An Overview of Various Techniques of Atmospheric Water Extraction from Humid Air

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1 Introduction

Water is one of the most precious resource available on the earth which is essential for existence of life. Water is available in plenty amount on our earth but only 3% of the total water resources can be stated as fresh drinkable water [1]. Specially in desert areas, many people face scarcity of fresh drinkable water. Many researchers have described numerous methods to solve this problem of fresh water scarcity. There is a need to develop new sources of pure water at low cost. Extraction of water vapors from surrounding air can be a viable approach at humid locations. India have a potential of utilizing this atmospheric water extraction technique due to humid weather at many locations throughout the year [2].

The atmospheric air is an abundant source of water which has huge potential in form of water vapors. These water vapors can be restored from humid air by practice of condensation of moisture and this water can be stored for its future use in harvesting, drinking, etc. In the present work, an attempt is made to discover these techniques to condense the moisture present in air with the help of atmospheric water generator. Water extraction from the air can be done using Peltier modules or by refrigeration method, mechanical method, adsorption method, or absorption method [4]. In this paper, an overview of solar assisted chemical desiccant-based adsorption and absorption method is firstly presented in which desiccants (Mostly $CaCl_2$ and its composites) are used to adsorp or absorp the water vapors from the surrounding air and solar energy can be utilized to regenerate the water vapors and these regenerated water vapors can be condensed in the form of fresh water.

In the later part, literature review of recent work in atmospheric water extraction using Peltier modules has been presented. Peltier device is composed of

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A. Kumar et al. (eds.), *Recent Advances in Mechanical Engineering*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-15-9678-0_9

ceramic substrates with n-type semiconductors and p-type semiconductors sandwiched between them. A Peltier device works upon Peltier effect in which when the device is provided an emf through an electric power source then it produces two junctions as hot and cold sides. This popular Peltier effect can be combined with a number of equipments such as heat sink, fans, cold fins to develop an atmospheric water generator as a solution to scarcity of water [19].

2 Review of Water Extraction Techniques Based on Adsorption and Absorption Methods

Fresh water can be generated from the humid air by various methods such as mechanical, refrigeration, adsorption and absorption. Many researchers have focused on adsorption and absorption method with various kinds of adsorbent and absorbent materials. In this section, an overview of some of the previous works have been presented.

Alayli et al. carried out an experiment to extract fresh water from humid air. In this experiment, authors used several mineral adsorbents to adsorb the water vapors present at the surroundings. Then, the adsorbed water vapor particles were evaporated using solar energy and lastly, 1 L of fresh water produced after condensation at the expanse of 1 m^2 composite material [3].

Abualhamayel et al. discussed an absorption method of extracting fresh water from surrounding air. In this work, authors selected $CaCl_2$ as absorbent and suggested a system with flat, one side glazed inclined surface and insulated bottom (Fig. 1). Strong absorbent, due to its less vapor pressure, absorbed the atmospheric water vapors at nighttime. Further, this weak absorbent get heated by means of solar energy in the

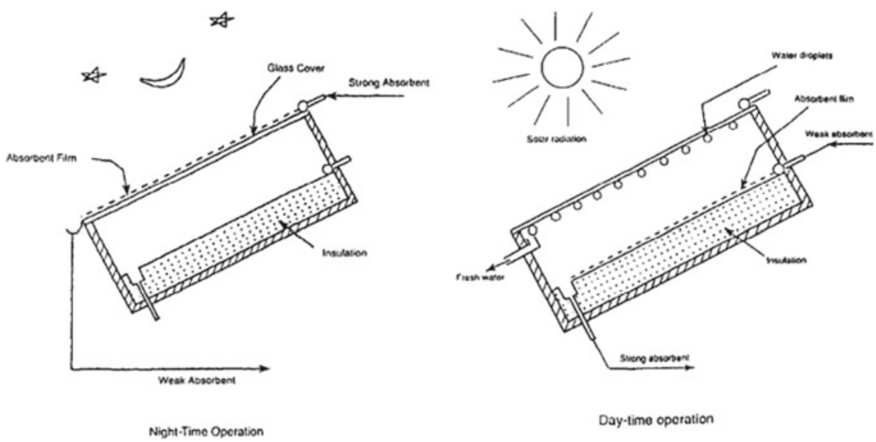

Fig. 1 Schematic diagram of model proposed by Abualhamayel et al. [4]

daytime and the regenerated water vapors get condensed under glazed layer. The temperature of glazed layer should be kept minimum to provide ease in condensation process. Authors also presented mathematical analysis to estimate the performance of water extracting system [4].

Aristov et al. proposed the use of SiO_2-based selective water sorbents in solar assisted air to water extraction process. 10 tonnes of the dry sorbents were employed in this experiment. The results showed that around 3–5 tonnes of fresh water produced after sorption and desorption stages [5].

Gad et al. used $CaCl_2$ as the working absorbent and presented a system comprised of a flat plate collector with a removable glass shield, a corrugated bed, and a condenser. The fresh water was produced after absorption and regeneration process consecutively in night and daytime. The results indicated that this system can provide 1.5 L of drinkable water per m^2 per day. In this work, mathematical analysis of absorption and regeneration process also presented and more than 17% system efficiency was estimated based on this analysis [6].

Kabeel proposed a solar assisted water extraction system of pyramidal structure with aluminum casings, glass faces, and $CaCl_2$ as employed desiccant. The system procedure included absorption of water vapors from surrounding air at night after the four sides of pyramidal structure are opened to surrounding air. All sides are shut in the daytime and regeneration of desiccant occur due to solar energy which subsequently followed by condensation of water vapors. The results showed that the volume of fresh water generated was 2.5 L per m^2 per day. The system efficiency was little less than twice the previously reported efficiency. The use of cloth bed system was recommended for greater efficiency [7] (Fig. 2).

Ji et al. proposed the use of a new composite adsorbent material which was prepared by a crystalline material MCM-41 as host material and $CaCl_2$ as a hygroscopic salt. The results indicated that this new composite material has a greater impact on performance of solar assisted atmospheric water extraction system. The amount of fresh water generated per day was more than 1.2 kg per m^2 of collector area [8].

Hamed et al. estimated the performance of solar assisted atmospheric generator using $CaCl_2$ as desiccant with sand bed. Experimental results showed that approximately 1.0 L/m^2 of fresh water can be produced using proposed system at the surrounding conditions of Taif, Saudi Arabia [9].

William et al. proposed an atmospheric water extraction system comprised of a trapezoidal prism solar collector with multi-layered bed. Hence, the surface area of bed (desiccant carter) was maximized. In this work, two types of bed, i.e., cloth bed and sand bed with $CaCl_2$ solution, were employed and the results depicted that the amount of water evaporated was 2320 g/m^2-day and 1235 g/m^2-day respectively for cloth and sand bed for initial saturation concentration of $CaCl_2$ at 30%. Similarly, system efficiency was calculated in both the case as 29.3% for cloth bed and 17.76% for sand bed [10].

Kumar and Yadav proposed the use of '$CaCl_2$/Floral foam' as desiccant in solar assisted fresh water generation from surrounding air. The system used in this work is shown in Fig. 3. The results depicted that the amount of water generated with the use of this new composite desiccant was 0.35 mL/cm^3/day [11].

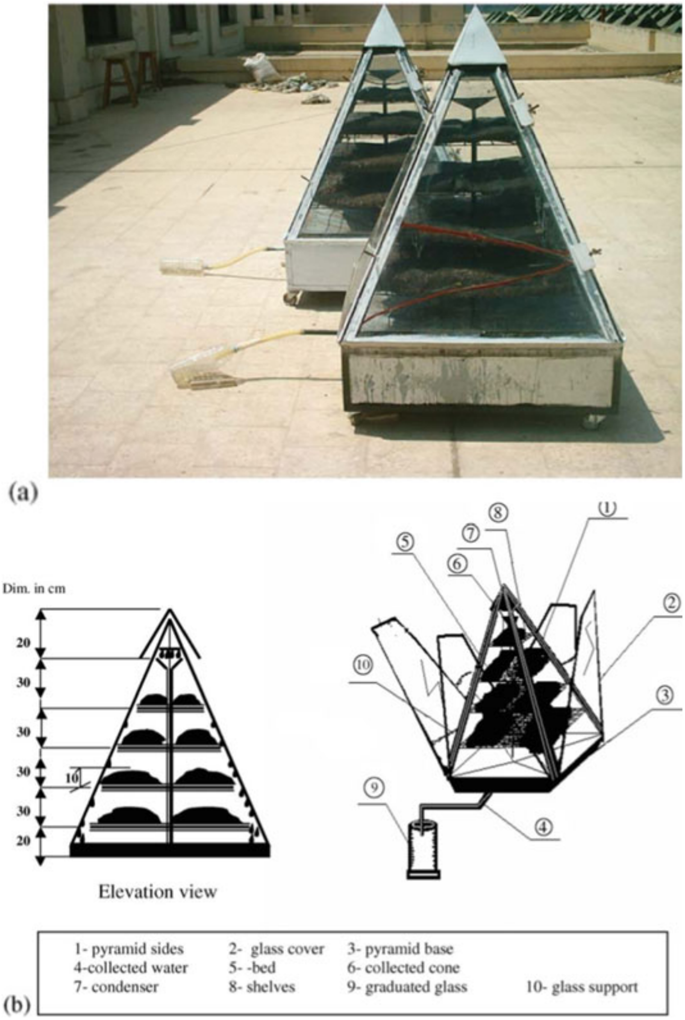

Fig. 2 **a** System used by A.E. Kabeel. **b** Elevation view and pyramids with open glass faces at night [7]

Kim et al. demonstrated an atmospheric water extractor even under low humidity condition (around 20%). In this work, a metal–organic framework-801 [Zr_6O_4 $(OH)_4$ $(–COO)_6$] was used due to its better ability of water adsorption. Solar irradiation (less than 1000 W/m^2) caused the desorption process and water vapors entered the refractive enclosure due to porous nature of MOF-801. Then these water vapors are condensed in the condenser placed at bottom and its latent heat is rejected by condenser to outside by means of a heat sink. This system could produce 2.8 L/day of fresh water at the expanse of 1 kg of MOF-801 [12].

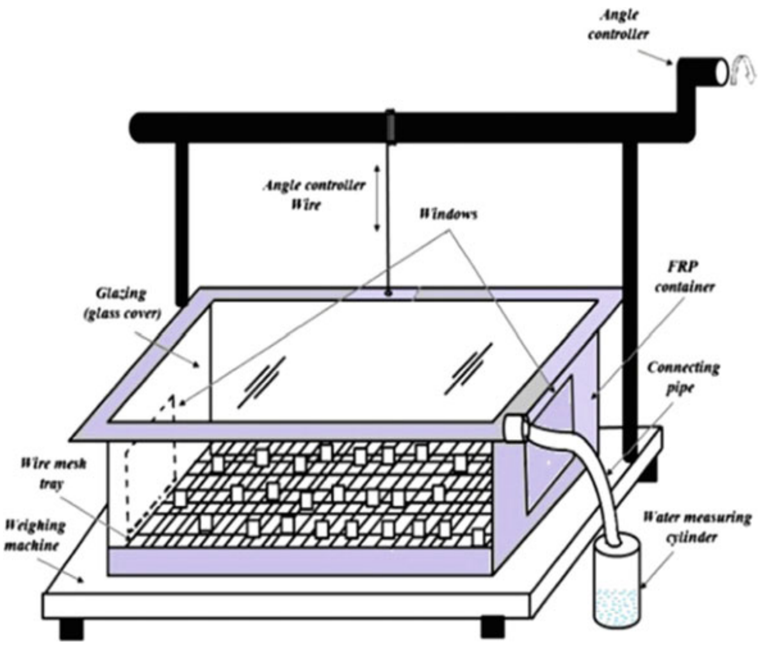

Fig. 3 Water extractor with $CaCl_2$/Floral foam desiccant [11]

Srivastava and Yadav performed experiments on solar-driven atmospheric water extraction technology at the location of NIT Kurukshetra, India. In this work, authors used sand bed as host material and three different types of materials LiCl, LiBr and $CaCl_2$, as salts to make composite desiccant. The setup used in this work is shown in figure. A Scheffler reflector (1.54 m^2 surface area) was installed with a receiver box at its focal point. Composite desiccants were placed into receiver box. All the sides of box were insulated with glass wool except the side in front of Scheffler reflector. The composite desiccant absorbed the water vapors from the surrounding air in the nighttime till the saturation condition is reached. The amount of water vapors absorbed can be determined by calculating the weight of desiccant before and after the absorption by means of a weighing machine. In the daytime, the desiccant was placed in the receiver box in front of Scheffler reflector and the regeneration of water vapors began due to solar energy. The regenerated water vapors condensed into water after passing through condensing tube and the condensate is stored in an air-tight vicker. The total water produced from atmospheric air was 90 mL for LiCl-based desiccant in 330 min at average solar irradiation 511.3 W/m^2. Similarly with LiBr and $CaCl_2$-based desiccant, water produced was 73 mL and 115 mL, respectively, in time duration of 270 min for both. The annual cost was lowest (0.53 \$/L) with $CaCl_2$-based desiccant and highest (0.86 \$/L) with LiBr-based desiccant [13] (Fig. 4).

Talaat et al. designed and studied a water extraction system at the location of Mansoura University, Egypt. This system comprised of conical see-through surface

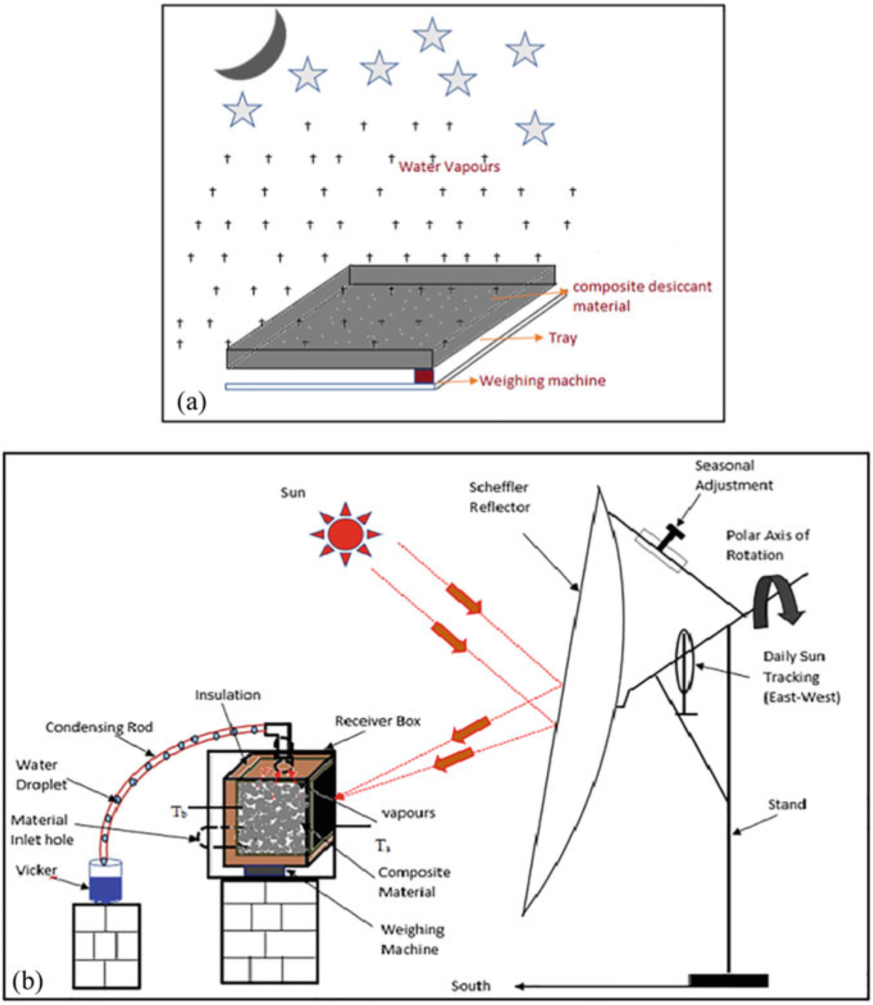

Fig. 4 Schematic diagram of **a** Absorption of water vapors at night. **b** Regeneration and condensation process using Scheffler Reflector and condensing tube [13]

which is made up of cloth bed and $CaCl_2$ (desiccant) solution. At night, when the desiccant is exposed to surrounding air, water vapors are absorbed and in the daytime, the system is enclosed with a transparent conical layer which is open to receive solar irradiation upon it. Due to heat provided from solar irradiation, water vapors evaporate and then condense into water after rejecting its latent heat to the adjacent surface. The condensed water is stored in a flask. The amount of water stored was calculated in the range 0.3295–0.6310 kg/m^2/day [14].

Elashmawy proposed an atmospheric water extraction system incorporated with tubular solar still and air circulation fan. The results depicted that the system could generate water up to 467 mL/m^2 in a day at 4 m/s speed of air under low humidity condition (12%) at Hail city, Saudi Arabia. Under natural speed of air, 230 mL/m^2 water could be generated in a day. The maximum thermal efficiency at natural airspeed was 12.2% while in case of air circulation 4 m/s by means of a fan, thermal efficiency was 25%. Hence, authors suggested to use such system with greater speed of surrounding air to augment the performance of system [15].

3 Recent Developments in Air to Water Extraction Technique Based on Peltier Modules

Kabeel et al. proposed a solar-based atmospheric water extraction technique incorporated with thermoelectric cells to enhance the temperature difference between evaporating and condensing regions (Fig. 5). Authors also performed CFD simulation of this solar and thermoelectric-based system under three different climatic conditions. This system could produce fresh water 3.9 L per hour per square meter [16].

Suryaningsiha Sri et al. performed an experimental work on a prototype of atmospheric water generator using Peltier modules techniques at the rural areas of Indonesia. Experimental investigations led to the development of a prototype of atmospheric water generator using Peltier modules with 12 V DC supply and single unit PWM controllable Brushless DC fan. The prototype comprised of four units of Peltier modules (Model number TEC1-12706) connected in parallel. The experimental tests were conducted for different configurations of Peltier modules

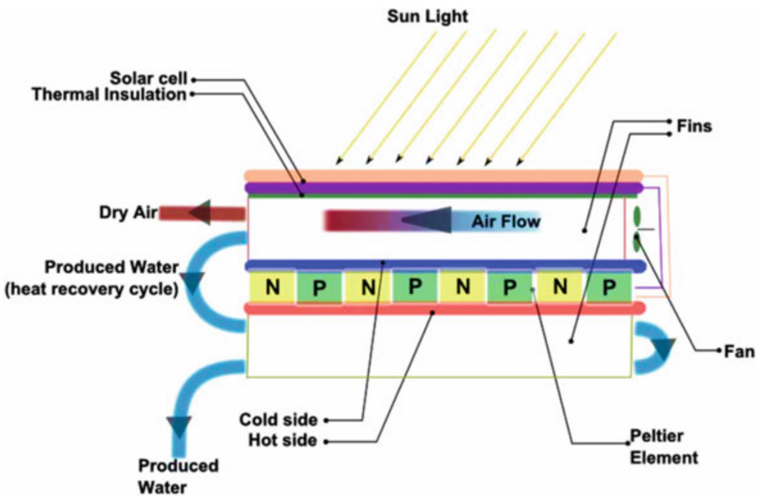

Fig. 5 Solar and TE based system used by Kabeel et al. [16]

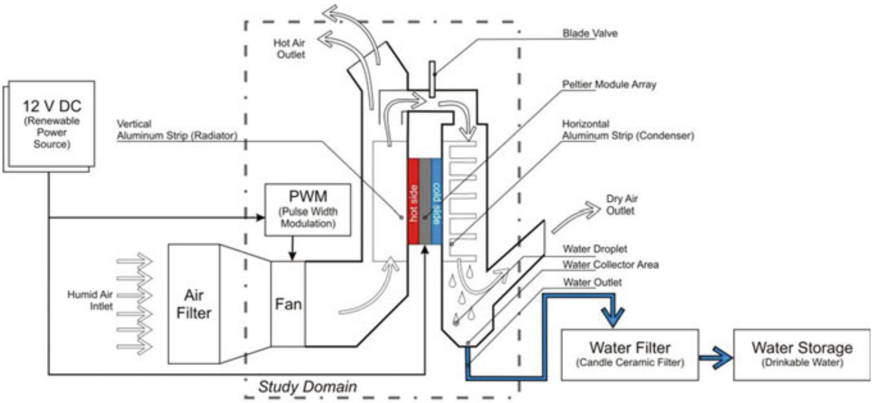

Fig. 6 Schematic diagram of the atmospheric water generator based on Peltier Module [17]

and different airflow conditions. Certain performance parameters including condensation ratio and production ratio were calculated. The results of the prototype were compared with the other available products of this category. The comparison leads to achieve a big success in the experimental effort. The production ratio for the amount of water derived from moisture of the air was obtained nearly 2 which fit the quantity of drinking water for approximately two persons. The results also concluded that the quantity of water from moisture can be increased by increasing the rate of humid airflow and also with increase in the power supply. The quality of water obtained by this method also accords to the standards of WHO [17] (Fig. 6).

Joshi et al. executed an experimental investigation to design and develop a thermoelectric fresh water generator which worked on the principle of thermoelectric cooling effect using Peltier modules. In this work, a prototype was built up consisting of a long cooling channel with ten Peltier modules arranged in an array. The experimental prototype was made to run for ten working hours. Peltier modules were arranged thermally in a parallel circuit while electrically in a series circuit. At the hot side of Peltier modules, the set up has an external heat sink serving the purpose of heat rejection. Heat sink also incorporated with four cooling fans to increase the rate of heat transfer through forced convection. An internal heat sink was used as an additional member in this set up to enhance the surface area for cooling the air and condensing the moisture. It also acts as a device which enhanced the turbulence in the motion of the moist air. In the experimental tests, observations were made on the amount of moisture condensed from the air by varying its mass flow rate, humidity and the amount of electric current supply provided. The experimental efforts derived direct proportionality relation of the amount of water condensed from the moist air with the mass flow rate of air, humidity of the air, and the electric current power supply. An important conclusion in this experiment was that the amount of water condensing from moisture rises up by 81% after employing the internal heat sink [18].

Kiara et al. projected a solution to cater the needs of a large number of human beings who are facing a very severe situation due to depleting fresh water resources. The research work explored out an experimental and numerical solution to the problem by designing two prototypes based on cross flow heat exchanger and Peltier effect, respectively. One prototype included a cross flow heat exchanger in an underground chamber where temperature was generally low, water performed as coolant cooled by the low temperature underground chamber. Another prototype was designed on the basis of Peltier effect. The prototype worked efficiently in a defined range of relative humidity of 52–100%. Mathematical modeling was executed to solve the governing equations of thermodynamics and heat mass transfer analysis to find out the variables which affect the performance of the prototypes and calculate the amount of water generated. The theoretical model results obtained from the mathematical equations were compared with experimental work. The observations concluded that the amount of water generated was nearly eight times in case of prototype based on heat exchanger model in comparison with Peltier effect-based prototype. However, the power consumption was low in case of Peltier effect-based prototype [19].

Anandhulal et al. developed a device for extraction of water from air whose working was based on the Peltier effect. The device developed for the research work was comprised of heat sink, cold sink, temperature regulator, fan and Peltier module. Fan brought the humid air in the assembly. The Peltier module was given electric force through a DC source of power due to which it produced hot and cold sides due to Peltier effect. The air when passed over the cold side, its temperature was brought down to the dew point due to which the moisture retained by the air gets condensed and can be collected. The research concluded that the device is simple in its configuration with no movable mechanical components, no harmful chemical as CFC's and a sufficient amount of drinkable water can be derived which might help for mountaineers, fishermen and several other purposes and it can also be transported easily from place to place [20].

Shanshan et al. developed a lightweight easy to transport device to generate water by condensation of the moisture present in the air with the help of two Peltier thermoelectric devices. A set up was designed to perform the research experimentally. The set up comprised of a humidifier, a mixing assembly, an air conduit, and a thermoelectric Peltier water generator. A cross flow fan led the atmospheric air into the mixing assembly where its relative humidity was controlled with the help of humidifier and forwarded to the air conduit. Finally from the air conduit, air was passed through the Peltier device where it brought down the temperature of air to its dew point. As the temperature reached the dew point, moisture in the air started to condense on the surface and for collection of water a pan was installed. Amount of water collected in the pan was measured every hour during the run of the experimental work. Three different flow rates of air were varied with the help of cross flow fan. The flow rates were quantified with the help of an anemometer. Temperature and humidity were quantified by the hygrothermographs. All the measured variables were fed to a data acquisition system. An enhancement was recorded with the increase in the relative humidity of the air for 6–7 h after the initiation of the test but afterward experiment reached to a stage where quantity of water generated approached to a constant mark. The above result was explained as the adhesion force of water to the condensing surfaces exceeds the force of gravity so the amount of water starts to become constant. For variation of relative humidity, current power source and inlet air temperature were kept unchanged. At the initial stage of the investigation, amount of water generated was less at higher flow rates but after stabilization it starts to increase. The experimental investigation explored that two thermoelectric devices were not sufficient to offer the cooling ability and the air was not able to come in contact with the condensing surface for a sufficient time at higher flow rate. The maximum amount water generated was 25.1 g/h with two Peltier devices and less power consumption [21].

Carson et al. conducted a research work in order to utilize the water present as moisture in the air. İn this work, authors depicted the effects of fin orientation of heat sink on the amount of water extracted from atmospheric air. Four different surfaces were brought into examination—a plane plate of aluminum, a PTFE coating equipped aluminum plate, a fanned aluminum plate and a finned aluminum heat sink. All the stated surfaces were oriented vertical and the air with high humidity was forced to flow over the surface in a horizontal direction. Two conditions as clear and unclear of the surfaces were compared for all the cases. PTFE coated plate showed an enhanced rate of water condensation as compared to aluminum plate. Clearing of the surface also enhanced the rate of collection of water. Seven orientation angles starting from 0° with an increment of 15° till 90° were experimented. The orientation of 60° provided the maximum rate of water collection. Several conclusions drawn from the research including an enhancement in the rate of condensation of moisture with the use of hydrophobic materials, clearing the moisture condensing at regular intervals enhanced the performance of the device, the finned heat sinks have a high condensation compared to flat plate heat sinks, with the increase in angles of orientation the water condensing gets filled up in large quantity between the spacing of the fins [22].

Wei et al. conducted a number of experiments for evaluation of an equipment of transportable atmospheric water generator. In the experimental work, two models A and B were designed and fabricated. Their performances were compared for various factors affecting the amount of water generated from the atmospheric air. Both the models were very much similar in their geometrical constructional features. Both the models comprised of a humidifier, a mixing assembly, an air conduit and a thermoelectric cooling device for water generation. Air channels worked to transport the air through the mixing assembly on the thermoelectric cooling device. Humidifier worked to control the moisture in the air. Thermoelectric device possessed a hot side and a cold side on the basis of Peltier effect. Both the sides have extended surfaces to promote rate of convection heat transfer. The cold surface brought the temperature of the air near to its dew point which led to the condensation of moisture in the air. In model A, the cooled air is bypassed on to the hot side to support the heat rejection from the hot side while in model B, cooled air is discharged directly outside system. Besides it, a hydrophobic substance was employed over the cool side surface fin to enhance the rate of condensation in the air in model A as compared to B. Several equations were incorporated in the work based on the psychometrics to calculate the amount of water generated and it was compared with the experimental observed values with the help of statistical graphs. The observations were taken for a test run of 10 h and the graphical comparison denotes a range of deviation between calculated and measured values. The calculated values were far above than the measured experimental values for the first 6 h run of the procedure. During the first hour the measured values ascend in a slow manner, increased in a fast manner for 2–5 h, the slope of the increment was sharp in the 5–6 h and afterward measured and calculated values have no range of differences. During the first hour, the process was just initiated so the amount was less, as the process progressed the rate of condensation got increased, the effect of gravity and air turbulence together contribute to the increased rate of condensation of moisture into water droplets. For the experimental work, an additional hydrophobic material is employed to enhance the rate of condensation. To acquire the variation of relative humidity, the airflow rate was kept constant and low. It was noticed that the amount of water accumulated due to condensation of moisture in the air gets increased up. The model A has a higher rate of condensation than model B for the above-stated variations. Graphical variation of rate of water accumulation was drawn with changing the rate of flow of air while the other parameters were kept unchanged. The yield of water was increased with increased airflow rates; it was higher for model A than B due to hydrophobic material [23] (Fig. 7).

Sajil et al. carried out an investigation to derive water from condensing the moisture present in the air. The investigation involved computational design and a model was assembled on that basis. Four Peltier devices (TEC 12706) were used for the research work carried out. The cooling draft fans were used to cool the moist air and also to create a vacuum for the moist air to enter the assembly. As the experiment was

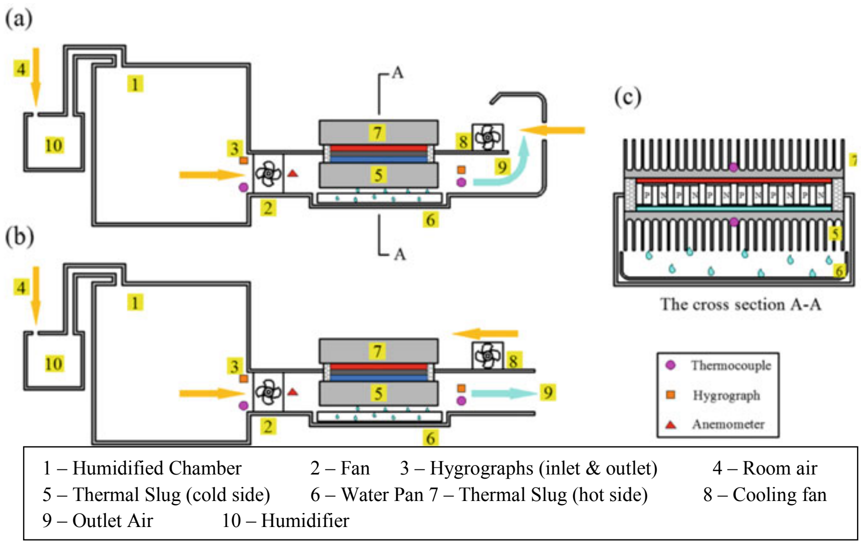

Fig. 7 Schematic diagram of Peltier module based water generator by He Wei et al. [23]

carried out the Peltier devices were provided the EMF the water starts condensing at the colder side and starts to accumulate over the surface, which decreases the rate of heat transfer and reduces the amount of moisture condensing, to prevent this to happen a wiping mechanism was incorporated in the assembly. The dew point temperature calculations were made using the data of the humidity of the air, temperature of the ambient air, and other parameters. At the completion of the experimental work the rate of work output of the assembly was recorded which was the amount of moisture condensing per unit time and it appeared as 5 mL/h. The results were not found to be very satisfactory but was a great attempt to cater the needs of the areas where a lot of lives faces the threat of scarcity of water [24].

Kadhim et al. executed an experimental research for deriving the water present in a moist air. Experiments were performed on an atmospheric water generator in which source of power was solar energy and the device for accumulation of water was based on the Peltier effect. The experimental prototype was build up on a small scale and only single thermoelectric Peltier module was used. The set up used in this experimental investigation includes a thermoelectric Peltier device, a finned heat sink, a fan, a cold side conical fin attached on the cold side of the Peltier module, a solar panel with a charge storage battery and a structural support to grasp and balance all these components. The experimentation aimed to determine the amount of moisture condensing from the air for that it includes variation of airflow velocities, relative humidity and temperature of the dry air. In the Peltier device as it receives the current from the power source one part gains temperature while other loses and becomes hot side and cold side, respectively. As the air comes into contact with the cold side and its temperature approaches dew point condensation of the air begins. A large number of observations were done for deriving any conclusion regarding the variation of the parameters on the amount of moisture condensing from the air. When airflow velocity was varied, the temperature and the relative humidity of the air were kept constant and the observations was recorded in the patterns of graphs. The graph for the variation of airflow velocity was plotted at 65% relative humidity for air temperatures 27 °C and 31 °C and an airflow velocity of 1 m/s produced satisfactory result of 10 mL/h of water condensing from the air. When the relative humidity was varied, it was observed that quantity of water generated almost gets constant with slow deviation as the relative humidity reaches 65% but when the air temperature was raised up the rate of condensation of moisture reaches double at 20 mL/h. The outcome of variation of air temperature is recorded with the time taken by the cooler surface to reach dew point of air and it was resulted into an increase of time required. To design an optimum surface for the further the experiment was concluded with the remarks that to improve the efficiency of the system more number of thermoelectric Peltier modules should be used [25].

4 Mathematical Analysis of Solar Assisted Absorption Method for Atmospheric Water Extraction

In this type of system, the desiccant solution is prepared by mixing of salt (e.g. $CaCl_2$) in distilled water. İf the mass of salt is 'm_s' and mass of distilled water is 'm_w', the total mass of desiccant solution given as:

$$m_{sol} = m_s + m_w \tag{1}$$

also,

$$X = \frac{m_s}{m_{sol}} \tag{2}$$

where 'X' is the fraction of amount of salt in desiccant solution.

The performance of system is primarily based on the rate of absorption and regeneration. The rate of absorption (G_a) and the rate of regeneration (G_r) can be calculated as [26]:

$$G_a = (m_{Sol} + m_1)\frac{d\omega}{dt} \tag{3}$$

$$G_r = m_{Sol}.\frac{d\omega}{dt} \tag{4}$$

Here, m_1 is the mass of water vapors absorbed by the desiccant in the nighttime and ($d\omega/dt$) is rate of change of moisture content. The maximum amount of water generated will be equals to m_1 when the complete water vapors absorbed by desiccant are regenerated and stored in the form of water.

The efficiency of the solar assisted absorption-based water extraction system can be estimated using the following formula:

$$\eta = \frac{M_w L}{I A(\tau\alpha)} \tag{5}$$

where

M_w mass of water produced
L Latent heat of water at mean bed temperature
I Intensity of solar radiation
A aperture area
T transmissivity
α absorptivity.

The above analysis is valid only in case of absorption method. For AWG with peltier modules, thermoelectric principles are used.

5 Conclusions

The present work has tried to summarize the different solutions to the scarcity of fresh drinkable water at remote locations. In this chapter, various methods of atmospheric water extraction have been presented. Mainly, solar assisted adsorption—regeneration or absorption—regeneration-based water extraction methods and water extraction methods using Peltier modules have been presented.

Based on the review, the adsorption method is less effective than the absorption method, as absorbents require less regeneration temperature in comparison with adsorption methods. Also the chances of mixing of dirt and dust with collected water vapors are greater in case of adsorption method. In a solar assisted absorption method, composite of $CaCl_2$ with sand bed can be effectively used as desiccant material which should absorb the water vapors up to saturated condition at the nighttime. The speed of air, surrounding temperature and the concentration of desiccant should be higher at the nighttime operation. Humidity condition also should be higher (not less than 20% relative humidity). The surface area of desiccant bed should also be higher so that maximum amount of moisture can be absorbed from the surrounding air. Once, the desiccant absorb water vapors from humid air up to saturated limit, it must be placed in an insulated box. In the daytime, solar radiations are impinged on the desiccant material in such a way that water vapors evaporate and then stored in a receiver and then water vapors are condensed into fresh water. For the better performance of this system in daytime, the surrounding air temperature and the solar irradiation should be higher and concentration and mass flow rate of desiccant should be less. It can be concluded that the quality of water produced through these methods can be safely used for drinking purpose. Still future research should be focused on chemical analysis of water produced through such methods, as when the higher ambient condition prevails, the concentration of desiccant can be high and it may possibly question the quality of water.

In this paper, a method of atmospheric water extraction using Peltier modules has also been presented. In this method, Peltier modules are arranged and incorporated with heat and cold sink fins, fan and an external power source to bring down the air to its dew point and condense the moisture present in the humid air. Future efforts should focus on design optimization of the system in such a way that more contact surface area is exposed to air. There is a need to enhance the rate of drop-wise condensation and there should be less adhesive force between contact surface and condensed water drops. Some experimental and computational works were also reviewed to discuss the Peltier effect on water generation from air. This method involves high energy consumption in comparison with absorption method. Future research should be focused to make this method cost-effective and to minimize the effects of various environmental parameters on system. With these modifications, the methods explained in the paper would be viable options to deal with the scarcity of fresh water at remote locations.

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