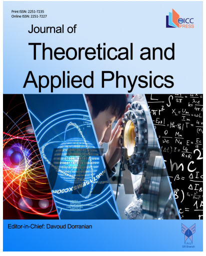

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Modification of painted steel surfaces in different thicknesses by cold plasma to increase extraction of water from the air

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Original Research

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Abstract:

In recent years, extracting water from the air in hot and humid areas has been studied as a clean and optimal way to supply fresh water. In this research, painted steel surfaces were modified by vacuum plasma, and hydrophilic and hydrophobic grooves were made on them in millimeter scale. Then, by building a steam reactor, the parts were tested to extract water from the air and it was observed that modifying the surfaces increases the amount of water produced several times. Next, the optimal thickness of the paint on the steels was determined.

Keywords: Extraction of water from air; Hydrophilic and hydrophobic; Vacuum plasma

1. Introduction

Given the recent water crisis, finding new, efficient, and economical solutions is essential for preserving the environment and sustaining life. In recent years, atmospheric water harvesting in warm and humid regions has been studied as a clean and efficient method for providing fresh water. This method does not cause pollution and environmental destruction, unlike traditional methods such as using nets, reservoirs, and stones to collect rain and dew [1].

Currently, according to the World Health Organization, each person on earth uses about 50 liters of water daily to meet basic needs such as drinking, food preparation, and hygiene. Scientists estimate that 4 billion people - more than half the world's population - do not have enough water for at least one month a year, and 500 million people are expected to reach this figure by 2050, with changes in climate and population growth [2]. Scientists and engineers are looking for a solution to the water scarcity problem. One of the water sources that they are interested in is atmospheric moisture, which even exists in deserts, thus providing the possibility of helping water-scarce communities anywhere. Therefore, they have been busy building various artificial devices and mimicking nature to collect moisture from the air [3].

In this study, the aim is to provide a novel and efficient method for atmospheric water harvesting in humid regions using plasma technology to create water-loving and water-repellent grooved surfaces, without causing harm to the environment.

Plasma is composed of neutral and charged particles that are created between two electrodes, with electrons moving from the anode to the cathode. The speed and acceleration of these electrons and ions depend on several parameters, which are introduced below [4].

- By reducing the pressure inside the plasma chamber, fewer particles collide with electrons, resulting in greater electron acceleration.
- Increasing the power results in greater speed and acceleration of electrons.

The gas used in plasma is another parameter that affects the

Figure 1. Layout of the used vacuum device.

speed and acceleration of ions because lighter gases move faster when they are converted to ions with greater speed between the two electrodes.

2. Experimental setup

Initially, 1 mm stainless steel sheets were cut into rectangular shapes with dimensions of 7×2.5 cm and cleaned with alcohol to remove any dust, stains, and grease. After preparing the samples, they were modified using atmospheric DC pulse gliding arc plasma device, and then colored. Subsequently, the pieces were colored step by step using a spray. The thickness of the paint was measured using a YOKSA EC100 thickness gauge and categorized in thicknesses between 30 micrometers to 450 micrometers.

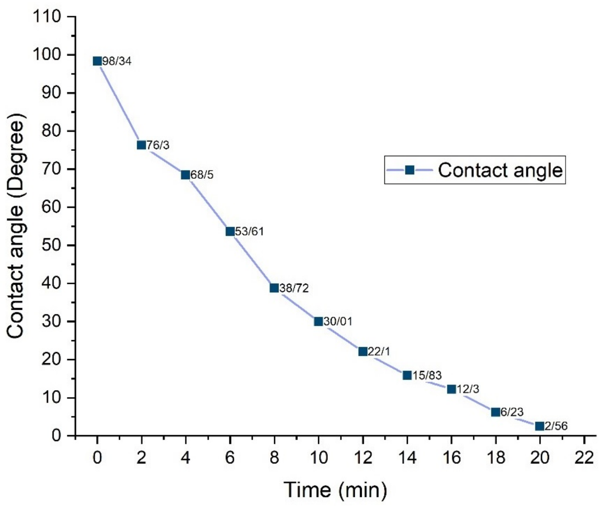

Figure 2. Comparison of the effect of different times of applying oxygen plasma on the contact angle of water with the steel surface.

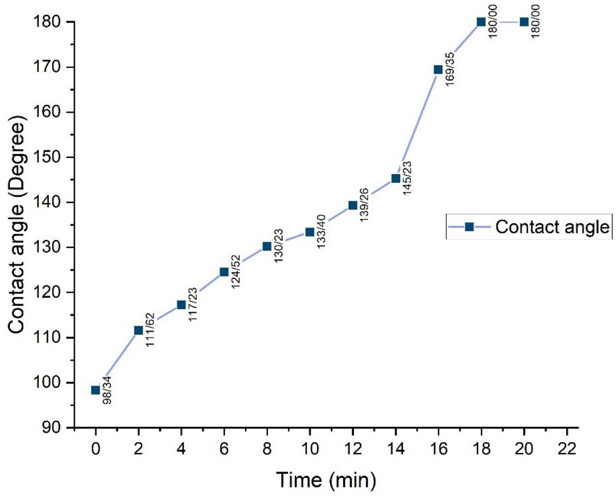

Figure 3. Comparison of the effect of different times of HMDSO plasma application on the contact angle of water with the steel surface.

In this study, the surface of the parts was modified and hydrophilic using a DC Pulse vacuum plasma device. Initially, by injecting argon gas into the vacuum device, the surface of the samples was activated to increase surface roughness. Then, by injecting oxygen gas into the vacuum device, oxygen groups were formed on the surface of the samples, making them hydrophilic.

To achieve hydrophobic surfaces, HMDSO was injected into the plasma device. The following plasma conditions were used to achieve hydrophobic and hydrophilic surface:

- The pressure inside the vacuum chamber was set to 0.1 mbar.
- The DC Pulse power supply with a power of 100 W, a frequency of 8 kHz, and a duty cycle of 8% was used.
- Argon gas was used to activate the surface.
- Oxygen gas was used to make the surface hydrophilic.
- HMDSO was injected into the plasma device to achieve hydrophobic surface.

To check the hydrophilicity of the surface modified by oxygen plasma, the contact angle of the water on the surface of the painted steel piece modified by oxygen plasma was measured by CCD camera and ImageJ software. 10 pieces of painted steel were subjected to vacuum oxygen plasma treatment for 2 – 4 – 6 – 8 – 10 – 12 – 14 – 16 – 18 – 20 minutes and the contact angle of water with their surface was measured, the results of which are shown in Fig 2.

Figure 4. Grooved painted steel piece.

Figure 5. Dew formation test set-up.

According to Fig. 2, it can be seen that after 20 minutes, the surface of the painted steel piece becomes hydrophilic to a completely acceptable level. As a result, in this research, the optimal time of applying oxygen plasma is 20 minutes. To check the hydrophobicity of the surface modified by HMDSO plasma, the contact angle of water on the surface of the painted steel piece modified by HMDSO plasma was analyzed by CCD camera and Image J software. During 2 – 4 – 6 – 8 – 10 – 12 – 14 – 16 – 18 – 20 times, 10 steel pieces were subjected to vacuum under HMDSO plasma treatment and the contact angle of water with their surface was measured, the results of which are shown in Fig. 3.
According to Fig. 3, it was observed that after 18 minutes of HMDSO plasma treatment under vacuum, the surface becomes super hydrophobic, therefore, the optimal time of applying HMDSO plasma to the steel surface in this study was considered to be 18 minutes.
To create hydrophilic grooves on hydrophobic samples, grooved masks with 1 mm grooves were prepared from 1 mm thick Plexiglas sheets with dimensions of 4 × 8 cm. The masks were glued onto the hydrophilic samples and then placed back into the vacuum chamber to make the grooves hydrophobic.

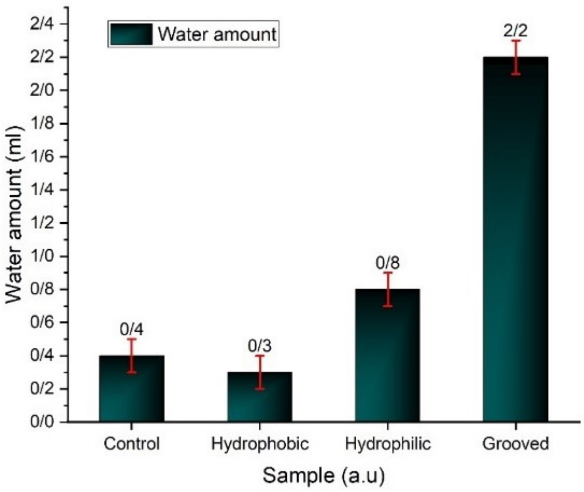

Figure 6. Comparison of the water production rate of control, hydrophilic, hydrophobic and grooved pieces.

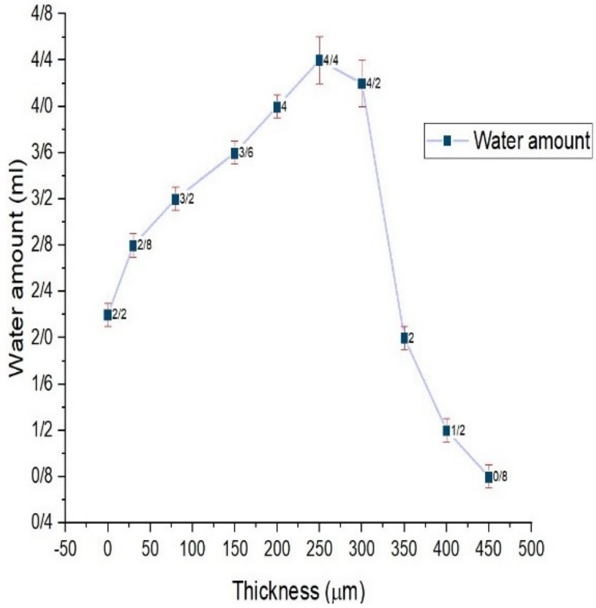

Figure 7. Comparison of the effect of different paint thicknesses on the amount of water produced.

Subsequently, a water vapor reactor was constructed using two fully waterproof plastic containers to simulate a saturated moisture environment, and dew formation on the stainless steel samples, as shown in Figure 5.
Five liters of 90° C water were poured into the first container, both containers were sealed, and the fan and the transformer were turned on until the water vapor reached 80° C and 80% humidity in the second container. Then, a petri dish was placed on a stand inside the second container, and the sample was placed on it at a 45-degree angle to the horizontal plane. This caused the droplets formed on the heated sample to roll down and collect in the petri dish, thus facilitating the measurement of dew formation. After the experiment was completed, the petri dish and the stainless steel sample were removed from the vapor container, and the collected water in the petri dish was measured using a syringe with an accuracy of 0.1 milliliters.

3. Results and discussion

To investigate the effect of hydrophobic and hydrophilic grooves on the amount of produced water, the experimental setup shown in Figure 3 was used. The colored stainless steel samples were placed on a holder inside a petri dish, and control, hydrophobic, hydrophilic, and grooved samples were tested, and the amount of water produced was recorded after 30 minutes. The comparison of these values is shown in Fig. 6.
According to the results, it was found that grooved samples significantly increased the amount of produced water. Completely hydrophobic samples had very low water production due to the lack of water absorption, and completely hydrophilic samples only slightly increased the amount of produced water.
To determine the optimal thickness of the paint on the samples, the experiment was repeated for different paint thick-

nesses between 30 to 450 μm for one hour, and the results were analysed in Fig. 7. As shown in the figure, the amount of produced water increased as the thickness of the paint increased until reaching the optimal thickness of 250 μm. Beyond this thickness, the trend was reversed, and the amount of produced water decreased. The experiments conducted with samples with a thickness greater than 250 μm showed that the paint on the upper layers melted due to lower adhesion compared to the underlying layers, caused by exposure to hot air and the accumulation of hot water in the hydrophilic grooves.

It can be concluded that if the paint on the sample is more than 250 μm thick, the upper layers of the paint will melt due to lower adhesion, and the water production will decrease as a result.

Furthermore, to investigate the suitability of this experiment for use in industrial desalination processes, an electrical conductivity test was performed on the produced water. Initially, 180 grams of salt were dissolved in 5 litters of boiling water in the first container, and the optimal stainless steel sample was tested. Then, the electrical conductivity of the saline water in the first container and the produced water from the modified stainless steel samples were measured using an electrical conductivity measuring device. It was observed that the electrical conductivity of the saline water was 73.55 mS, while the produced water from the grooved samples had an electrical conductivity of 0.4 mS. These numbers indicate that the produced water from the grooved samples has been desalinated.

4. Conclusion

Based on the data obtained from this study, it can be concluded that by creating hydrophilic and hydrophobic grooved stainless steel surfaces and exposing them to water vapor in a high humidity chamber or environment, it is possible to produce fresh water, and the amount of water produced is higher compared to the unmodified stainless steel piece. Furthermore, it was observed that with an increase in the thickness of the color coating on the stainless steel surface, the water production rate increased, reaching its optimum level at a thickness of 250 μm. At higher thicknesses, the color coating on the piece is prone to cracking when exposed to water vapor, resulting in zero water production.

Ethical approval
This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Authors Contributions
Shadi Sabzevari: conception, setup design, experiment, data analysis, draft writing and finalizing the paper; Mohammad Hossein Mohajer: experiment and data analysis; Motahare Monfaredi: experiment; Mohammad Sajad Nikouei Fard: experiment and Hamid Reza Qomi: conception, setup design and finalizing the paper.

Availability of data and materials
Data presented in the manuscript are available via request.

Conflict of Interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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