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A Software and Hardware Supported System Suggestion for Obtaining Potable Water from Air with Solar Energy

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Abstract

Fresh water is one of the most important resources consumed. However, droughts due to global climate change, rapid population growth increasing construction sector activities and the lack of importance to protect freshwater resources during these activities increase the problems related to water. This study aims to raise awareness among people about the protection of freshwater resources. For this purpose, a software and hardware-supported system has been developed to obtain fresh water by cooling and condensing the humidity in the air with the help of thermoelectric modules and fans. The developed system can automatically become active or passive according to the weather conditions and uses less energy than its counterparts. The system, which can also operate independently of the grid with solar energy, can also purify the water obtained by producing ozone gas with the effect of static electricity on the surface where water droplets form and make it drinkable.

***Keywords**: Water cycle, potable water, condensation, dew point, solar energy, thermoelectric cooling.*

Güneş Enerjisiyle Havadan İçilebilir Su Elde Edebilen Yazılım ve Donanım Destekli bir Sistem Önerisi

Öz

Tatlı su, Yeryüzünde tüketilen kaynaklar arasında en önemlilerinden bir tanesidir. Ancak küresel iklim değişikliğine bağlı kuraklıklar, hızlı nüfus artışı ve artan inşaat sektörü faaliyetleri ve bu faaliyetler sırasında tatlı su kaynaklarının korunmasına gereken önemin verilmemesi su ile ilgili sorunları giderek arttırmaktadır. Bu çalışma ile insanların tatlı su kaynaklarının korunmasına yönelik bilinçlendirilmesi amaçlanmıştır. Bu amaç doğrultusunda, havadaki nemi termoelektrik modül ve fanlar yardımıyla soğutup yoğuşturarak tatlı su elde edebilen yazılım ve donanım destekli bir sistem geliştirilmiştir. Geliştirilen sistem, hava şartlarına göre otomatik olarak aktif veya pasif hale geçebilmekte ve emsallerinden daha az enerji kullanmaktadır. Güneş enerjisi ile şebekeden bağımsız olarak da çalışabilen sistem, aynı zamanda su damlacıklarının oluştuğu yüzeyde statik elektrik etkisiyle ozon gazı üreterek elde edilen suyu arıtmakta ve içilebilir hale getirebilmektedir.

***Anahtar kelimeler:** Su döngüsü, içilebilir su, yoğuşma, çiğ noktası, güneş enerjisi, termoelektrik soğutma.*

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1. Introduction

The World Commission on Environment and Development defines sustainability as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The sustainability–architecture relationship rests on three basic pillars. These are minimizing energy consumption, minimizing negative environmental effects, and efficient use of resources. The concept of sustainable architecture, shortly, means creating healthy living environments that aim to minimize negative environmental effects, and energy and resource consumption. Water, which is at the centre of sustainable development, is the most important among natural resources.

1.1. Defining the Problem

The construction Sector in Turkey started with railway lines and large water projects in the first years of the Republic. Later, with the subsequent public sub-investments, urban transformation projects, the increase in the rate of urbanization with the increase in population, and the increase in the infrastructure needs related to this, the construction activities gradually gained speed and became one of the basic sectors. However, the damage to the environment, the consumption of natural resources, and the deterioration of ecosystems during these construction activities have become a threat to future generations. Two of the most important resources consumed during the activities of the construction sector are energy and water. Although the construction sector is not in the first place in the ranking of the sectors that consume the most water, there is an increase in water use with the increasing rates of housing and urbanization (Pamuk & Kuruoğlu, 2016).

When viewed from space, our Earth may appear as a water planet, with ¾ of it being covered with seas and oceans. However, the distribution of water on the Earth's surface is uneven. Only 3% of the world's water is freshwater, a large amount of which is frozen in the polar ice cap. Unfortunately, due to global warming, the glaciers melt into the sea day by day. Fresh water in lakes and rivers constitutes less than 1% of the total water in the world. Most of the underground waters are located very deep from the surface as brackish water and those close to the surface are constantly drawn as drinking and utility water (Shiklomanov, 2009).

Although it is true that the freshwater used returns with a water cycle consisting of phenomena such as absorption, infiltration, evaporation, and precipitation, rapid industrialization and the spread of urbanization to the basins where water cycles take place causes this cycle to be disrupted. Especially, horizontal settlements located on permeable soils make it difficult for rainwater to percolate and reach groundwater (Booth, 1991).

Following the international agreements on watershed protection, Turkey has initiated fundamental modifications in the watershed management and planning process. However, sustainable management of water resources involves various economic, social, and ecological dimensions, and it is not a straightforward process (Pouya et al., 2020).

Freshwater resources are distributed unevenly on the earth's surface in proportion to population density. Just by looking at the precipitation maps, it can be understood how unequal the distribution of water on Earth is. The water use demands that have arisen with the increasing urbanization have reached the amounts that the water resource capacity in the areas where the city plan is made cannot handle. Today, approximately 1/5 of the world's population lives in areas with high water sensitivity and this ratio is expected to increase further in the coming years (Heidari et al., 2021).

Considering the increasing needs, it can be said that water resources are regionally finite resources according to place and time. All signs point to a growing shortage of clean and fresh water in many parts of the world in the future. In 2022, more than 4 trillion m3 of fresh water was consumed worldwide. It is expected that the world population will reach 10 billion by 2050, and the amount of water consumed will increase by 50% (Wada et al., 2013).

1.2. Literature Review

Water, which can be found in the form of solid, liquid, or water vapor on Earth, is in a constant state of change. Water interacts with the weather as it passes from one state to another with the change of environmental conditions. The atmosphere contains a large amount of moisture in the form of water vapor. The dew point is the temperature at which air must be cooled to become saturated with water vapor. Fog and mist form when the water vapor concentration in the atmosphere reaches saturation. These airborne structures are visible aerosols of tiny water droplets suspended in the air near the earth's surface on cold nights. When the air gets colder, the water vapor in it condenses to form water droplets or dew. This situation occurs especially as a result of the contact of air layers close to the ground level with cold surfaces.

Various organisms in nature have special adaptations to capture dew and meet their water needs. These include cactus, grass, moss, shrubs, desert beetles, lizards, rattlesnakes, and spider webs. Collecting fog water is a simple and sustainable way to obtain drinking water for agriculture or humans and animals. It is known that the techniques of condensing water in the air have been used by humans since ancient times. The Incas were able to sustain their civilization by collecting dew on the rainline and then changing it into cisterns for distribution to their living spaces. One of the first methods used to obtain water from the atmosphere is the passive mesh-based fog or dew collection method. It is known that this method has been used in Central and South America and South Africa since the middle of the 20th century, and in Europe and Asia since the beginning of the 21st century (Bhushan, 2020).

"Warka Water", one of the new projects using a passive mesh-based fog or dew collection method, was developed in 2014 by the Italians for the mountainous regions of Ethiopia. The tower-type structure, consisting of a bamboo mesh frame, obtains water by condensing atmospheric water vapor on the surface of the mesh (Verbrugghe & Khan, 2023).

A system that produces drinking water by collecting water vapor from the atmosphere using metal-organic cages composed of metals and organic molecules and has a very large surface area with hollow structures has also been developed at the University of California, Berkeley. Prof. Dr. Omar Yaghi and his team, during their tests in the Mojave Desert with the prototype device they produced in 2019 managed to obtain 0.2 litres of water in a day with 1 kg of the metal-organic cage at an air temperature of over 25^{o}C and a humidity of around 7% (Yang, Clark & Yaghi, 2021).

Today, it is possible to obtain water almost anywhere in the world from atmospheric water vapor constituting a large part of greenhouse gases with water generators. Atmospheric water generators are clean and safe water sources in arid or unsanitary areas. Water generators draw in moist air and transform it into water by cooling it in a condensation chamber. However, electrical energy is used in such systems producing water from the air. Most modern plants, especially those designed to produce large volumes of water, are powered by compressors and connected to the electricity grid, which replaces one problem with another (Maleki, Eslamian & Hamouda, 2021).

In general, thermoelectric chillers work best in small spaces where there is not enough room for a compressor-based chiller. In a small-sized chiller, these systems are highly efficient and consume less energy than a compressor-based unit of the same size which is also portable.

Thermoelectric coolers work with the thermoelectric effect which is also called the Peltier effect. With the thermoelectric effect, the temperature difference and the electrical potential difference can be converted into each other. When thermoelectric modules are connected to a direct current generator, a temperature difference begins to occur between their faces. If there is a temperature difference between the faces with any heat exchange, this time it works like a direct current generator. The main application area of the Peltier effect is cooling. However, it can also be used for heating or temperature control (Balkrishan et al., 2016).

Some of the studies carried out to obtain water from the atmosphere by using a thermoelectric cooler are as follows:

Avhad et al., (2021) and their team simulated the thermoelectric cooler device using TEC-12706 Peltier modules they developed at Savitribai Phule Pune University in India using Ansys Fluent software by entering the data of four cities in India. In the simulation, the largest amount of water, with 44 mL/hr, was obtained from the city of Mumbai with an average relative humidity of 87%, followed by the cities of Bangalore, Agra, and Cherrapunji (Avhad et al., 2021).

Alenezi et al., (2023) and their team obtained 405 mL of water in 8 hours under 40^{o}C temperature and 85% relative humidity in the climate chamber with a prototype device with a 24 W thermoelectric cooler. In the experiments they carried out in the open air, the amount of water they obtained varied according to the relative humidity. While the device was able to produce 22.5 mL/hr of water at 52% RH, it produced 42.5 mL/hr at 94% RH. (Alenezi et al., 2023).

Eslami et al. (2018) and team produced 26 mL of water in 1 hour from air at 75% relative humidity and 45^{o}C with a 20 W thermoelectric cooler device in their experimental study in Iran (Eslami et al., 2018).

Liu et al. (2017) and his team, in their experimental study in China, conducted experiments at different relative humidity levels with a 52 W thermoelectric cooler device. The device they developed produced 11 mL/hour of water in 68% relative humidity air and 25 mL/hour in 93% relative humidity air (Liu et al., 2017).

Kadhim (2020) and his team conducted experiments in different relative humidity levels with a 70 W thermoelectric cooler device in their experimental study in Iraq. The device they developed produced 10 mL/hour of water in 65% relative humidity and 20 mL/hour in 75% relative humidity air (Kadhim, Abbas & Kadhim, 2020).

In a study conducted in Turkey by Özcan et al. (2022), a smart irrigation system with a 240 W thermoelectric cooler charged with solar energy was developed and tested to irrigate houseplants or hobby gardens by utilizing the water vapor in the atmosphere (Özcan et al., 2022).

When we look at the studies carried out to obtain water from the atmosphere, it is seen that the amount of water obtained varies significantly according to the air temperature and relative humidity. In addition, the power drawn by the system and the used cooler and fan capacities also affect the results. However, it can be said that the amount of water obtained in experimental studies with thermoelectric coolers in the literature is generally below 100 mL/hour.

Among the systems developed and patented for obtaining water from the atmosphere, the studies in the US 6,945,063 B2 patent document, the US 7,337,615 B2 patent document, and the US 6,868,690 B2 patent document can be counted.

The device, which is included in the US 6,945,063 B2 patent document, produces water by condensing metal surfaces with the photoelectric effect and works with the principle of obtaining water from the relative humidity in the air by using only the Peltier effect (Max, 2005). Although the basis of the device in the US 7,337,615 B2 patent document which produces drinking water with the thermoelectric effect is similar, this device is different in shape (Reidy, 2008). The device in the US 6,868,690 B2 patent document, which can obtain drinking water through gas cooling obtains water through gaseous systems used in refrigerators (Faqih, 2005).

2. Materials and Methods

The literature can be consulted for the precautionary measures to be taken or to be taken in the face of the problem mentioned above. In this study, a portable device was designed and tested to help meet the drinking water needs of an ordinary house. The feature that distinguishes this developed device from systems that produce water from atmospheric humidity by working with active energy 24 hours a day is that it can automatically become active or passive with software support, which makes energy optimization. The device will first condense the gaseous water in the atmosphere, then purify it to make it usable for drinking purposes. Thus, a step is taken to contribute to the protection of freshwater resources, use renewable energy, and raise awareness about protecting natural resources.

The method of this paper is based on experimental work and theoretical analysis. In the study, to contribute to the protection of freshwater resources, a system producing water from atmospheric humidity supported by software and hardware consisting of mechanical and electronic parts has been developed and the usability and performance of the system has been demonstrated by experiments and theoretical calculations. With the developed system, the water vapor in the air is cooled to the dew point on the surface of the thermoelectric cooler module and condensed by controlling it with the energy-optimizing "C" software.

2.1. Experimental Design

The system developed and tested in this study obtains water from the humidity of the air by performing dew point analysis with the psychrometric diagram algorithm. The dew point temperature can be calculated using the psychrometric diagram, which is a graph of the thermodynamic properties of moist air used in energy physics calculations (Figure 1).

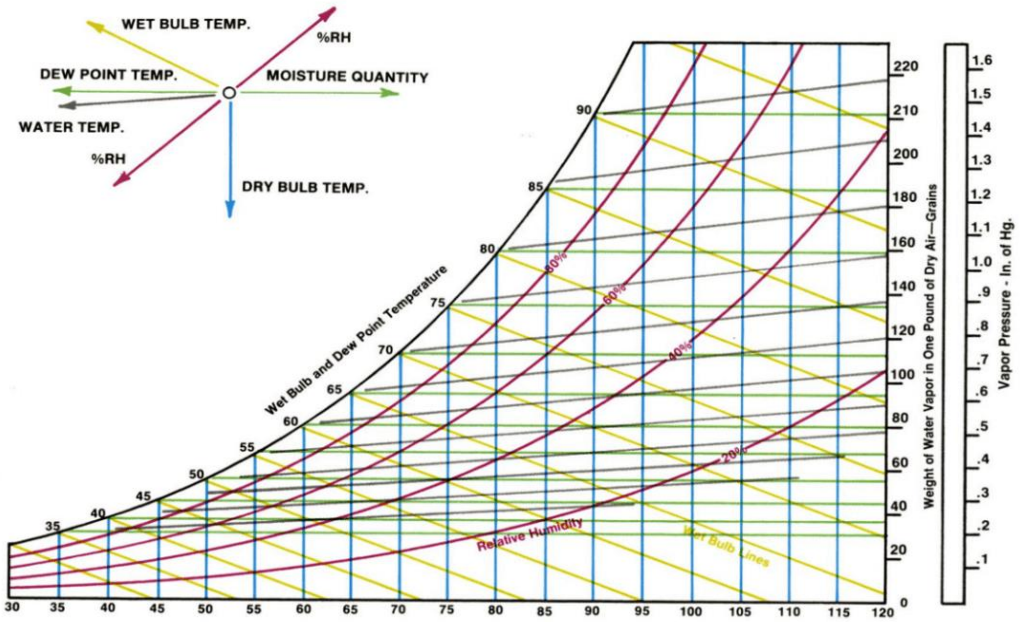

Figure 1. Psychrometric chart (Parameter Generation & Control, 2019)

The amount of moisture the air can absorb varies depending on the temperature. For example, a 1 m^3 air mass is capable of carrying about 2 g of moisture at –10^{o}C while it can carry about 80 g of moisture when the temperature rises to 50^o C (Figure 2).

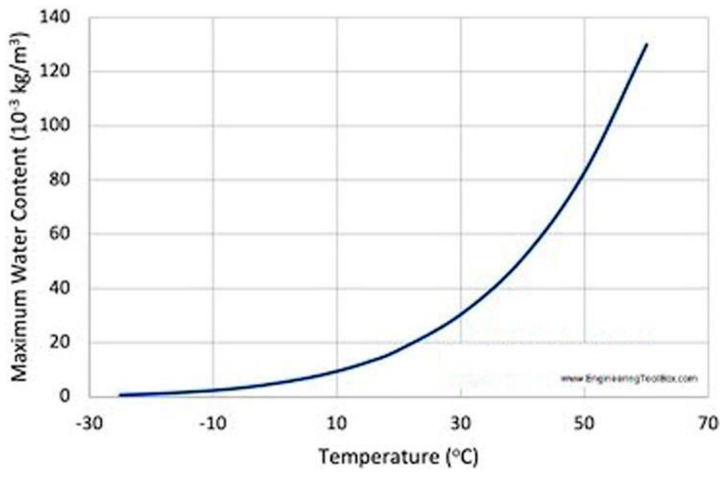

Figure 2. Maximum moisture carrying capacity vs. temperature (The Engineering Tool Box, 2023)

Some terms related to air pressure, temperature and humidity are explained below;

Absolute humidity	The mass of water vapor in a unit volume of air.
Specific humidity	The mass of water vapor contained in the air per unit mass.
Saturation point	1 m^3 of air can hold at a certain temperature.
Relative humidity	The ratio indicates what percentage of the maximum amount of moisture that the air *(at a certain temperature)* can carry.
Dew point	The temperature at which moisture in the air begins to condense depends on air pressure and humidity.
Dry bulb temperature	The temperature of the air at any degree of humidity.
wet bulb temperature	The lowest temperature that can be achieved by evaporative cooling in an area of the air.
Enthalpy	The total internal energy of a thermodynamic system depends on pressure and temperature.

The difference between absolute humidity and maximum humidity is called the humidity gap of the air. When the absolute humidity reaches the maximum humidity, the relative humidity becomes 100% and the air reaches the saturation point. There is an inverse relationship between temperature and relative humidity. When the air temperature increases, the relative humidity decreases and the air moves away from the saturation point, even if the absolute humidity does not change. Relative humidity is low in deserts and inland. The relative humidity is high on the sea, in the equatorial region, at the poles.

Weather data in the atmosphere constantly changes according to the hours. Therefore, in systems that produce water from atmospheric humidity by working with active energy for 24 hours, it is necessary to make heating-cooling adjustments according to changing weather conditions or to make it passive so that the system does not run in vain when it cannot produce water, and there are difficulties in doing this manually.

In this study, electronic hardware and software are integrated into the system to eliminate these difficulties and to make the operation of the mechanical part more efficient. The added software enables the system to operate economically by analysing the instantaneous temperature and humidity values of the environment according to the psychrometric diagram.

2.2. Experimental Setup

The system used in the experiment; consists of mechanical and electronic parts. The mechanical part consists of a thermoelectric heat exchange unit and an air circulation tower. The air circulation tower was printed with a 3D printer. In this part, ambient air is sent to the thermoelectric cooler by means of fans. When the dew point is reached under the current ambient conditions, the thermoelectric cooler converts the water vapor molecules in contact with the metal surface into water droplets.

In the electronic control part of the system, Xiaomi (II) temperature and humidity sensor, ESP32, and a tablet are used. ESP32 is a low-cost and low-power microcontroller. In this study, software with "C" language is loaded on ESP32, and the operation of thermoelectric modules is controlled through this software. Temperature and humidity values, cooling, heating, and waiting times can be observed via the Phyton software installed on the tablet. At the same time, the system can be turned on or off via the tablet.

ESP32 connects to the temperature and humidity sensor via bluetooth and to the tablet via wi-fi. When the system is turned on, ESP32 starts to communicate continuously with the temperature and humidity sensor via bluetooth and at the same time sends the data to the tablet (Figure 3).

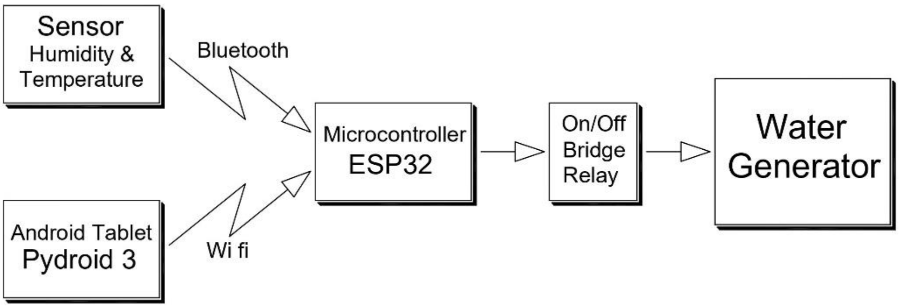

Figure 3. Connection diagram of the system elements

The main function of the ESP32, a micro-computer, is to determine the enthalpy of the air according to the data coming from the temperature and humidity sensors. Accordingly, it cools or heats the surface of the thermoelectric module or goes into inactive standby mode. The situation regarding the operation of the system is shown in Figure 4 of the Psychrometric diagram.

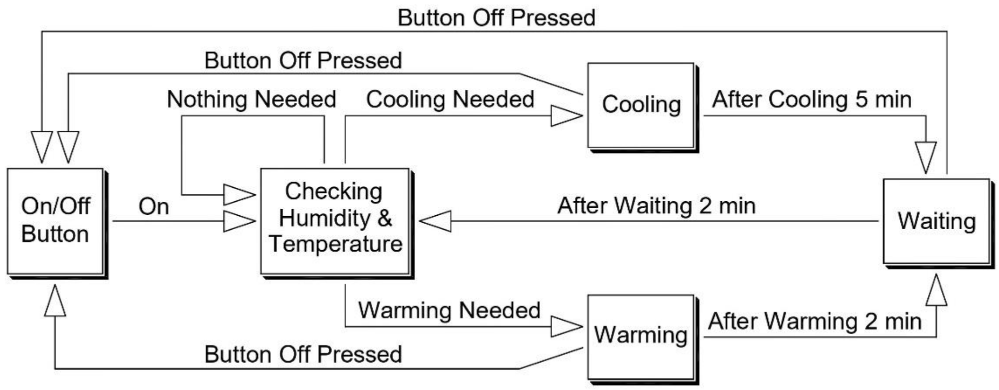

Figure 4. State diagram

The system is designed to work with solar energy in order to use energy efficiently. It can work either connected to the grid *(on grid)* or independent of the grid *(off grid)*.

The system is shown in Figure 5. The technical features and cost prices of the parts used in the system are shown in Table 1.

Figure 5. Cyclic water generator system view

Table 1. Material-price list

Material	Price ($)
Monocrystalline solar panel (75 watts, 18.5 volts max)	65
Thermoelectric heat sink module block with aluminum/copper heatsink, fan circulation, (2 x TEC 12715, 12 volt 240 W)	36
External surface airflow fan, (8 cm case fan 12 volts)	2.5
Battery, (12 volt 24Ah Gel)	34
Solar charge control module, 12 volt 30 A	4.5
ESP 32 bluetooth-wifi circuit	20
Negative ion Generator	5
Temperature - humidity sensor II (Xiaomi)	10
3D printing air circulation tower and water tank	2.5
Carrying case	25
Connectors cable-terminal	1.5
Total	206

Another function of the system is making the water it produces drinkable. For this, ozone is produced with the effect of static electricity on the metal surface where the water condenses. The condensation water is purified from viruses and bacteria. The chemical and biological properties of the water collected in the tank after condensation have been tested and shown to be drinkable.

The ozone generator in the system is used for the disinfection of living ambient air and removal of harmful substances from water as well as in swimming pools, wastewater treatment, the food industry, cold storage, and removal of colour and odour. Ozone is a gas with a very high oxidation power and the strongest disinfectant known. The disinfection effect of ozone gas is 3125 times more than chlorine under the same conditions, so it is more effective than chlorine against spores, cysts, and viruses (Seydim, Greene & Seydim, 2004).

In addition, since ozone is obtained through the breakdown of oxygen in the air, it always turns into oxygen, which is its raw material, after completing its disinfection task due to its unstable structure. The fact that ozone gas is the only disinfectant that does not leave any residue after disinfection makes its use especially in the food and livestock industry advantageous compared to other disinfectants. It is not harmful to human health as it leaves no residue (Seydim, Greene & Seydim, 2004).

3. Findings and Discussion

In the experimental study, 12 experiments were carried out in different weather conditions, and frost, ice, or water formation was observed on the metal cooler surface according to the air temperature and relative humidity values. In the experiments, the ambient temperature and relative humidity were placed on the Psychrometric Diagram, and the corresponding H [kcal/kg air] enthalpy values were found. The Psychrometric Diagram of this study is shown in Figure 6.

A table was created by ordering the enthalpy values corresponding to the air data during the experiments, from smallest to largest, and the results were recorded in Table 2. In this table, the H = 10.6 [kcal/kg air] value, in which the water on the cooling surface passes from the ice/snow phase to the liquid phase, is determined as the limit value. The enthalpy values in Table 2 are the experimental values obtained according to the capacities of the fan and cooling units in this study. The values obtained differ according to the cooler and fan capacities in different systems.

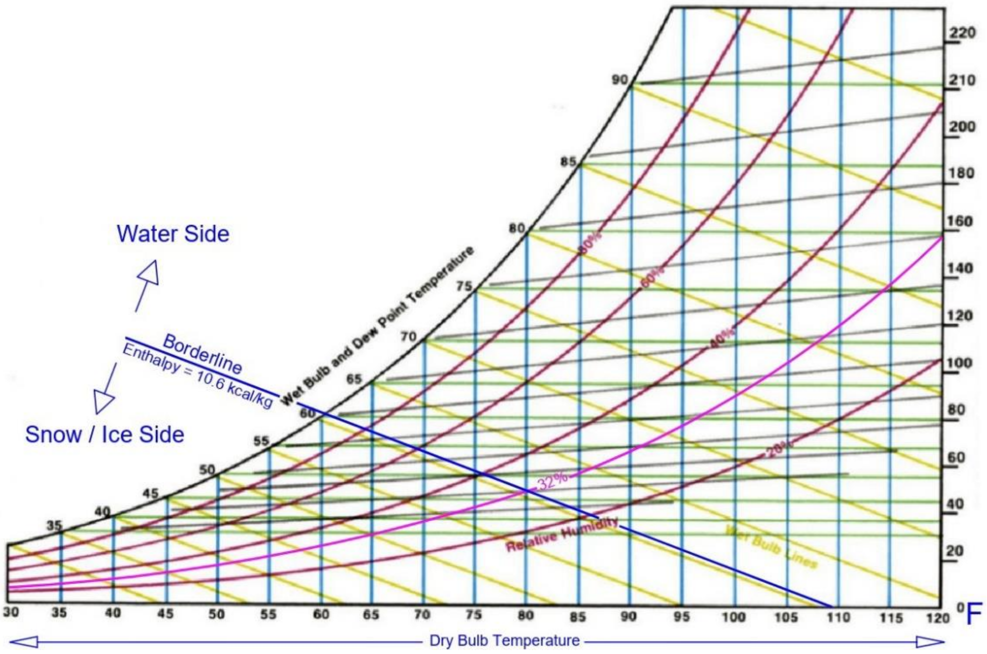

Figure 6. Psychrometric diagram of experiments

Table 2. Ambient temperature and humidity were measured during the experiments and enthalpy values

No.	Temperature [°C]	Relative humidity [%]	Enthalpy [kcal/kg air]	Conclusion
06	18.7	50	8.7	Snow
02	16.4	69	9.0	Snow
01	16.7	74	9.4	Snow
03	17.9	70	9.5	Snow
08	18.5	63	9.5	Snow
10	23.4	41	9.5	Snow
09	14.6	99	9.8	Ice
07	20.6	53	10.6	Snow / Water
11	27.2	32	10.6	Snow / Water
04	21.0	63	11.0	Water
05	25.9	42	12.1	Water
12	28.3	62	12.4	Water

According to the results obtained from the experiments, it is noted that when the enthalpy value is greater than 10.6 kcal/kg for this tested system, water formation will be observed on the cooling surface and the system is set to continue operating with a cooling function in this case *(the case of H>10.6 kcal/kg air).*

When the enthalpy value is H<10.6 kcal/kg of air, since frost or ice will form on the cooler surface, the system will then cut off the cooling and become passive and wait for the ice on the cooler to melt. However, in cases where the ambient temperature is below +4°C *(as this temperature cannot melt the ice on the surface)*, the system will switch to heating mode. It is the critical temperature range where the solid-liquid phase change of water occurs between 0°C and +4°C under 1 atm pressure.

The chemical and bacterial analysis of the water obtained as a result of the experiments was carried out in the laboratories of the Ministry of Health. The results obtained are given in Table 3 and Table 4. In addition, TDS (hardness degree) value was found as 25 mg/L in the hardness measurement. This shows that the mineral balance is suitable for drinking. Some images from the test are shown in Figure 7 (World Health Organization, 2017).

Figure 7. Views from the experiments

Table 3. Chemical analysis of produced water

Contents	Amount [mg/L]/Availability
pH	7.8
Organic matter	Suitable
Chloride	0.89
Ammonium	0.03
Sodium	1.48
Sulfate	6
Aluminum	0.003
Iron	<0.001
Chromium	<0.001
Bullet	<0.001
Manganese	<0.001
Turbidity rate	Suitable

Table 4. Bacterial analysis of the produced water

Content/Feature	Quantity/Status	Analysis method
Enterococcus	0 cfu/100ml	TS EN ISO 7899-2
Escherichia coli	0 cfu/100ml	TS EN ISO 9308-1
Coliform	0 cfu/100ml	TS EN ISO 9308-1
Foreign matter	None	Organoleptic
Smell	Idiosyncratic	Organoleptic

4. Conclusion and Recommendations

In this study, an advanced system that can economically obtain potable water from the humidity of the air and can be controlled by software has been designed, and the usability and efficiency of the system have been tested in different weather conditions. The system also can work on sunny days without the need for mains.

When similar studies are examined in the literature, it is seen that the results obtained vary not only according to the air temperature and relative humidity rates but also depending on the power of the cooler used and the amount of air passing through the unit surface.

The results obtained in the experiments within the scope of this study varied according to the air temperature and humidity. The amount of moisture that the air can absorb at certain temperatures is constant. However, there are different climate types in Turkey just like in any area in the world, and the air temperatures vary according to the climate. For this study to be used throughout the world, +4 ^{o}C, the temperature at which water is in the most density, has been determined as the heating temperature limit. This system developed in the study can operate efficiently in regions with high relative humidity and produce water.

The energy efficiency of the system developed in this study has been increased with software support. Unlike similar examples, the system performs psychrometric diagram analysis with the help of software installed on the control unit, which automatically switches to heating or cooling conditions when necessary and shuts itself off when it does not need to work, thus saving energy.

Another purpose of this study is to test the quality of the water produced. The method used is water purification by condensation. While the water is purified physically and chemically, ozone gas is produced with the effect of static electricity on the surface where water droplets are formed, and the water obtained is purified from viruses and bacteria.

In addition, in the hardness measurement, it was seen that the mineral balance was suitable for drinking. As a result of the chemical and bacterial analysis, it was observed that the water generator system is supported by software and hardware, that can obtain drinkable water from the air with solar energy which can reach the drinking water values accepted at world standards.

Based on the results obtained in the experiments, it is suggested that in future studies, the production of large-capacity water generators with the aforementioned method and their use in humid climates are suggested as an alternative solution to water scarcity.

Acknowledgments and Information Note

The article complies with national and international research and publication ethics. Ethics committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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