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Solar-powered portable apparatus for extracting water from air using desiccant solution

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A B S T R A C T

In this paper, experimental and theoretical study of a portable apparatus for extracting water from atmospheric air is presented. The experimental water-extraction unit is designed, manufactured, and tested at the Faculty of Engineering, Mansoura University, Egypt (latitude 31.0409 N and longitude 31.3785 E). The unit extracts water from atmospheric air by using solar energy as the heating source and Calcium Chloride ($CaCl_2$) solution as desiccant material. The unit consists of double-faced conical-finned absorber (64 cm diameter and 64 cm height), double-faced conical transparent surface (68 cm diameter and 68 cm height). The unit is provided with a telescopic stick (carrier), and base. At night, the conical absorber which is made from cloth layer impregnated with desiccant solution is exposed to atmospheric air to allow Calcium Chloride solution to absorb moisture. During daytime, the absorber is covered with the tightly-closed double-faced conical transparent surface which is exposed to solar radiation. As solar energy increases the absorber temperature, the absorbed vapor evaporates from the solution and condenses on the surface. The condensate is collected in a bottle through a hose. Radiation intensity, temperature, cover temperature, ambient temperature, and productivity are recorded at a number of different operating days year-round. The measured accumulated productivity is found to range from 0.3295 to 0.6310 $kg/m^2/day$.

1. Introduction

According to the Global Water Institute (GWI), about 97.5% of water on the earth is salty water found in oceans and seas. The remaining 2.5% is presented as surface water, polar ice, and groundwater. Some countries which have enough water resources may have an unequal distribution of these resources, so water shortage problem arises in many places [1]. World Health Organization (WHO) reported that, about 20% of the world's people live in regions which do not have enough water for their needs [2]. It is also reported that more than 2.8 billion people in 48 countries will face water stress or conditions of scarcity by 2025 [1]. The problem of water shortage or the lack of it thereof can be solved by transportation of water from other locations, saline water desalination which depends on the presence of saline water resources and, extraction of water from atmospheric air which has about 14000 km^3 of water [3]. Water can be extracted from atmospheric air by using one of the following methods:

1. Condensing moisture by exposing atmospheric air to surface temperature lower than that of the air dew point temperature.
2. Wet collection from the fog.
3. Water absorption from atmospheric air using desiccant material with subsequent regeneration of desiccant.

Moisture condensation by exposing atmospheric air to surface has temperature lower than that of the air dew point temperature can be classified according to the condenser type into radiative (passive) condenser and active condensers. The radiative condenser depends on using the physical properties of the dew formation process and the condensation surface material to avoid using any additional energy input. The radiative condenser surface has high emittance in the infrared region of the spectrum. This property gives it the advantage of cooling faster than other surfaces at nighttime [4]. The low productivity of passive condensers and the multiple energy conversion processes which are required for cooling moist air to a temperature lower than the air dew point temperature reduces the overall system efficiency. Absorption of moist from

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Nomenclature

Area, m^2	A
Constants in equations (17) and (18)	a, b
Apparent solar radiation at air mass zero, W/m^2	A_s
Annual cost, $	AC
Annual maintenance operational cost, $	AMC
Annual salvage value, $	ASV
Atmospheric extinction coefficient	B_s
Heat capacity, J/Kg °C	C
Diffused radiation factor	c_s
Capital recovery factor	CRF
Cost per kilogram, $/kg	CPK
Shape factor	F
View factor	$\overline{F}$
The angle factor between sky and surface	F_{ss}
fixed annual cost, $	FAC
Hour angle, degree	H
Beam radiation on horizontal surface, W/m^2	H_b
Beam radiation at normal incidence, W/m^2	H_{bn}
Heat transfer coefficient between cover and ambient, W/m^2 °C	$h_{cov.a}$
Diffuse radiation, W/m^2	H_d
Beam radiation on a tilted surface, W/m^2	H_t
Solar incidence angle, degree and Interest per year	I
Latitude angle, degree	L
Latent heat, J/kg	L_b
Mass, kg	M
Average annual productivity, kg/year	M
Day number and number of years	N
System productivity, kg/sec	P
Present annual cost, $	PC
Heat transfer rate per unite area,W/m^2	Q
Beam radiation tilt factor	R_b
Surface tilt angle, degree and salvage value	S
Sinking fund factor	SFF
Temperature, °C	T
Uncertainty of the variable x	$u(x)$
Wind speed, m/sec	V
Solar zenith angle, degree	Z

Greek symbols

Solar altitude angle, degree	α_s
Declination angle, degree	Δ
Efficiency	η
Layer thickness, m	δ_b
Relative humidity of atmospheric air	$\varnothing$
Solar diffuse reflectance of the earth's surface	ρ_g
Stefan Boltzmann constant $= 5.67 \times 10^{-8}\ W/m^2k^4$	Σ
Transmissivity	τ

Subscripts

Ambient air	A
Bed	b
Bed surface	*bs*
Between Cover and ambient	cov.a
Between Cover and sky	cov.sky
Conduction	C
Cover	Cov
Desiccant	D
Dew point	dp
Evaporation	E
Host material	H
Radiation	R
Real surface area	br
Real cover surface area	cov.r
Saturation	sat
Water	W

atmospheric air by desiccant and subsequent regeneration needs an energy source. One of the most promising renewable energy-source is the solar energy. In the absorption–regeneration method, however, if the design of the absorption–regeneration system is efficient, the amount of heat loss will reduce and, consequently the overall efficiency will increase.

Many attempts have been made to extract water from air by using desiccant substances. Edmund [5] presented a method for gaining water out of the atmosphere by using a hygroscopic substances. At night the hygroscopic substance is exposed to atmospheric air to absorb vapor from it. Subjecting the substance to the sun's rays during daytime, the absorbed water is evaporated and would be condensed in order to liquefy it. Since that researchers and inventors presented many attempts to understand and improve the performance (water productivity and efficiency) of the water recovery system, considering different weather conditions and different design parameters.

In order to understand the parameters which affect the absorbed water quantity and the regenerated one, Hamed [6] presented the theoretical cycle to describe the water absorption from air and subsequent regeneration processes. Mass and heat balance equations to predict the influence of ambient conditions have been developed using $CaCl_2$ as an absorbent. The theoretical analysis showed that the cycle efficiency is highly affected by solution concentration. In order to investigate the mass transfer for absorption and regeneration processes through parallel plates of cloth layers, Hamed and Sultan [7] impregnated cloth layers with calcium chloride solution which was subjected to an air stream. Desiccant concentration in the range from 0.2 to 0.5 was applied in this study. They evaluated experimentally mass transfer coefficient and Sherwood number. Hamed et al. [8] presented the working principles of water extraction systems from atmospheric. They summarized the analytical and experimental studies which investigated the systems performance. They also introduced solar-powered desiccant systems. William et al. [9] presented a simulation model for extracting water vapor from atmospheric air by $CaCl_2$ solution as a desiccant material. Their model improved the theoretical results by about 15% compared to previous models. Also, they investigated the system performance for Cairo and Alexandria weather conditions by using the simulation model. The total produced water from the system in spring is about 3.11 kg/m^2/day and 3.02 kg/m^2/day in Cairo and Alexandria, respectively.

Kumar and Yadav [10] investigated the design parameter that affect a device used to extract water from atmospheric air for Indian climatic conditions at NIT Kurukshetra, India. The parameters were air gap height, inclination angle, effective thickness of glass, and effective number of glazing layers using silica gel as desiccant material. They found that the maximum productivity occurred when air gap height as 0.22 m, inclination in angle as 30°, effective thickness of glass as 3 mm, and number of glazing layers. In order to compare the productivity of different desiccant material used in water extraction from atmospheric air, they performed experiments using Silica gel, Activated alumina and Molecular sieve 13 X [11]. They used experimental results to drive a correlation between