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A TECHNICAL REVIEW ON THE EXTRACTION OF WATER FROM ATMOSPHERIC AIR IN ARID ZONES

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Abstract

Fresh water supply is one of the most limiting conditions for the populations of arid regions. The present paper covers the working principles of systems and processes for extracting water from atmospheric air. Moreover, a summary of the experimental and analytical studies which investigate system performance has been made. Some new designs that greatly expand the solar desiccant technique for absorption with subsequent regeneration are also introduced. The research activities in this sector are still increasing to solve the crucial points that make these systems not yet ready to compete with other systems as water distillation.

Keywords and phrases: solar energy, extraction, regeneration, air, absorption, liquid desiccant, dew collection.

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1. Introduction

Shortage of drinking water is chronic, sever, and widespread in the regions of Northern Africa, Middle East, and Central and Southern Asia. The problem of providing arid areas with fresh water can be solved by the following methods [1]:

1. transportation of water from other locations;
2. desalination of saline water (ground and underground);
3. extraction of water from atmospheric air.

Transportation of water through these regions is usually very expensive, and desalination depends on the presence of saline water resources, which are usually rare in arid regions. Atmospheric air is a huge and renewable reservoir of water. This endless source of water is available everywhere on the earth surface. The extraction of water from atmospheric air has several advantages compared with the other methods. Air as a source of water is renewable and clean and the amount of water in atmospheric air is evaluated as 14000 km^3, and the amount of fresh water in the earth is only about 1200 km^3 [2].

The extraction of water from atmospheric air can be accomplished by different methods, the most common of these methods are cooling moist air to a temperature lower than the air dew point, and absorbing water vapor from moist air using a solid or a liquid desiccant, with subsequent recovery of the extracted water by heating the desiccant and condensing the evaporated water.

In some regions of the world, dew water – if available – appears to be a simple solution to complement sources of potable water. Dew water is indeed used by plants and small animals where, in arid and semi-arid environment, it is significant to sustain their activity.

Choice of methods is an engineering decision dependent on local climatic conditions and economic factors such as capital, operating, and energy costs. On the other hand, patented devices vary in scale and potable water output from small units suitable for one person's daily needs to structures as large as multi-story office buildings capable of supplying drinking water to an urban neighborhood. The objective of the present work is to highlight the different technological processes used for moisture or dew collection from the atmospheric air.

2. Literature Review

2.1. The earth-collector

One of the first works dealing with water extraction from atmospheric air was published in Russia [3]. An apparatus consisting of a system of vertical and inclined channels in the earth to collect water from atmospheric air by cooling moist air to a temperature lower than its dew point has been proposed. The earth-water collector as proposed by Kobayashi [4] is shown in Fig. 1. The earth essentially consists of three layers. When the sun shines brightly, the surface of the earth becomes dry, creating a dry layer. The depth of the dry layer varies according to the type of soil, amount of rainfall, depth of the capillary layer, etc. Under the dry layer there lies a moist layer that remains wet through capillary action as it is in contact with the underground water. By capillary action, this water is sucked up to the surface of the earth through tiny crevices in the soil. When the ground surface is heated by the sun, this water dissipates in aqueous vapor. To collect this vapor in the form of droplets, a quadrilateral frame with a glazing at a slope, called as earth-water collector, is used. When the earth surface is heated by solar energy, the water vapor that evaporates from the surface rises to the glazing by convection and it is condensed on the underside of the glazing. The condensate flows along the glazing by gravity into condensate.

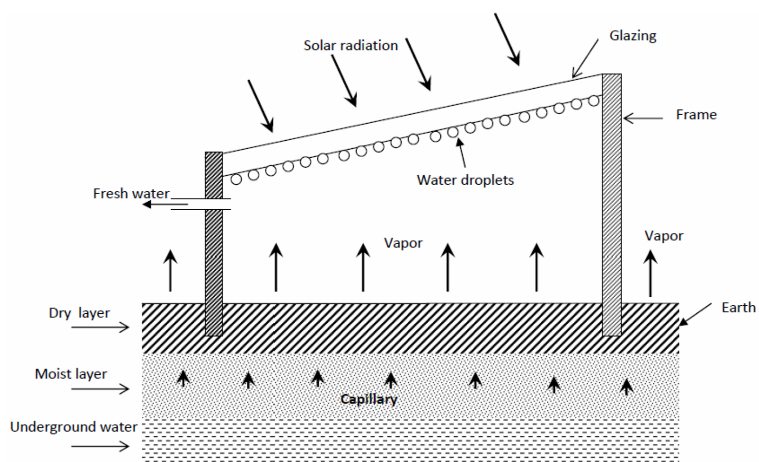

Figure 1. Principle of earth-water collector [4].

Different technological processes are proposed by numerous investigators to extract water from the ambient air using solar energy as a power source. Flow diagram of technological processes of separation of water from moist air using solar energy which is presented in [5] is demonstrated in Fig. 2. In this diagram two main methods are described by using solar energy. One of them is by cooling the atmospheric air to a temperature lower than the dew point and the second by sorption with subsequent regeneration. In the following subsections the operation of such systems will be discussed.

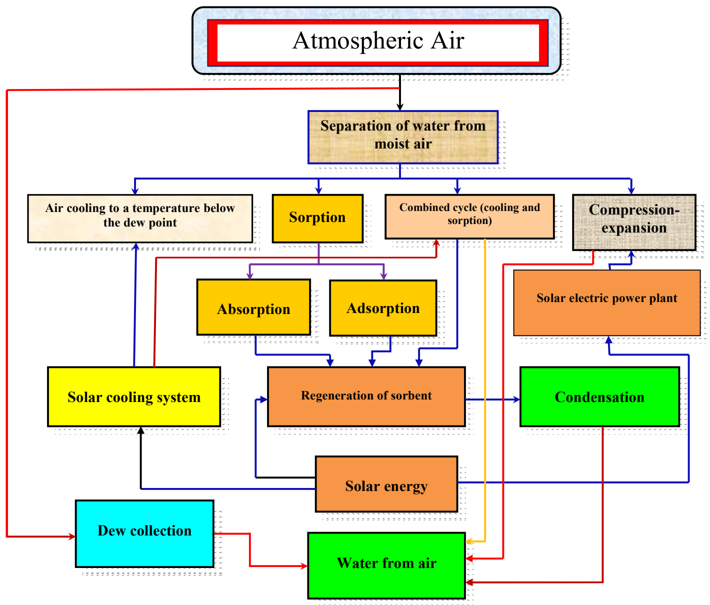

Figure 2. Flow diagram of technological process of separation of water from moist air using solar energy [5].

2.2. The absorption-regeneration cycle

Description and analysis of the theoretical cycle for absorption of water vapour from air with subsequent regeneration, by heating is presented in [1]. A theoretical limit for the maximum possible amount of water which can be collected from air using the desiccant through the absorption regeneration cycle at certain operating limits of ambient conditions, heat to be added to the desiccant during regeneration and maximum available heating temperature could be evaluated through the analysis of this cycle. The absorption regeneration cycle, which can be applied for the production of water from atmospheric air, is shown in Fig. 3. The theoretical cycle is plotted on the vapour pressure-concentration diagram for the operating absorbent and consists of four thermal processes which are:

1. Process 1-2: isothermal absorption of water vapour from air.

2. Process 2-3: constant concentration heating of the absorbent.

3. Process 3-4: constant pressure regeneration of absorbent.

4. Process 4-1: constant concentration cooling of absorbent.

This cycle can be applied in desiccant systems with different configurations and different heat sources. As the purpose of this cycle is to produce water from air and the input energy to the system is the heat added during the regeneration process, then the efficiency of the cycle can be defined as the ratio of heat added to regenerated vapour to the total heat added. Theoretical analysis showed that, strong and weak solution concentration limits play a decisive role in the value of cycle efficiency. However, a modified cycle is described and analyzed by Sultan [6]. In this modification, the practical considerations are taken into account.

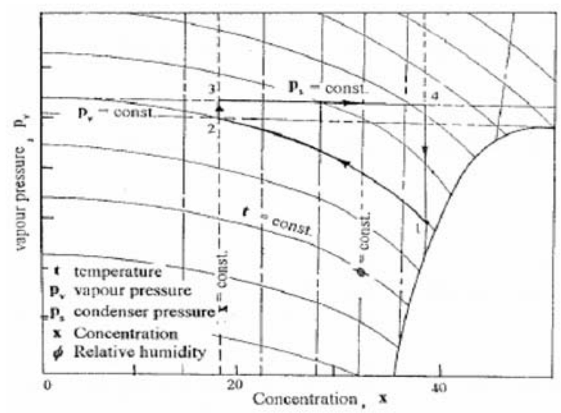

Figure 3. Absorption-regeneration cycle [1].

2.3. Desiccant systems

Hall [7] proposed a system for the production of water from atmospheric air by absorption using ethylene glycol as a liquid desiccant with subsequent recovery in a solar still. The effects of temperature and humidity on the recovered water were studied and the results presented in the form of a composition-psychometric chart, but the paper does not provide any information about the mass of recovered water. Sofrata [8] constructed a non-conventional system to collect water from air based on an adsorption-desorption process using a solid desiccant. The paper also discussed the feasibility of the application of air conditioning systems for collecting water from moist air by cooling it to a temperature lower than the dew point. Alayli [9] used a typical S-shaped composite material for absorption of moisture from atmospheric air with subsequent regeneration using solar energy. Hamed [10] tested two methods to extract water from atmospheric air using solar energy. The first method was based on cooling moist air to a temperature lower than the air dew point using a solar LiBr–H_2O absorption cooling system. The second method was based on the absorption of moisture from atmospheric air during the night using calcium chloride solution as a liquid desiccant, with subsequent recovery of absorbed water during the day. As a result of this study, the second method was recommended as a most suitable application of solar energy for water recovery from air.

Abualhamayel and Gandhidasan [11] proposed a system for water recovery from air. A schematic of this system is shown in Fig. 4. It consists of a flat, blackened, tilted surface and is covered by a single glazing with an air gap of about 45 cm. The bottom of the unit is well insulated. At night, the strong absorbent flows down as a thin film over the glass cover in contact with the ambient air. If the vapor pressure of the strong desiccant is less than the vapor pressure of water in the atmospheric air, mass transfer takes place from the atmosphere to the absorbent. Due to absorption of moisture from the ambient air during the night, the absorbent becomes diluted. The water-rich absorbent must be heated during the day to recover the water from the weak absorbent. Therefore, during the day, the weak desiccant flows down as a thin film over the absorber surface. The weak absorbent is heated by solar energy, and the water that evaporates from the solution rises to the glass cover by convection where it is condensed on the underside of the glass cover and the absorbent leaving the unit becomes strong. The performance of the unit at night depends on the potential for mass transfer, which is the difference in water vapor pressure between the ambient air and desiccant.

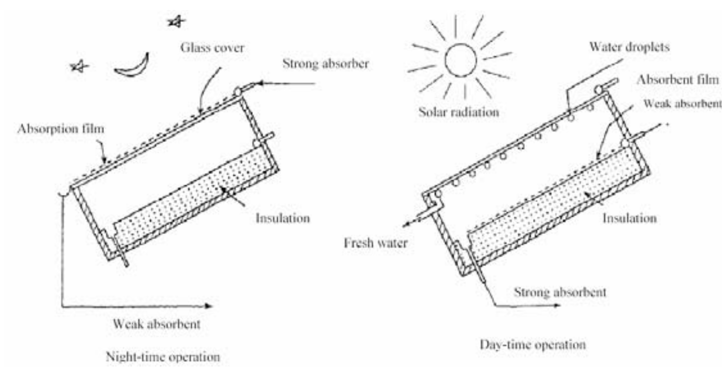

Figure 4. Schematic of the unit proposed by [11].

The performance of a desiccant/collector system with a thick corrugated layer of blackened cloth to absorb water vapor at night from atmospheric air with subsequent regeneration during the day, using solar energy, was reported by Gad et al. [12]. Fig. 5 shows a schematic diagram of the experimental apparatus. It consists mainly of three parts: a flat plate collector with a movable glass cover, a corrugated bed and an air-cooled condenser consisting of two parallel flat plates. The inner surface of the collector is a box of cross section $1.42 \times 1.42\,\mathrm{m}, 0.3\,\mathrm{m}$ in height. Three square openings of $0.2 \times 0.2\,\mathrm{m}$, are distributed on one side of the box. In each opening, a fan of 10 W power is supported. The box is insulated by a high density foam of 0.05 m thickness, covered with aluminum sheets which form, by riveting, the outside case of the apparatus. A glass cover which has a square cross sectional area of $2\,\mathrm{m}^2$ and 6 mm thickness is supported by a metallic frame to form the upper side of the apparatus. The frame is hinged with the box from one side. To support the cloth layers which comprise the bed, a metallic frame made of steel wires is used (Fig. 5). The bed height is 0.2 m, the horizontal distance between each two successive steel wires is 5 cm. The corrugation increases the absorption area to about 4.1 times the area of the box. A steel frame with a tilt angle of 30° supports the apparatus. An air-cooled surface condenser with two parallel flat plates and total surface area of $2\,\mathrm{m}^2$ is connected to the solar collector from the back (north) side through a small steel duct. The condenser is made of steel sheets of 0.5 mm thickness. A condensate collection flask is located below the condenser. The condenser is connected to the system to evaluate its effect on the system productivity and operation. Actual recorded results show that the solar operated system can provide about 1.5 l of fresh water per square meter per day.

The need for economical realization of solar-desiccant systems for water production in arid areas is of great importance. Moreover, the inconvenience and relatively high capital cost of the desiccant bed limits the utilization of such units in large scale. In desert regions, mixing a sandy layer of the ground surface with desiccant as a promising method to minimize the cost of the vapour absorption bed was proposed [13]. The sandy layer impregnated with desiccant is subjected to ambient atmosphere to absorb water vapour in the night. During the sunshine period, the layer is covered with a greenhouse where desiccant is regenerated and water vapour is condensed on the transparent surface of the greenhouse or any other cold surface. Prediction of the absorption cycle requires knowledge of the percentage approach to saturation. In view of the design parameters of the absorption bed, the desiccant to sand mass ratio is an important factor affecting the rate of absorption and consequently the rate of water production. Extracting water from air by using sandy bed solar collector system is explored by Kabeel [14]. The system is studied theoretically and experimentally to evaluate the performance of the sandy bed impregnated with 30% concentration $CaCl_2$ to produce water from moist air. It is reported that the system can provide up to about 1.2 l fresh water per square meter of glass cover per day.

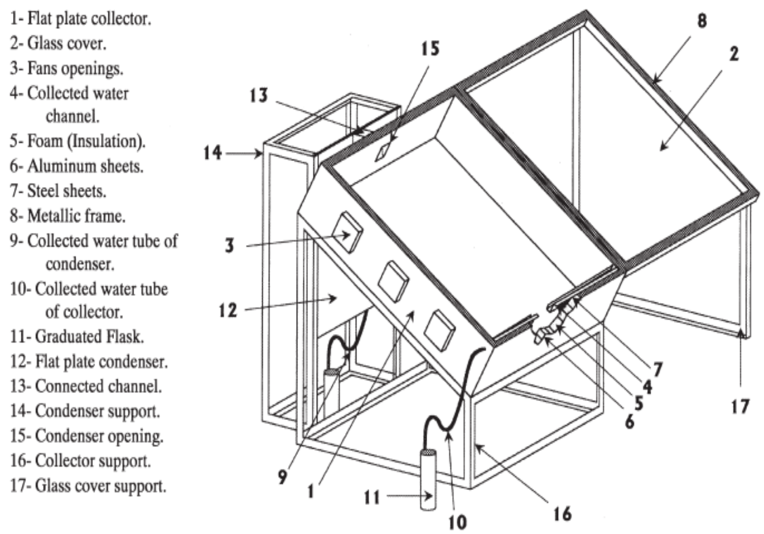

Figure 5. Schematic diagram of the experimental solar-desiccant collector for water recovery from air [12].

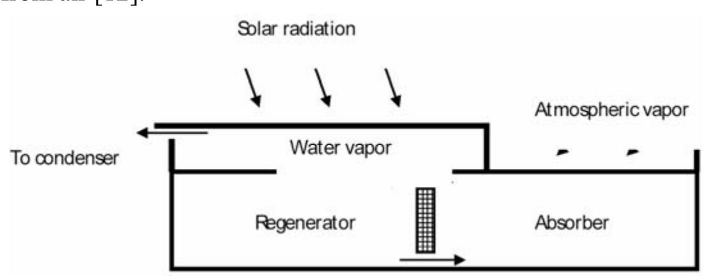

Figure 6. Desiccant pond for absorbing moisture from the air [16].

The application of solar concentration for frish water production from the atmospheric air is reported in [15]. The results obtained in the AQUASOLIS project for assessing the use of solar trough concentration plants for applications other than heating and cooling, in particular for the production of fresh water for human consumption and for agriculture for Mediterranean countries. Fig. 6 prsents an apparatus for extracting moisture from the ambient air that includes a desiccant pond for absorbing moisture from the air to produce a water rich desiccant [16]. The atmospheric vapour is absorbed in the absorber section and the weak desiccant is circulated to the generator for heating and vapour condensation.

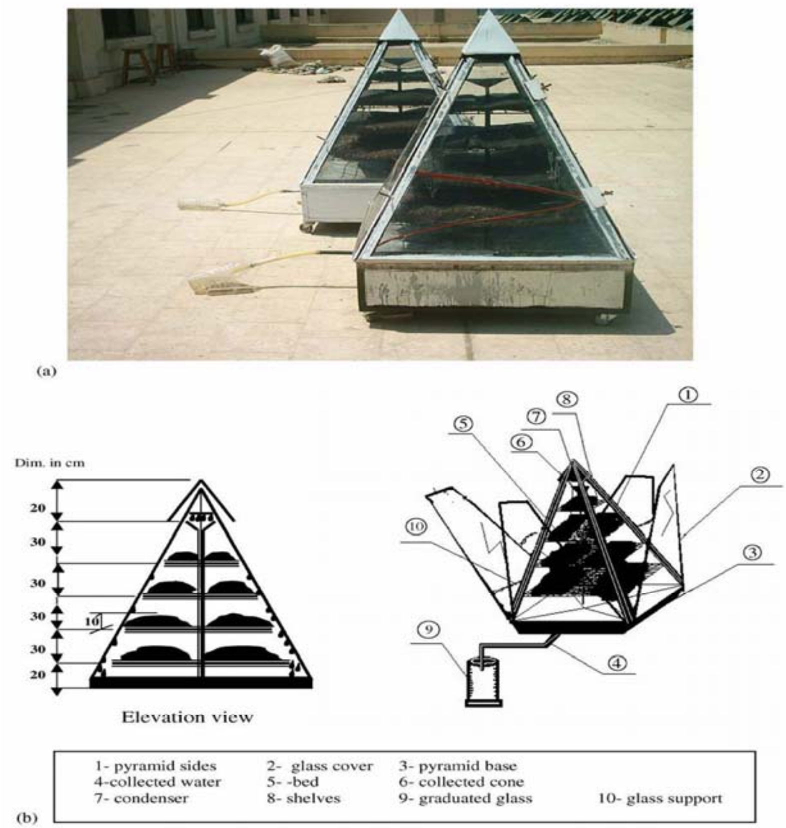

Figure 7. Water production from air using multi-shelves solar glass pyramid system [17].

The capability of the glass pyramid shape with a multi-shelf solar system to extract water from humid air is explored in [17]. Two pyramids were used with different types of beds on the shelves (Fig. 7). The beds are saturated with 30% concentrated calcium chloride solution. The pyramid sides were opened at night to allow the bed saturated with moist air and closed during the day to extract the moisture from the bed by solar radiation. The bed in the first pyramid was made of saw wood while it is made of only cloth in the second pyramid with the same dimensions. The system was experimentally investigated at different climatic conditions to study the effect of pyramid shape on the absorption and regeneration processes. Preliminary results have shown that the cloths bed absorbs more solution (9 kg) as compared to the saw wood bed (8 kg). Adopting this approach produces $2.5\ 1/(\text{day m}^2)$.

Selective water sorbents developed at the Boreskov Institute of Catalysis (Novosibirsk, Russia) for fresh water production from the atmosphere are reported by Aristov et al. [18] The results of their lab-scale tests have demonstrated a feasibility of the fresh water production with the output of 3-5 tones of water per 10 tones of the dry sorbent per day. Also, selective composite adsorbent for solar-driven fresh water production from the atmospheric air is presented in [19]. It is synthesized by a patented ultra-large pore crystalline material MCM-41 as host matrices and calcium chloride as a hygroscopic salt. Adsorption capacity of the new composites is as high as 1.75 kg/kg dry adsorbent, which is higher than composites synthesized by silica-gel and calcium chloride, and the adsorption rate of the new composites is also found attractive. A solar-driven water production test unit using the new adsorbent is also presented and tested. The experimental tests of this developed unit demonstrated a feasibility of the fresh water production with the daily water productivity more than kg/m^2 solar collector area.

The production of water from air on a continuous, 24-hour basis using more compact adsorption units by applying forced convection adsorption in packed porous bed is proposed in [20]. Figure 8 shows a typical plant layout arranged for this method. The system operates in two modes; namely adsorption mode and desorption mode. In the adsorption mode, ambient air is forced onto the sorbent bed where the moisture is adsorbed and desiccant concentration decreases with time. At the top of the sorbent bed, air is exhausted outside the system through the air exhaust valve, which is opened during this mode of operation. At the end of this stage, inlet and exhaust air valves are closed and the bed is isolated from the outside air. During the desorption mode, sorbent bed is heated and desiccant is regenerated. Vapour pressure on the desiccant air surface increases and as a result water vapour flows to an air cooled condenser through the vapour valve. Simultaneous evaporation from the bed and condensation on the condenser surface take place during desorption mode. The condensate is collected through the condenser opening shown in figure.

Regeneration ends when desiccant concentration in the bed reaches its initial value at start of adsorption process. New cycle starts when bed temperature decreases to the initial sorption temperature (ambient temperature).

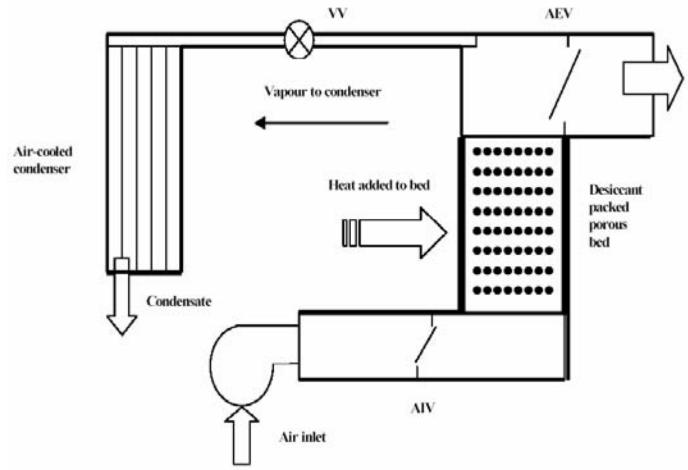

Figure 8. Typical layout of the absorption/desorption system producing water from air [20].

2.4. Air cooling

A similar study was conducted analytically [21] for the climatic conditions of UAE coastal regions, and it was reported that the quantity of fresh water obtained depends on the properties of humid air, air velocity, cooling coil surface area, and the heat exchange arrangement. It is to be noted that this system uses chlorinated fluorocarbon compounds (CFCs) identified as contributors to depletion of the ozone layer.

For typical hot humid weather (Jeddah, Saudi Arabia, 21^o 23^o N and 39^o E), Habeebullah reported that the daily variation of water yield showed to follow the relative humidity pattern with minimum during midday hours. On the basis of actual climatic data, the monthly estimated average water yield during August and February were 509 and 401 kg/m^2, respectively [22].

2.5. Dew collection

On clear nights, the moisture in the air begins to condense on any surface where the temperature has fallen below the dew point due to radiation. Cloudiness, surface temperature, air humidity, and wind speed influence the dew formation. This type of water collection is possible whenever humid air and clear night time skies exist simultaneously. This kind of dew formation can occur over large land areas in a humid but clear environment as in coastal areas. Jacobs et al. [23] reported the experimental results of a specially designed 1 m^2 insulated planar dew collector, set at a 30° angle from horizontal, covered with a thin (0.39 mm) polyethylene foil and subsequently replaced with 4 mm polyvinyl chloride. A second dew collector, in the shape of an inverted pyramid, was constructed to reduce the view angle to only the nighttime sky (Fig. 9).

A simple surface energy-budget model and an aerodynamic model were used to simulate the dew collected by both collectors. The planar collector collected about 90% of the dew at the grass cover while the pyramid collector collected about 1.20% of the grass cover. The aerodynamic model was able to predict the amount of collector data to within 50% for the planar collector and 60% for the inverted pyramid collector. The pyramid collector design was able to collect about 20% more dew than the inclined planar collector. They also reported that Both dew collectors are efficient in collecting dew and the collected amounts are comparable with the natural dew at a grass cover, despite the need for the dew drops to drain towards the measuring recorder.

A project called Dew Equipment for Water (DEW) was initiated for a 15.1m^2 roof in the island of Bisˇevo (Croatia), equipped with commercial plastic cover selected for its superior dew collection properties (Fig. 10). Measurements of both rain and dew water were performed over several years and data will be correlated with meteorological data collected in situ. Preliminary measurements during the period 21 April - 21 October 2005 showed that dew water contributed significantly, 26% of the total collected water [24].

To predict the performance of the dew collector, a steady state mathematical model is developed by Gandhidasan and Abualhamayel [25]. The dew collector performance predicted with the model shows a good agreement with the experimental findings. Experiments are conducted in Dhahran, Saudi Arabia, with $1\,\text{m} \times 1\,\text{m}$ dew collecting panel and about 0.22 L/m^2 of water is collected during a single night of operation.

In the southwestern region of Kingdom of Saudi Arabia there is a potential to provide an alternative source of freshwater. A fog collection project has been carried out in Asir region of Saudi Arabia. Three Standard Fog Collectors (SFC) were designed, manufactured and installed. Three different sites were chosen based on topography and altitude and data from April 2006 to April 2007 were obtained. Measurements with the SFCs were made for regions with 2,260 to 3,200 m elevation. The results indicated that at highest altitudes (at Alsooda), it is feasible to obtain an average water production of 6.215 L/m^2 day over the studied period, and in the lower altitudes, which are in Abha city, it is possible to collect more than 3.3 L/m^2 day [26].

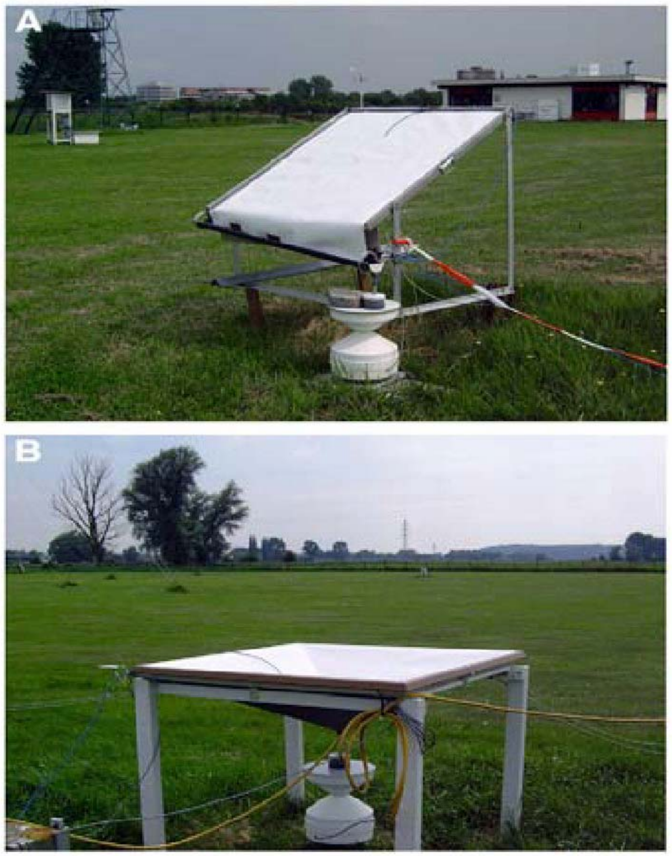

Figure 9. The planar dew collector and the inverted pyramid collector. Both collectors have condensing surfaces inclined at 30° [23].

Figure 10. The house in Salbunara bay, NW of Bisˇevo Island. The 17.1m^2 roof [24].

In the literature review of the extraction of water from air using air processors [27], it is reported that each cubic meter of air throughout Earth's 100-600 m thick atmospheric boundary layer contains 4-25 g water vapour, potentially allowing water supplies almost anywhere people inhabit. Absolute humidity (meteorological normals) ranges from 4.0 g of water vapour per cubic metre of surface air in the atmosphere (Las Vegas, Nevada, USA) to 21.2 g/m^3 (Djibouti, Republic of Djibouti). An extensive research work is still needed to maximize the utilization of this huge and endless source of water.

3. Conclusion

The technology of water extraction from atmospheric air is still at an early stage compared with other systems such as water distillation. However, if the experience of the studies carried out in desiccant cooling is applied in this area, improved and more efficient units could be designed. Also, rapid development of appropriate and reliable systems for water recovery from atmospheric air could be facilitated by adapting financial investment and using friendly energy sources. Collecting dew is still a viable option to get water from air, however, the application of dew collection is restricted by the availability of dew.

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