanger. An unglazed convective- radiative cooling system has been proposed by Hosseinzadeh et al. (2012) to cool water flow rate. About 7 ℃ temperature drop with 52 W/m^2 have been achieved for a water flow rate of about 0.05 kg/s. In the last decades with the water crises, it started to be used for water condensation and plant irrigation (Alnaser and Barakat, 2000). Radiation heat transfer between the surface and the air temperature occurs, resulting in a drop of the surface temperature for the plate. As a result of convection-radiation heat transfer, moist air temperature reaches the dew point where water droplets start to formulate on the plate surface. In his study, bulk lubricant infusion in poly-dimethylsiloxane enhanced condensation and led to a more than 40% higher dewing on the substrate (Sharma et al., 2022).

AWH by AAE technique

The dew point temperature of moist air was mainly achieved through lowering air temperature by extracting heat from air. Subiantoro (2017) reached the dew point by reducing the pressure, rather than temperature, in a piston cylinder device with reciprocating motion. The principle of extracting water from atmospheric air by expansion is shown in Figure 7.

The expander shown in Figure 7 was used to harvest atmospheric water. The main advantages of AAE are compactness, simplicity, bulk effect on air and low energy consumption. The system was modeled at air temperature 30 °C and 80% RH, it expands air to 0.7 bar and 0 °C at the end of the expansion process. Water production was 11.5 g/kg air expanded, the average power per cycle was 3.374 W and SEC 117 Wh/L.

AWH by sorption methods

The sorption can be defined as a physical and/or chemical process in which a substance (typically a gas or vapor) (sorbate) accumulates within another substance (sorbent) or on its boundary

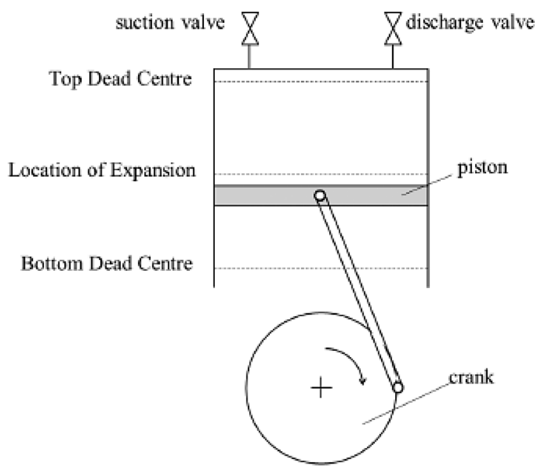

Figure 7. Schematic of the AAR AWH technique

Table 3. AWH by sorption technology, description, water productivity and energy consumption

Reference	Description	Water productivity	Energy consumption
Wang et al., 2019	Graphene oxide-based aerogel as a salt-resistant absorber ($CaCl_2$ 50 wt% solution), 70% RH night adsorption – day desorption	2.89 L/m² per day	solar
Ni et al., 2020	Integrated hygroscopic photothermal organogel (POG) to achieve a solar-powered atmospheric water harvesting (AWH)	2.43 L/m² per day	solar
Elashmawy et al., 2020	Black cotton cloth bed saturated with calcium chloride solution, low manufacturing cost, 26.5% RH	1.06 L/m² per day	solar
La Potin et al., 2021	Dual-stage device to improve productivity by recycling the latent heat of condensation commercial zeolite (AQSOA Z01) 20 °C, 68% RH	0.77 L/m² per day	solar
Wang et al., 2022	$CaCl_2$ review sorption for comparison	2.5 L/m² per day	up to 1000 m³ per day
Elashmawy et al., 2020	0.51 L of water for each kilogram of the desiccant (calcium chloride); concentrated tubular solar system	0.51 $L/kg_{desiccant}$	solar
Zhao et al., 2019	Hygroscopic polypyrrole chloride penetrating in hydrophilicity switchable polymeric network of poly N-isopropylacrylamide	3.9 $g_w/g_{desiccant}$	solar
Entezari et al., 2019	Combining silica gel, salt, and polymers that show faster dynamic, improved regeneration properties and sorption capacity	0.43 $g_w/g_{desiccant}$	20 C, 70% RH
Luna et al., 2019	ZJNU-30 is a thermal, hydric, and chemically stable Zr-based MOF, used as water generator and air cooler	1.2 $g_w/g_{sorbent}$	low pressures (near p/p0 = 0.3)
Zhou et al., 2020	A composite hydrogel composed of alginate chains modified with binary salts and functionalized multi-walled carbon nanotube (FCNT) as an efficient solar absorber is demonstrated as the moisture harvester (Bina/FNCT)	5.6 $g_w/g_{sorbent}$	solar
Ejeian et al., 2020	Enhanced LiCl /$MgSO_4$/ACF composite	2.29 $g_w/g_{adsorbent}$	solar
Jin et al., 2017	Li and Ca supergel sodium alginate by occupying both G-blocks and M-blocks with more hydrophilic cations	5.6 $g_w/g_{desiccant}$	at 70% RH
Li et al., 2018	$CaCl_2$, 0.25 L/kg of MOF/day, arid region (10–40% RH)		

(Pourret et al., 2022). This can happen by absorption (within a liquid substance) or adsorption (on the surface of a solid substance). Therefore, the principle of AWH by sorption is to collect water vapor through use of desiccants due to the affinity of these desiccants to water vapor.

A list of the thermally dependent sorption AWH systems are included in Table 3, it absorbs moisture during night time and extracts water as a result of solar or thermal heating during day time. Different $CaCL_2$ compounds and Li Ca super-gel are used in such systems, 2.89 L/m² per day water was achieved by (Wang et al., 2019). The capacity of water generation 5.6 gw/g sorbent was achieved with a composite hydrogel composed of alginate chains modified with binary salts (Jin et al., 2017). The sorbent-based AWH that depends on solar thermal energy is limited to 0.25–10 L/day water production relative to household needs and hygiene, which is about 50 L/capita per day (Humphrey et al., 2020). Sorbents are still under development to maximize the achieved amount of water per day.

AWH shape property extraction technology

Metal-organic framework (MOF) [$Zr_6O_4(OH)_4$(fumarate)6] has high capability of sorption water. It can absorb more than 0.25 L of water per kg MOF within a day (Kim et al. 2018). MOF has a good performance of AWH in the desert, due to its high-water uptake at low RH (about 0.25 g/g when the RH is 10%) and excellent stability (Pan et al., 2020). Tailored interfacial solar absorbers have been combined with an ionic-liquid-based sorbent to generate a simultaneous adsorption-desorption process (Qi et al., 2019). This AWG enables a high rate of water production (≈0.5 L/m²) and 2.8 L/m² per day for the outdoor environment. A membrane water harvesting and cooling device was proposed by (Zaho et al., 2019), novel rectangular shaped membranes with multiple holes were used for ultrafiltration. A low-pressure recirculation sweep stream reduce heat needed for cooling the air stream. At 60 mbar, only a small fraction (5% for 10 L/min, 13% for 32 L/min) is required to cool the sweep stream of the energy needed to cool ambient air to the same temperature in an application working without membranes (Lord et al., 2021).

AWH by bioinspired structures method

In order to discover more ways of harvesting water from moist air or fogs; researchers studied various plants and animals to learn lessons from nature. Different structural shapes were found to collect water than others, these shapes are called bioinspired structure, as it has been taken from desert animals and plants. Bioinspired water harvesting structures were tested experimentally. Flat, cylindrical and conical surfaces with various thicknesses and angles were analyzed by Shi et al. (2018), Jin et al. (2017), Chen et al. (2022), and various designs for AWH were proposed. The effect of an array of vertical wires – "fog harps" – have been studied to understand the water condensation behavior. Fog harps with different wire diameters were tested. The mid-sized wires exhibited the largest fog collection rate. Moreover, the fog-harvesting rate continually increased with decreasing wire diameter for the fog harps due to efficient droplet shedding that prevented clogging. Another bioinspired material has been developed as integrated hygroscopic photothermal organogel (POG) to achieve solar-powered atmospheric water harvesting. This POG could absorb about 16 kg/m^2 at 90% RH and produce up to 2.43 kg/m^2 water per day from ambient air (Ni et al., 2020).

AWH with renewable energy systems

Referring to Table 1, the house requires almost 400 L/day with 4.2 kW of power needed for operation. The cost of a household water for about 16 years exceeds the expected life of the AWH machine. Wind turbines have a lower price but higher maintenance cost, for farms or rural areas wind turbines may represent a logical electrical or water harvesting solution (Table 4). The expected cost of the wind turbine of a 5 kW power may reach $2500, this results in a water cost of a household for 10 years (Evans et al., 2018). Wind turbines have the disadvantage that they cannot be mounted in a city, but they are suitable for countryside or rural places.

Table 4. Wind turbine specifications (Qingdao Allrun New Energy Co.)

Model number	AR10KW
Output voltage	96V 110V 220V 380V
Rated power	10 kW
Rotor diameter	6.0M
Blades quantity	THREE
Tower height	6M TO 25M
Start-up wind speed	2.0 m/s
Wind turbine type	Horizontal

Moreover, ammonia vapor absorption cycle is a simple low-cost cycle that passively converts the heat into a cooling load (Elberry et al., 2016). This heat can be absorbed from the sun/geothermal with no cost and used to generate a low-cost AWG.

CONCLUSIONS

The review and prospects of AWH methods and machines available on the market are important in developing the sector and give hope for food security, especially in the developing countries. As it appears from the review of the market machines, low, medium, and high AWG are available on the market. The use of R134a, R410a and R407c, 20 L/day up to 10000 L/day is possible, the specific energy consumption of these machines ranges from 200 to 600 Wh/L depending on the design used. The water generated by the machines available on the market is more expensive than the price of the water on the market. A VAC machine produces 14 L/day with specific energy consumption about 3 kWh/L. The VAC requires more research to improve the available machines due to its advantage of free energy input. TEC has a low water production with high specific energy consumption. Atmospheric air expander consumes low energy but requires large systems and compressors. Sorption methods are promising with fast developing technology, AWH with 3 L/m^2·day is possible using solar energy, 6 kg/kg desiccant has been achieved with Li Ca supergel at 70% RH, low RH areas focus on the MOF with passive techniques.

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