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ORIGINAL ARTICLE

Potable water production from ambient moisture

Ramazan Şenol[1] · Osamah Salman[2] · Zekeriya Kaya[2]

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Abstract

Nowadays, with the rapid increase in world population, potable water shortage has started to create serious problems. Many factors such as increased water consumption, environmental problems and climate change cause the decrease in potable water resources. In this study, a fully automatic system which produces water from ambient humidity developed to provide solutions especially in areas where access to clean and potable water resources is difficult. Moisture and salt are used for raw material. $CaCl_2$ salt is not very good for moisture absorption, but when compared with other salts, it can provide a great advantage under human health and cost. The machine is also reinforced with electrical equipment and measures the ambient temperature, pressure values and humidity, consumed energy and prints it on the memory card (SD card) in real time. While the system is running, it can be controlled and read over the phone. Experiments have been carried out and the changes in the amount of water produced and the amount of salt consumed depending on the ambient humidity and temperature have been investigated. The amount of energy consumed by the system was also analyzed. It was observed that the amount of water produced was directly proportional to the ambient humidity.

Keywords Water production · Dehumidification · Potable water production systems · Automatic control system

Introductıon

Recently, shortage of potable water has become a serious problem. With the increase in population, potable water consumption has led to depletion of traditional potable water resources due to different reasons such as increased water pollution and climate change (Richey et al. 2015). In order to eliminate the problem of potable water, water is produced by using different methods such as separation of sea water from salt and dehumidification (Ünal 2015; Fraunhofer-Gesellschaft 2009). By using methods such as cooling the ambient air or applying pressure on the air, it is possible to reach the condensation temperature of the water and produce water (Wahlgren 2001).

According to the new WHO (World Health Organization)/UNICEF Joint Monitoring Programme (JMP) report, 2.1 billion people worldwide do not have access to safe, easily available water, and 4.4 billion people are deprived of safely managed health problems. Today, there are about 2.4 billion people who cannot use advanced healthy and clean water and 663 million people who do not have access to advanced water resources. More than 800 children die every day from diseases caused by lack of clean water (UNICEF 2019) by 2025, and half of the world's population is reported to be living in water-borne areas. According to a report published by the WHO on June 14, 2019, 5.3 billion people used safe managed drinking water services in 2017, while 2.2 billion people do not receive safe water services.

Cooling is widely used to produce water from ambient humidity. The cooling method is divided into absorption and vapor compression; the study of (Anbarasu and Pavithra 2011) is based on the steam compression, cooling system (Abualhamayel and Gandhidasan 1997). The air passing through the filter is transferred to the condenser with the help of a fan, and the water temperature is reduced to the condensation temperature (Anbarasu and Pavithra 2011). Since the energy consumption of the systems based on cooling method is high in general, it increases the price of the produced water (Kinder et al. 2017). The second method is obtainable in water by compressing the moist air taken from the environment. However, this method is not suitable for

✉ Ramazan Şenol
ramazansenol@isparta.edu.tr

1 Faculty of Technology, Electrical and Electronics Engineering, Isparta University of Applied Sciences, Isparta, Turkey

2 Faculty of Technology, Mechatronics Engineering, Isparta University of Applied Sciences, Isparta, Turkey

use due to costly machinery and high energy consumption (Abualhamayel and Gandhidasan 1997). According to the laws of thermodynamics, when the temperature is constant, if the pressure decreases, the saturation temperature of the water decreases, and as the pressure increases, the condensation temperature of the water decreases. (Çengel and Boles 2008). Another method is the use of metallic membrane technology to dry the air used in the National University of Singapore project, thus saving 40% energy in air conditioning systems and producing 12–15 L of water during cooling (National University of Singapore 2018).

Humidity can be absorbed by using chemical salts such as calcium chloride ($CaCl_2$), lithium chloride (LiCl) and lithium bromide (LiBr) (Xiu-Wei et al. 2008; Fumo and Goswami 2002; Ko 1980). These salts are also used to absorb moisture in industrial applications or construction applications. Comparisons of salts prepared using (Studak and Peterson 1988; Jones 2008; Ren et al. 2019; Fekadu and Subudhi 2018; Peladow DG Calcium Chlorıde 2014; Lithium Bromide Lab 2019; Lithium Chloride Granular Reagent 2019; Calcium Chloride Anhydrous 2019) sources are presented in Table 1.

As can be seen in Table 1, LiCl salt dehumidification rate is high, while health hazard and price are quite high. $CaCl_2$ salt has low dehumidification rate, but its health hazard ratio is considerably lower than other salts, and it is a salt type used in food production. Finally, it is seen that LiBr has the worst characteristics for producing potable water according to the evaluation criteria in the table.

A solution is formed by absorbing the moisture in the environment with chemical salts. The resulting solution contains water, salt and dirt. To produce pure water from the resulting solution, one of the filter and desalting methods in Scheme 1 should be used.

Table 1 The amount of moisture absorption depends on the salt type

Salt Name	Dehumidification Rate	Price	Corrosion	Health Hazard
$CaCl_2$	Low	***Low***	High	***Low***
LiCl	***High***	High	***Low***	High
LiBr	Medium	High	***Low***	High

The required values of the dehumidification rate, price, corrosion and health hazard parameters are expressed in bold and italics

In this study, a fully automatic system which produces water from ambient humidity is developed to provide solutions especially in areas where access to clean and potable water resources is difficult. Experiments have been carried out and the changes in the amount of water produced and the amount of salt consumed depending on the ambient humidity and temperature have been investigated. The amount of energy consumed by the system was also analyzed.

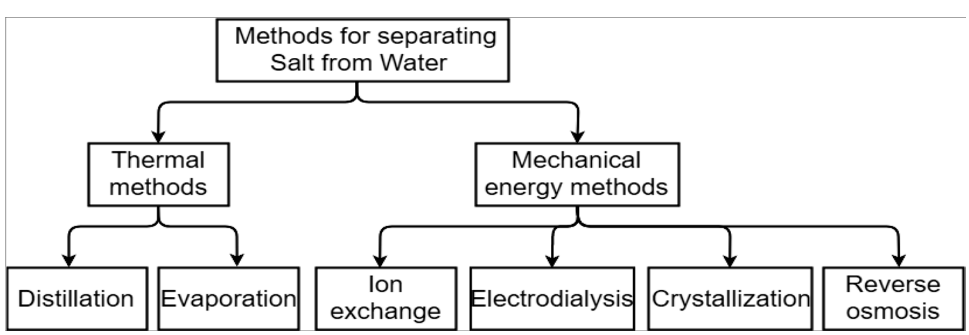
Material and method

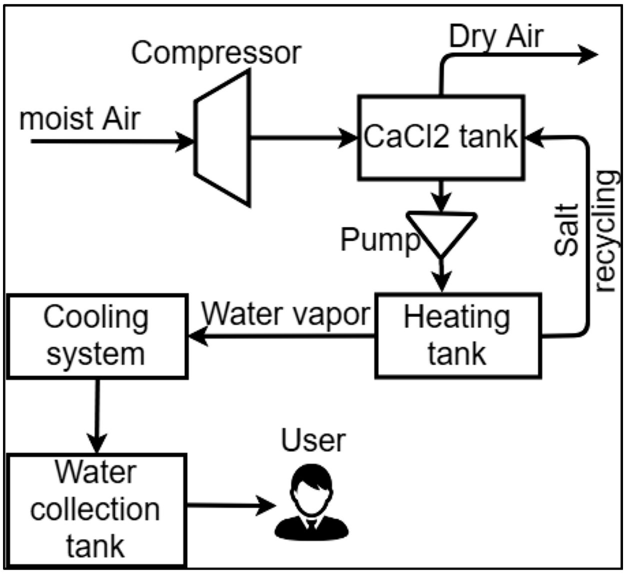
Material

In this study, $CaCl_2$ (Calcium Chloride) salt was used to absorb the moisture in the environment; AC 220–240 Volt and 24 Watt industrial type fan was used to give speed and pressure to the air. Since the corrosion effect of the salt used in the study is high, all parts that will come into contact with the salt were made of Chrome st304 and plastic materials. The solution containing salt and water is heated with the help of 400 Watt resistance, and the components are separated from each other. A 6-m copper tube was preferred to allow the evaporating water to pass back into the liquid phase. Two geared DC motors and one stepper motor were used as sieves.

Electronic components are PIC18F45K22 and AT Mega 2560 as micro-controller, 10A SSR relay for control, 12 V DC relay, PTC, IRFZ34N mosfet A4988 stepper motor driver and SHT11 humidity-temperature sensor for data acquisition, DS3231 real-time clock (RTC), BMP180 pressure sensor and SD card. Android-based phone interface with HC-05 Bluetooth module was designed to provide remote control. The software was implemented with MicroC, arduino, MIT App inverter.

Scheme 1. Desalination methods (Can et al. 2002)





Scheme 2. General operation diagram of the machine

Method

Nowadays, the consumption of potable water sources due to different reasons such as population increase, consumption of potable water, increase in water pollution and climate changes causes thirst and drought. In order to overcome all these negativities, a machine design was also needed which was also assisted by natural resources. In Scheme 2, the humid air in the environment is conveyed to the salt tank with the help of the fan, the moisture in the air is absorbed and the dry air is thrown to the outside environment. The resulting brine solution is transferred to the heating tank by a pump. The water whose temperature is increased here is transferred to the vapor phase and distilled in the cooling system and collected in the water collection tank. The salt accumulated in the heating tank is transferred back to the salt tank for recycling.

30 × 30 aluminum sigma profile has been chosen to provide easy usage, transport, durability, lightness and easy assembly of the elements of the designed machine with the dimensions of 110 × 52 × 71 cm. The main parts to be connected to this profile, salt and air absorbing reservoir (Fig. 3) 50 × 50 × 32 cm dimensions were mounted to the bottom base of the system by bolt connection. Chromium st304 was chosen as the storage material because it does not react with salt and water. $CaCl_2$ salt, which can contain moisture in the air, was preferred because of its low cost and little negative effect on human health (Table 1). The air flow required for the salt to absorb the moisture in the air better was provided with the help of an industrial fan. This provided air flow forms a salt water solution with molecules impinging on the salt particles. The resulting solution is transferred to the brine separation tank (Fig. 3) by means of a pump with a flow rate of 240L/h to defecation. In this transferred solution, the mixer operating with 12 V geared DC motor was used in order to prevent homogenization of the mixture temperature, settling of the dissolved salt in the salt water solution and sedimentation in the tank bottom. This mixture, which is prevented from settling, was brought to the desired temperature with the help of 400 Watt resistance. The water in the solution, which has reached a sufficient temperature level, is evaporated and distilled by a 6-m shaped copper pipeline and the product produced is collected in the clean water tank (Fig. 3). After this process is completed, the screw shaft connected to the stepper motor is turned and the cover of the salt water separation tank is lifted up. Through the DC motor, the salt water separation tank (Fig. 1) is rotated by approximately 100 degrees and the $CaCl_2$ salt deposited on the tank floor is transferred to the air absorption tank. The reason for this is to use $CaCl_2$ salt in recycling. After draining, the salt water separation tank is restored to its original position by a geared DC motor. The cover which is connected to the screw shaft is closed by starting the stepper motor. Based on the principle of continuity of the mechanical component after completing this one cycle, the system achieves the desired purpose by circulating the mechanism in this way.

Images of different parts of the system are given in Fig. 2. This figure showing different parts of the system was created from the images taken during the experiments. Figure 3 shows the use of the PIC18F45k22 and At Mega 2560 microcontrollers to achieve the intended machine control. The PIC18F45K22 microcontroller was used to measure the water level produced. The water level consists of 10 levels. In the MicroC environment, the code written to the PIC18F45K22 reads the data and shows the water level. At the same time, the value of the water level is continuously sent to the arduino via serial communication protocol. The AT Mega 2560 microcontroller was used for control and data acquisition. A drive card was designed for each of the DC motors, water pump and stepper motor in the machine. Driver boards with mosfet and relays have been produced for DC motor direction and speed control. The water pump has one way control with BC547 transistor and relay. Finally, using the L298N driver board, the stepper motor was limited to two buttons. 10A SSR relay type was found suitable for AC-operated fan and resistance controls. Drivers and relays used in the system are controlled by a microcontroller. In this study, different sensors such as SHT11 humidity and temperature, BMP180 pressure, DS3231 real-time clock, PTC temperature and water level were used for both data collection and control purposes. To store data, the SD card has been added to the study and all data have been continuously recorded. To display the read data, 2 × 16 LCD screen and Andorid-based interface written in MIT App inverter

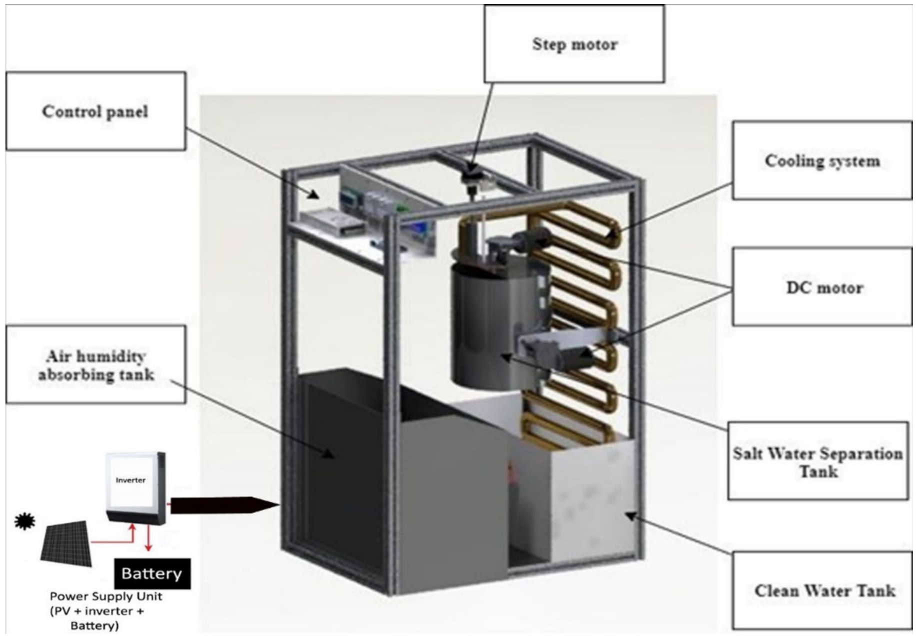


Fig. 1 Design of the machine

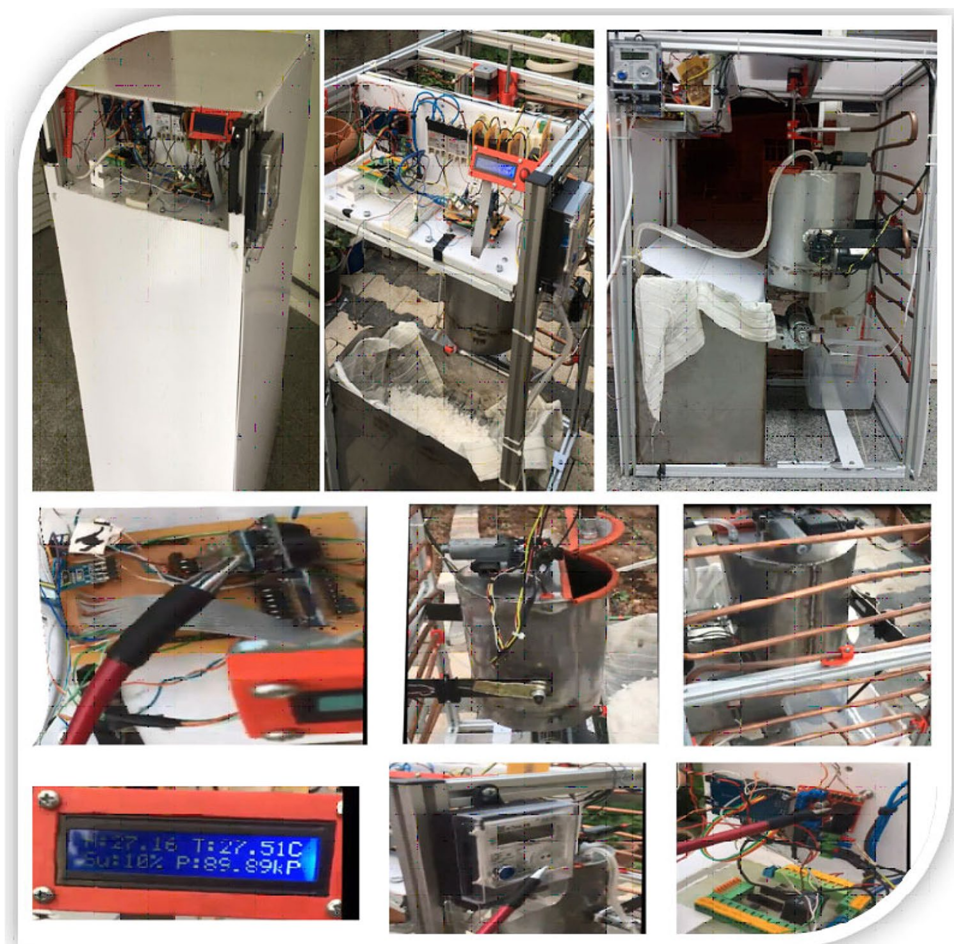


Fig. 2 View of the system's components

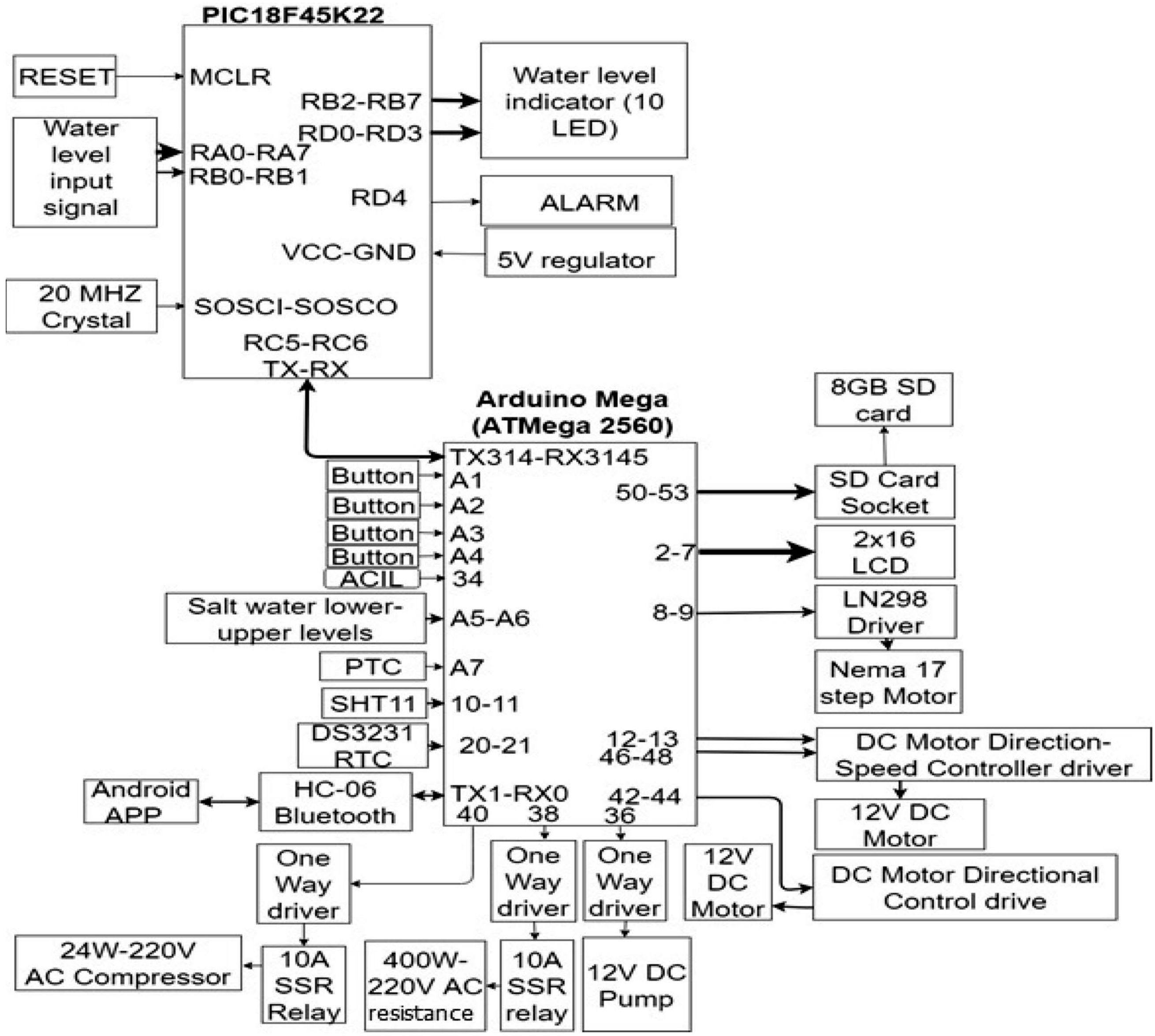


Fig. 3 Electronic connection block diagram

were used. The bluetooth HC-05 module has been selected to communicate the project with the phone.

As shown in Fig. 4, when the system is powered, the moving parts of the system are returned to their main positions. The first stage immediately after entering the operating cycle is the parameter safety stage and all elements are de-energized by remote or manual control in any emergency. When the system is first started, the motors and other components are reset to the main positions. Humidity, temperature, date, time, water level are read after the system returns to its initial position. (These values will be read and recorded at the beginning of each cycle, but there will be no recordings during salt recycling, because delays in reading data will not allow for more precise control of the conversion stage). These data, which are reflected and read on the LCD screen and the remote controller, are saved to the SD card. After these operations, the compressor is started and when the amount of solution accumulated in the tank by absorbing salt and moisture in the air reaches a certain level, controller pump is started. The solution is pumped to the salt and water separation tank by means of the pump. When the accumulated solution level drops to the desired level, the pump is stopped. The heater and the mixer become active with the presence of solution in this tank. The compressor, heater and mixer continue to operate until the temperature of the solution reaches 150 °C. When the desired temperature is reached, the stepper motor is operated and the cover of the heating tank is opened. The stepper motor cover continues to

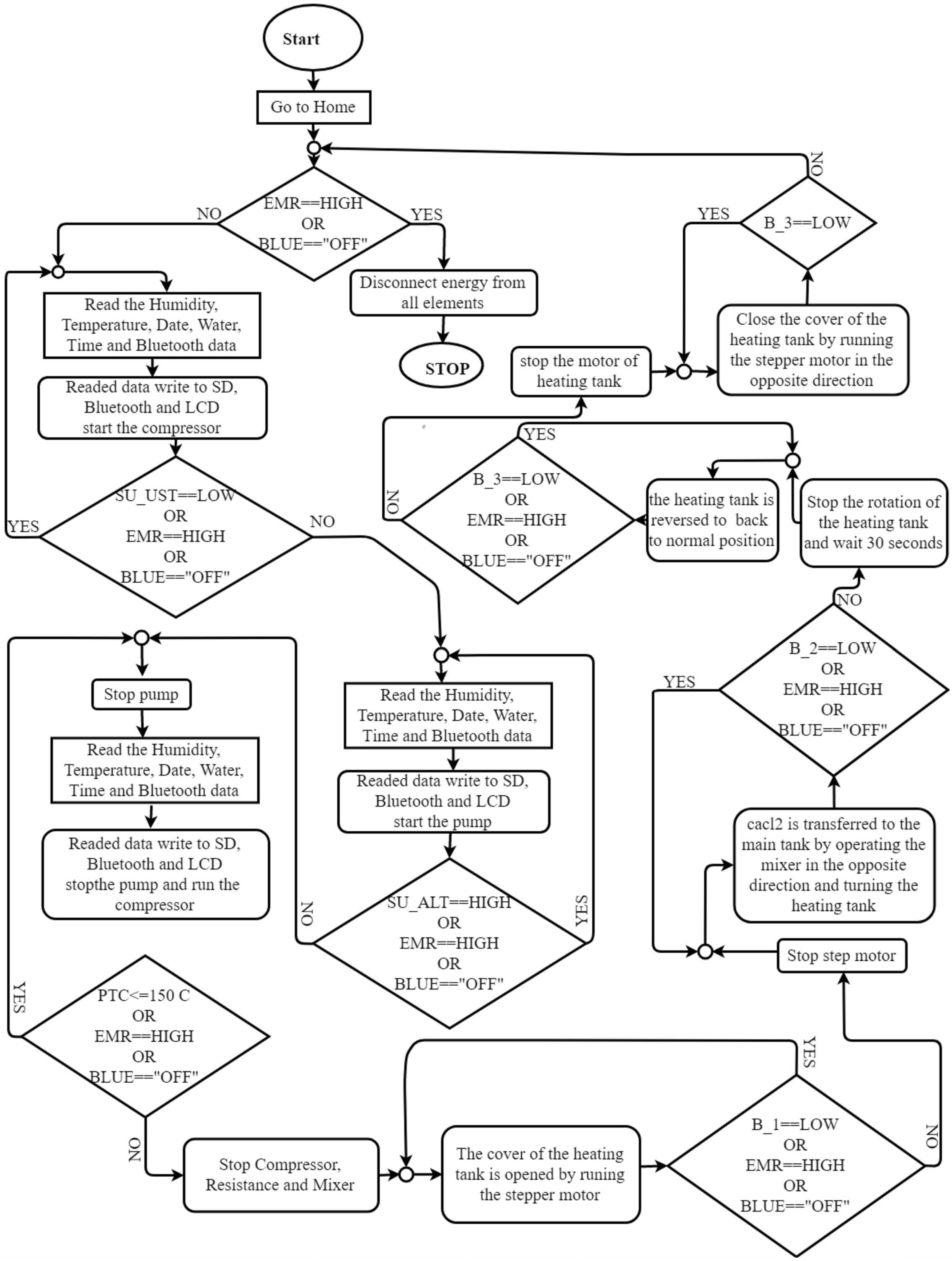


Fig. 4 Working algorithm

move up until the cover contacts the limit switch. Then, the mixer runs in the opposite direction and the turning process continues until the heating tank is turned and the button in the salt and air absorbing tank is activated. The waiting time for this operation is 30 s. After the elapsed time, the heating tank will be reversed to its normal position until it signals to the limit switch connected to the sigma. The brine/salt water separation tank that reaches the desired position is

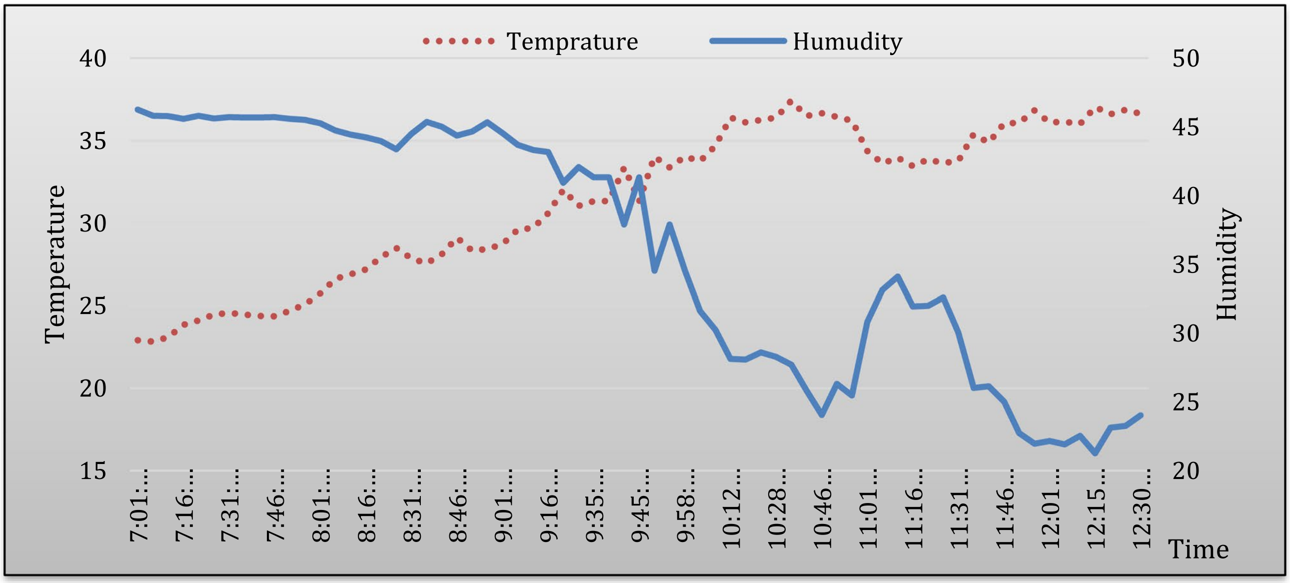


Fig. 5 Results of the experiment carried out on 05.29.2019

closed by lowering the tank cover by operating the stepper motor in the opposite direction. The signal from another stepper motor limit switch indicates that the cover is closed and the entire cycle is complete. After this point, the system is worked fully and produced the desired product. In this way, the desired goal is achieved by continuing and showing continuity.

Results and discussion

After the design, manufacturing, installation and control of the system, the tests were started. It is aimed to make experiments with different humidity values on different days in Isparta weather conditions. For this reason, experiments were carried out on five separate dates: 29.05.2019, 15.06.2019, 16.06.2019, 31.10.2019 and 4.11.2019. Experiments were carried out on different days and hours but with equal duration in terms of total time. The system was operated daily for 5 h 35 min. The data obtained at the end of this period are given in Figs. 5, 6, 7 and 8.

The experiment was carried out on 29.05.2019 with 2.6 kg of $CaCl_2$ salt. 0.1 kg of $CaCl_2$ was used during the experiment, and 2.5 kg of $CaCl_2$ remained at the end of the experiment. The experiment was conducted between 07:00 and 12:30. Ambient humidity was measured between 46 and 40% with the SHT11 sensor at the time interval of 07:01–09:16. These values varied between 32 and 20% between 09:30 and 12:30. Temperature and humidity changes of the experiment are shown in Fig. 5.

The experiment which was carried out on 15.06.2019 was started with 3.850 kg $CaCl_2$ salt and by using 0.06 kg $CaCl_2$, 3.79 kg $CaCl_2$ remained at the end of the experiment. The experiment was conducted between 09:30–13:00 and 14:30–16:30. In the experimental period, ambient humidity was measured with SHT11 sensor and ambient humidity was found by 40–30% in the morning and afternoon and measured between 50 and 40% at noon. The measured temperature and humidity changes are shown in Fig. 6.

The experiment which was conducted on 16.06.2019 was started with 3.79 kg of $CaCl_2$ salt and by using 0.05 kg $CaCl_2$, 3.74 kg $CaCl_2$ remained at the end of the experiment. The experiment was conducted between 16:30 and 22:00. Ambient humidity was measured between 59 and 50% at night with the SHT11 sensor. During the experiment, ambient temperature, humidity, pressure values were measured by SHT11 and BMP180 sensors and recorded to SD card in 5 min intervals. Digital monophase meter was used to calculate the amount of energy the system would spend. Temperature and humidity changes of the experiment are shown in Fig. 7.

The experiment was carried out on 10.31.2019 with 1.5 kg $CaCl_2$ salt and using 0.07 kg $CaCl_2$, 1.43 kg $CaCl_2$ remained in the end. The experiment was conducted between 15:30 and 21:00. The ambient humidity was measured between 40 and 65% with SHT11 sensor. Temperature and humidity changes of the experiment are shown in Fig. 8.

The experiment was carried out on11.04.2019 with 1.43 kg $CaCl_2$ salt and using 0.04 kg $CaCl_2$, 1.39 kg $CaCl_2$ remained in the end. The experiment was conducted between 11:00 and 16:30. The ambient humidity was measured

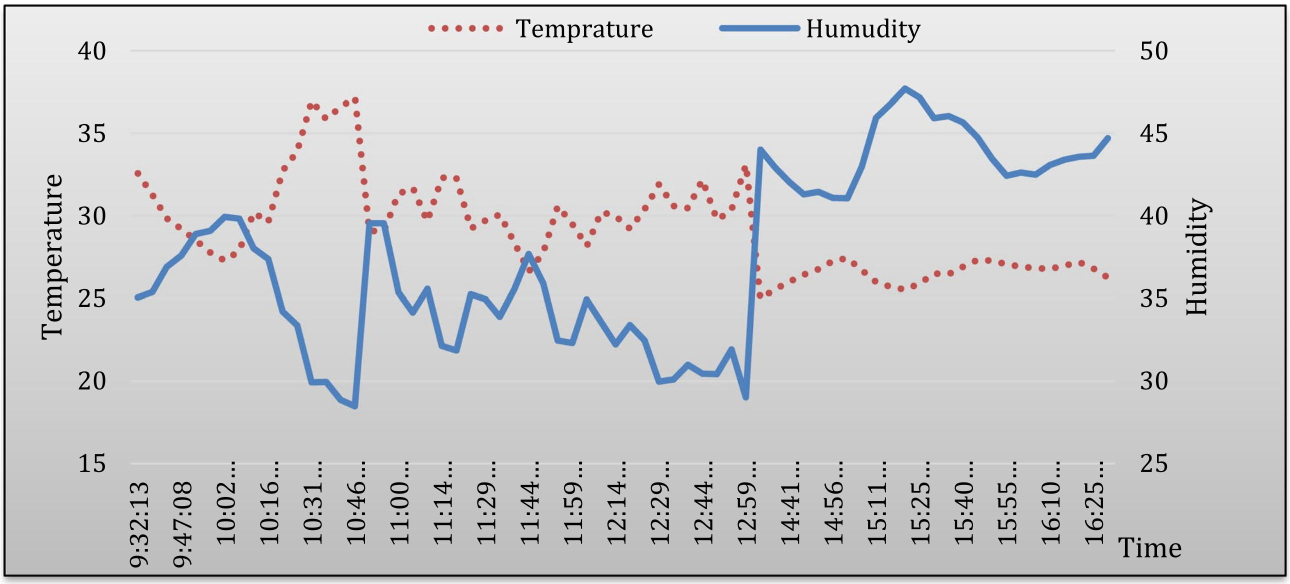


Fig. 6 The results of the experiment carried out on 06.15.2019

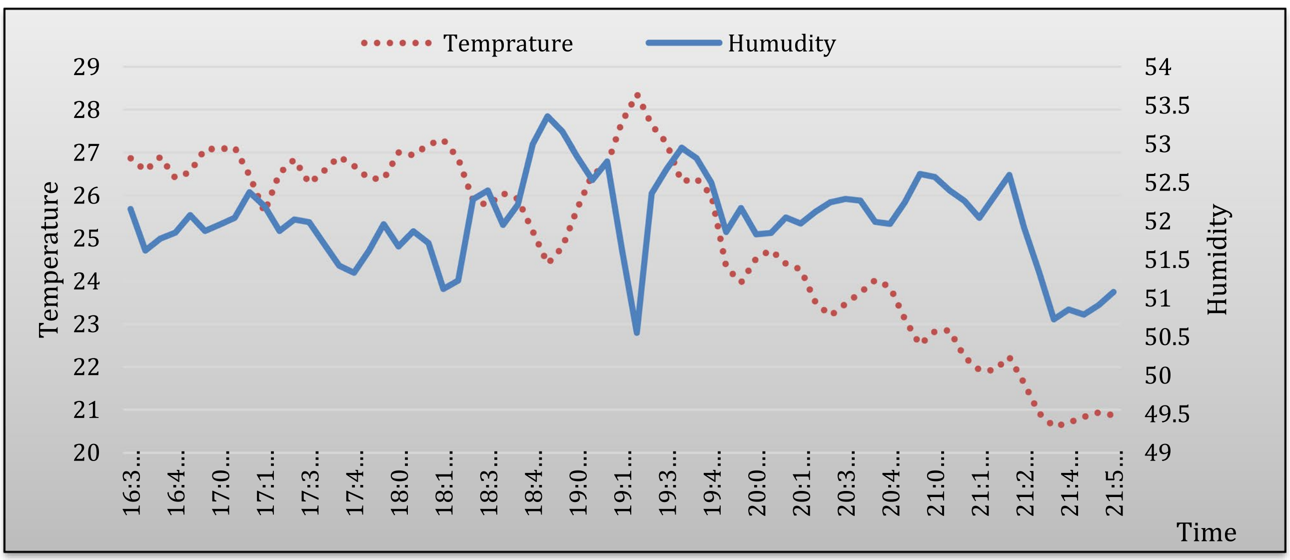


Fig. 7 Results of the experiment carried out on 06.16.2019

between 35 and 55% with SHT11 sensor. Temperature and humidity changes of the experiment are shown in Fig. 9.

In Fig. 10, the daily average humidity, temperature values, total salt consumed and total water produced daily are given comparatively. When Fig. 10 is examined, it is seen that the change of ambient humidity is more effective in the amount of water produced (Fig. 10).

The energy consumption amounts for the experiments performed on different days shown in Fig. 11 consist of two different components. These two components are given as the sum of the energy consumed by the fan and the energy consumed by the heater. In Fig. 12, the energy consumption amounts are given only based on the energy consumed by the heater. This is due to the fact that the power of the fan in the system is low, the operating time is long, and on the other hand, the electrical power of the heater is high and the operating time is low. During the experiments, the fan runs continuously and the heater is operated as long as necessary to evaporate the water at the end of the experiments. Therefore, when an average of 5 h of experiment is

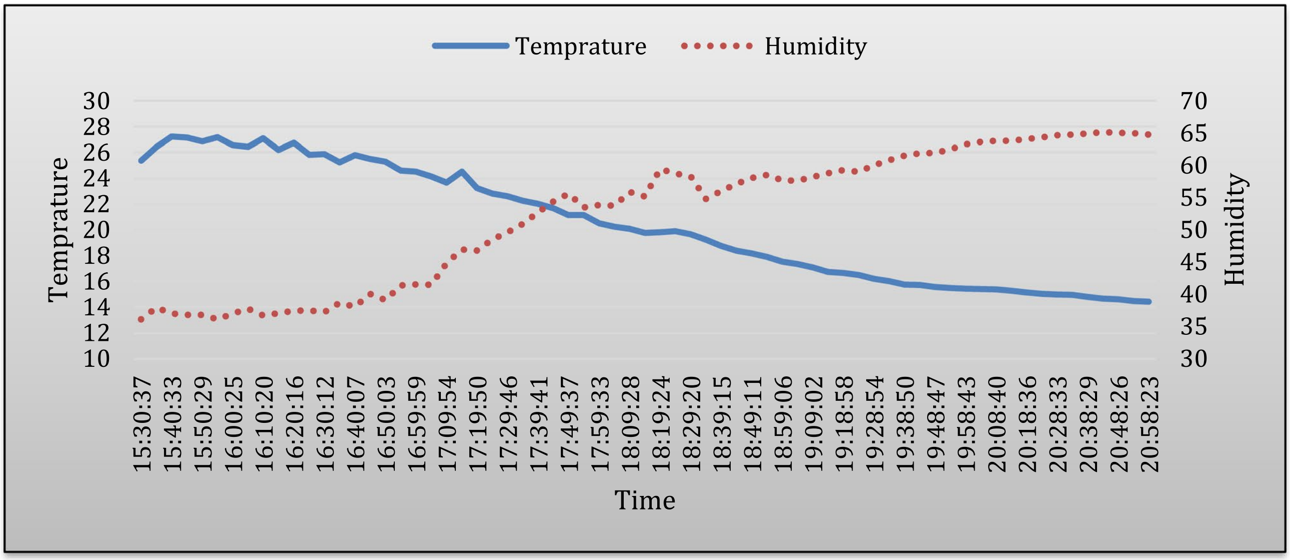


Fig. 8 Results of the experiment carried out on 10.31.2019

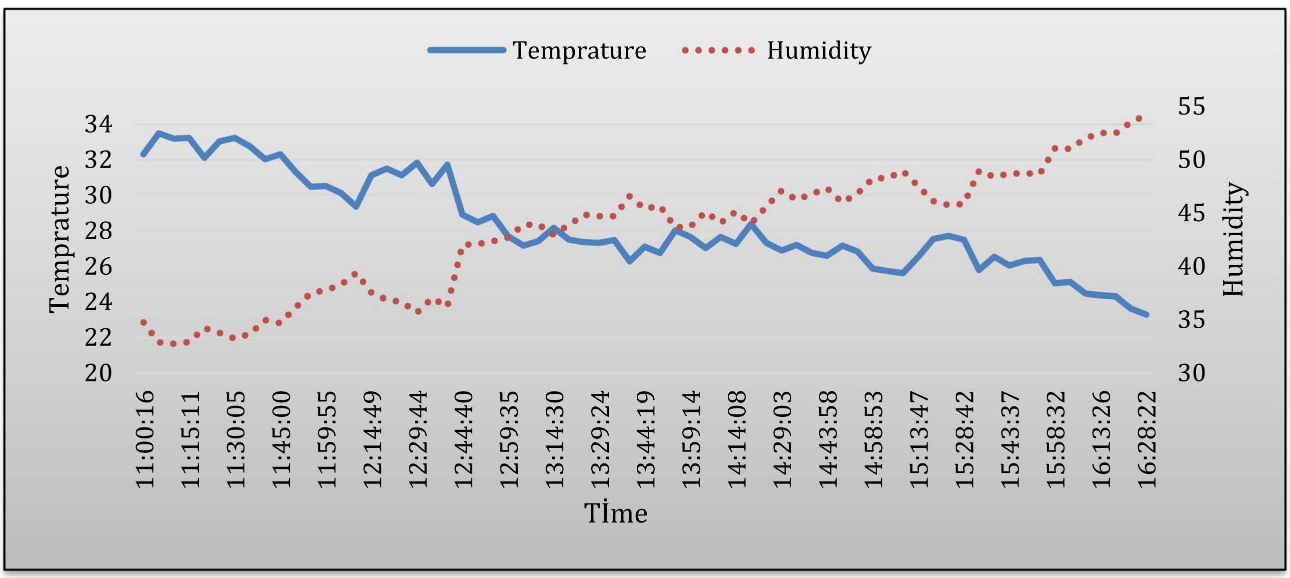


Fig. 9 Results of the experiment carried out on 11.04.2019

performed each day, the fan operating time and the amount of energy consumed remain the same, while the heater operating time and the amount of energy consumed vary. When the results given in Fig. 11 are examined, it is seen that the moisture value and the amount of water produced are related to each other. In the experiments conducted on 06.15.2019 and 11.04.2019, it is seen that the measured moisture content is approximately equal to each other. In the experiment on 06.15.2019, the fan speed was set to 100% and in the experiment on 11.04.2019, the fan speed was set to 50%. Thus, it is seen that the amount of water produced decreases by decreasing the fan speed. Figure 11 shows the amount of water produced, the amount of salt and energy consumed. It is seen in the graph in Fig. 11 that the energy consumed increases as the amount of water produced increases when it runs for an average of 5 h 35 min. The amount of salt consumed varies depending on the statue (open/close) of air humidity absorbing tank top cover during the experiment.

When the results given in Fig. 12 are examined; it is seen that the energy consumed by the heater and the amount of

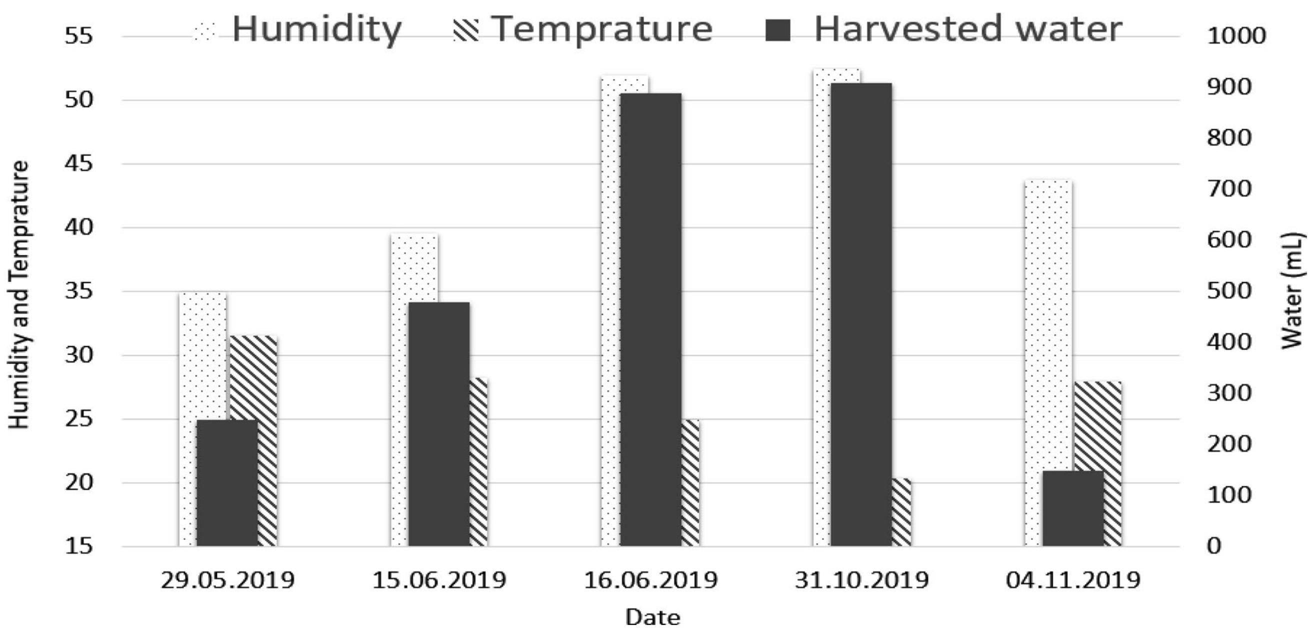


Fig. 10 Comparative representation of the parameters

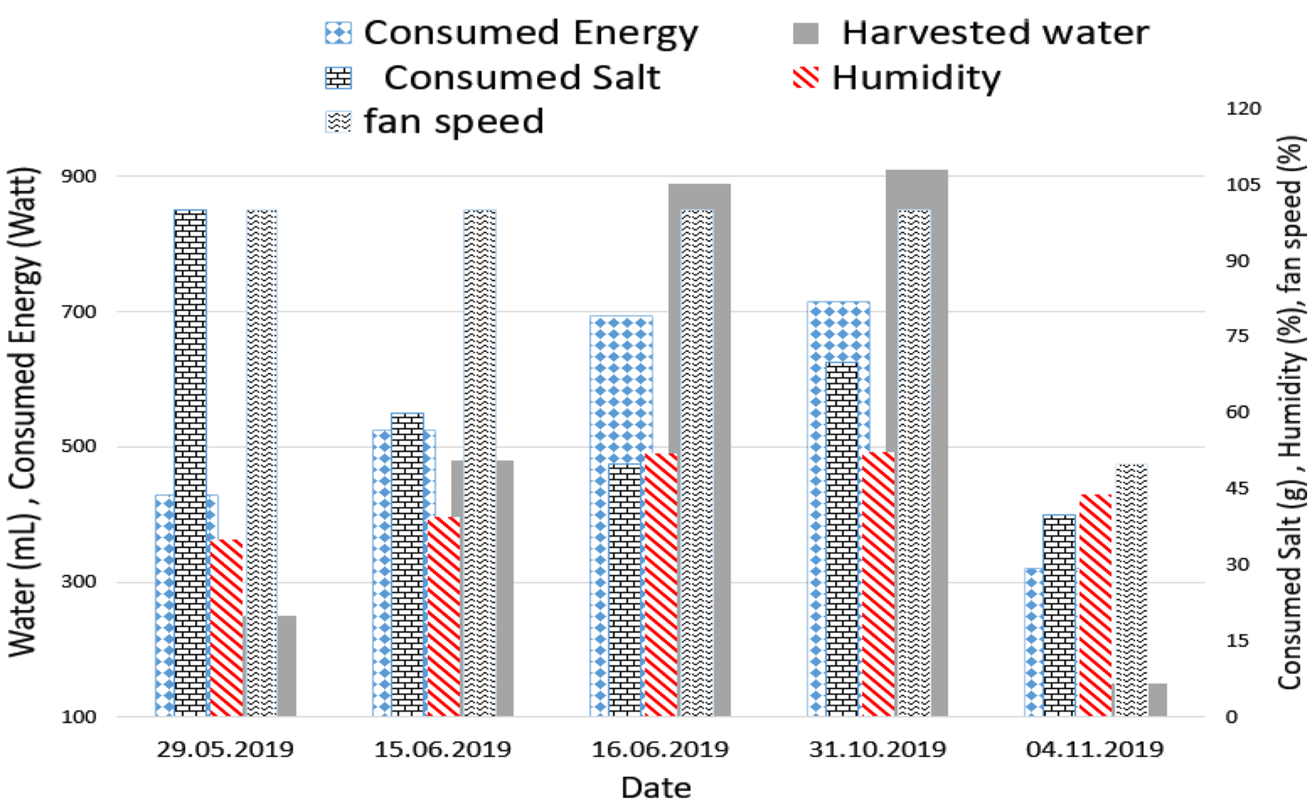


Fig. 11 Variation in the amount of water produced, the amount of salt and energy consumed for the system

water produced are directly proportional. As the moisture content increases, the amount of water produced increases. It is seen that the cost of water produced at low humidity values is high and the cost of water produced at high humidity values is low.

In this study, an automatic system that produces water from ambient humidity has been developed. As a result of

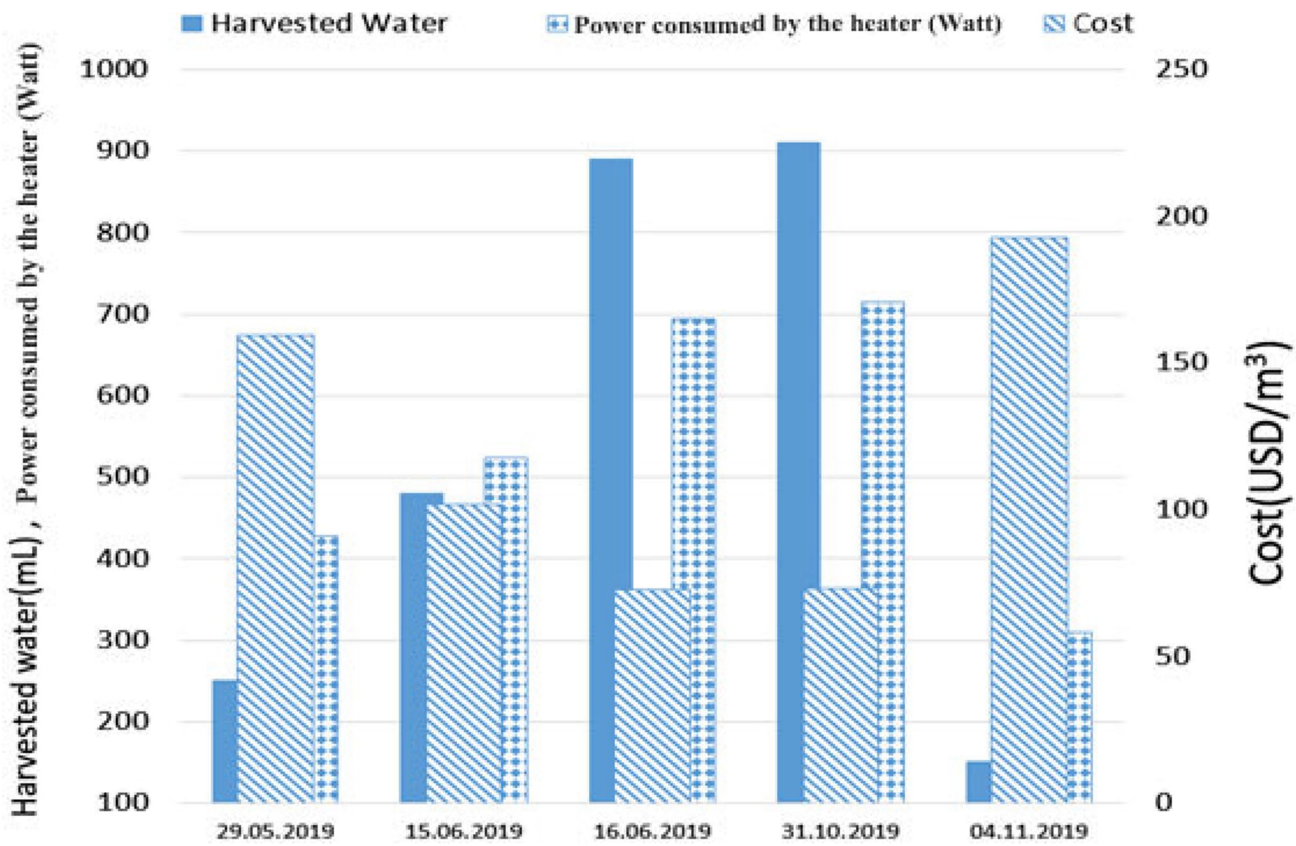


Fig. 12 Cost of water production

Table 2 Unit costs of drinking water obtained using different techniques

Application number	Application type	Feed water	Target quality	Cost (USD/m^3)
[23]	Reverse osmosis	peat water	Drinking water	0.30
[24]	Electrode ionization	Well water	Boiler feed water	0.53
[25]	Reverse osmosis	Sea water	Drinking water	0.527
[26]	Low-pressure reverse osmosis	Sea water	Drinking water	0.116
[27]	Atmospheric water generator (AWG) by using a compressor and coolant	Air humidity	Drinking water	317
Our study	Atmospheric water generator by using $CaCl_2$ (Calcium Chloride) salt	Air humidity	Drinking water	73

the experiments, clean and potable water was obtained by absorbing the ambient moisture with $CaCl_2$ (salt). It was observed that the amount of water obtained in the experiments with high ambient humidity was higher and the amount of water produced decreased with the decrease in ambient humidity. The yield of the salt depends on the relative humidity of the environment, the contact area of air and salt, the saturation rate, the flow and pressure of the air.

Potable water production studies given in Table 2 were obtained from fresh/salt water source by reverse osmosis, electrode ionization, low-pressure reverse osmosis methods and atmospheric water generator (AWG) by using ambient moisture as source. In order to compare the unit cost of the water produced by the method used in this study and the unit cost of the water produced in similar studies, the values in Fig. 12 and Table 2 were used. It is seen that in Fig. 12, the lowest unit cost of potable water produced as a result of experiments carried out on different dates is approximately 73 USD/m^3, while in Table 2, the unit cost of potable water produced by using atmospheric water generator method (AWG) is 317 USD/m^3. With the system developed in the study, a very economical unit has been developed compared to the existing system in the literature.

Conclusion

Drinking water supplies are rapidly decreasing in the world. According to the JMP report by WHO and UNICEF, access to clean and potable water resources is decreasing with each passing year. For example, it is understood from WHO reports that in 2025, approximately half of the world's population will experience water shortages. In places where access to clean and potable water resources are difficult or impossible, therefore, studies are being carried out worldwide in order to prevent the factors threatening human health. For this reason, the production of clean and potable water is more important today.

Figures 11 and 12 are to be considered together for approximate equal amounts of moisture (06.15.2019–11.04.2019); it is seen that the fan speed and the amount of water produced are directly proportional, the fan speed and the unit cost of the produced water are inversely proportional. If the fan speed is reduced for equal humidity values, the amount of water produced decreases and the unit cost of the produced water increases. The unit cost of the water produced by the method used in this study was found to be approximately four times less than the unit cost of the water produced by similar methods in the literature.

As can be seen, using the current technology, the energy requirement of atmospheric moisture collection by direct air cooling is significantly higher than the desalination process by reverse osmosis.

In future academic studies; instead of using a fixed unit as the salt unit and collecting the ambient humidity from a single surface, it is thought that an increase in the amount of water produced can be achieved by taking the humidity from more than one point with a rotary unit.

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Declarations

Conflict of interest The authors declare that we have no conflict of interest.

Ethical Standards For this type of study formal consent is not required.

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