Article

Low-Energy-Consumption Wastewater Evaporation Using Single-Electrode High-Voltage Electric Field Enhancement

Haiting Liu, Zhiming Xu * and Junqi Zhang

School of Energy and Power Engineering, Northeast Electric Power University, Jilin 132012, China; lhtnedu@163.com (H.L.); spjunqizhang@163.com (J.Z.)
* Correspondence: xuzm@neepu.edu.cn

Abstract: High energy consumption is a pressing issue in the development of wastewater evaporation technologies. In this paper, a low-energy-consumption approach utilizing single-electrode high-voltage electric field-enhanced evaporation is proposed. Experimental studies were conducted on the evaporation process of adhered liquid droplets in a single-electrode high-voltage electric field environment. The influence of the electric field on the liquid surface morphology and evaporation modes was analyzed, and the effects of droplet salt concentration, ambient temperature, and voltage on droplet evaporation were investigated. The results indicate that the evaporation enhancement effect of a high-voltage single electrode on droplets mainly occurs when the gas–liquid interface of droplets is unstable. At a voltage of 8 kV, evaporation occurs on the droplet surface, reducing the evaporation time by 5.3% compared to no-electric-field conditions. Furthermore, the effect of the single-electrode high-voltage electric field on droplet evaporation weakens with increasing temperature and salt concentration.

Keywords: single-electrode high voltage; droplet evaporation; enhanced evaporation; non-uniform electric field; charged droplets

1. Introduction

Water pollution is an important environmental protection problem in the world at present, which is also the main reason for the shortage of fresh water resources. Currently, there are over 1 billion people living in water-scarce areas globally, and by 2025, up to 3.5 billion people will face water scarcity [1]. This highlights the increasingly severe global water shortage situation, and extracting usable water from wastewater is an important approach to addressing this issue. At present, there are many kinds of common wastewater treatment processes, as shown in Table 1. Among them, wastewater evaporation treatment technology is one of the most common wastewater treatment methods [2–4]. Compared with other wastewater treatment technologies, wastewater evaporation can improve the stability of the system, but high energy consumption is the key to limiting the development of wastewater evaporation technology.

In 1976, Japanese scholar ASAKAWA [5] discovered that the application of an external electric field can enhance the evaporation of water, increasing its efficiency by up to 1.5 times, a phenomenon known as the “Asakawa effect”. Since no direct current circuit is formed in this process, the energy consumption required to maintain the electric field is very low. Therefore, electric field-induced evaporation technology is a feasible approach to address the issue of high energy consumption in evaporation. However, in an electric field environment, the evaporation process of salt-containing solutions is a complex multi-physical field coupling process [6,7]. Investigating the mechanism of electric field-induced evaporation of salt-containing solutions is crucial for solving the high-energy-consumption problem in the evaporation of high-salinity wastewater. Some scholars [8–12] have characterized the relationship between evaporation rate and solid–liquid contact angle using...
They discovered the capillary effect during droplet evaporation, and their research indicates that under the influence of an electric field, the charge distribution between the liquid and the gas interfaces of droplets changes, leading to variations in the solid–liquid contact angle and surface tension. Roero [13] found that the solid–liquid contact angle decreases with increasing electric field intensity during the evaporation of charged droplets. Furthermore, under the application of an external electric field, droplets undergo morphological changes and exhibit instability phenomena. Takano [14] compared the experimental results of droplet evaporation with and without an electric field and found that electric field forces have a strong promoting effect on droplet evaporation and induce instability in the droplets. Additionally, for non-polar droplets, the enhancement effect of electric field forces on droplet evaporation is not significant due to the longer charge relaxation time of non-polar droplets. However, non-polar droplets still exhibit instability phenomena under the influence of an electric field. Wang [15] conducted experimental research on high-pressure electrostatic field-assisted multi-effect evaporation of gas–liquid contacts. The results showed that the system concentration rate increases with the increase in initial water temperature and voltage intensity. Compared to other thermal concentration techniques, the energy consumption is only 8.8 kW·h/t, which can save approximately 50% of the energy consumption compared to other energy-saving high-salinity water treatment technologies. It also reduces energy consumption by 16% compared to conventional multi-effect evaporation technology. Li et al. [16] conducted a study on the electrical wetting behavior of different types of fluid droplets and found that the degree of electrical wetting varies with the type of liquid. They demonstrated that the reverse electrical wetting phenomenon can be achieved by reversing the electrodes, thereby controlling the contact angle of the droplets. Eow [17] conducted experimental research on pure water droplets in a parallel electric field and found that the deformation of the droplets in the parallel electric field is influenced by factors such as conductivity, interfacial tension, and density. Zhang [18] used molecular dynamics simulation to study the statics and dynamics of nanoscale water droplet wetting on nanostructured surfaces under the influence of a vertical electric field. The results showed that the electric field induces electric stretching, electrical wetting, modified solid–liquid interfacial tension, and triple-line pinning of the nanoscale droplets, which collectively affect the spreading index and static contact angle of the nanoscale droplets.

Table 1. Common wastewater treatment processes and existing problems.

<table>
<thead>
<tr>
<th>Common Process</th>
<th>Main Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration process of high-salt wastewater by membrane filtration</td>
<td>It is not suitable to deal with situations of complex water quality; the membrane is easy to foul; the operation reliability of the system is poor; and the investment cost is expensive, so it can only achieve wastewater concentration and cannot achieve the zero-discharge process alone.</td>
</tr>
<tr>
<td>DT-RO membrane filtration concentration process</td>
<td></td>
</tr>
<tr>
<td>Electrodialysis membrane filtration and concentration process</td>
<td></td>
</tr>
<tr>
<td>(Positive osmosis) heat-source evaporation–crystallization process</td>
<td>The membrane is easy to foul; the operation reliability of the system is poor; the investment cost is high; the heat source needs to be consumed; and the energy consumption is high.</td>
</tr>
<tr>
<td>(Membrane concentration) heat-source evaporation–crystallization process</td>
<td></td>
</tr>
<tr>
<td>Multi-effect evaporation process of heat-source steam</td>
<td>The equipment is easy to scale and block; it produces solid waste; it is inconvenient to deal with; it has a high operating cost; it requires a high equipment investment; and the energy consumption is high.</td>
</tr>
</tbody>
</table>

In this study, it was found that the high-voltage static electric field generated by a single electrode has a certain enhancing effect on droplet evaporation. This phenomenon has been rarely reported, as most related research focuses on the morphological changes in droplet evaporation in electric field environments formed by dual electrodes, and dual electrodes are prone to corona in high-voltage environments, resulting in direct charge
In this study, it was found that the high-voltage static electric field generated by a single-electrode high-voltage environment is highly valuable for achieving low-energy treatment of wastewater.

2. Experimental System

The experimental system for droplet evaporation is shown in Figure 1. The system consists of a thermostatic chamber, needle-shaped electrode, electronic balance (with an accuracy of 0.0001 g), electronic microscope (YW500), and monitoring server. The thermostatic chamber is used to control the environmental temperature for droplet evaporation. To avoid the influence of the temperature and humidity inside the thermostatic chamber on the accuracy of the electronic balance, the electronic balance is placed outside the thermostatic chamber. The change in droplet mass is measured using the suspended platform at the bottom of the electronic balance. The stainless steel substrate (liquid surface) on the suspended platform is coated with a hydrophobic layer. The electronic microscope is used to observe and record the real-time morphological changes in the droplets.

Figure 1. Droplet evaporation experiment system.

During the experiment, the liquid droplet on the substrate is positioned directly below the needle-shaped electrode, which is connected to a high-voltage DC power supply. The initial relative humidity inside the thermostatic chamber is controlled at 30–33%. The droplet volume is 10 µL, and the distance between the needle-shaped electrode and the liquid surface is 5 mm. The thermostatic chamber temperature is first set, and once the temperature inside the chamber stabilizes, a 10 µL droplet is quickly dispensed onto the substrate using a pipette. Then, the power supply is turned on. During the experiment, the electronic balance above the thermostatic chamber continuously measures the readings. The real-time morphological changes in the liquid surface are captured using an electronic microscope. MATLAB is used to extract the contour feature data of the liquid surface at different time points. The current value of the DC power supply is recorded during the experiment, and in this case, the current value is 0, indicating that no breakdown or current circuit is formed between the electrode and the liquid surface. Since the focus of this study is to investigate the effect of a single electrode under high-voltage DC conditions on the evaporation process of the liquid droplet, the substrate carrying the droplet is not grounded.
When the single electrode is energized, the electric field is distributed in a spherical shape centered on the electrode. Due to the absence of a grounded electrode, a higher voltage is required to affect the mass transfer process on the liquid droplet surface.

3. Discussion of Experimental Results

3.1. Effect of Voltage Variation on Liquid Surface Morphology

During the experiments, it was found that when a single electrode is connected to an HVDC power supply, the droplet evaporation time becomes shorter. At the same time, when the voltage reaches a certain value, the liquid surface deforms to a certain extent. The continuous morphological changes in the liquid surface can induce mass transfer at the gas–liquid interface, and the fluctuation of the liquid surface area is directly caused by the morphological changes. Figure 2 shows the morphological changes in the droplet during the application of an electric field. The temperature inside the thermostatic chamber is set at 25 °C. From 0 s to 2 s, the voltage is increased from 0 kV to 8 kV. The results show that when the voltage rises to 4 kV, the top of the liquid surface moves closer to the needle electrode, the contact angle decreases, and the droplet tends to be conical. The current droplet is in a stretched state, but there is no continuous change in the shape of the liquid surface. It is not until the voltage is raised to 8 kV that the liquid surface begins to become unstable, showing deformation and up-and-down vibration. At the 3 s mark in Figure 2, the voltage has already risen to 8 kV, and the droplet’s vibration becomes more intense. This intense vibration process weakens significantly after about a minute.

![Figure 2. Deformation of pure water droplet after electric field is applied.](image)

When the surface of a droplet vibrates up and down, the area of the gas–liquid interface fluctuates. At the same time, this vibration phenomenon can also accelerate the flow rate of the liquid surface, which may affect the efficiency of droplet evaporation. In order to further analyze the cause of the instability of the liquid surface induced by the electric field, we analyze it in conjunction with the force acting on the droplet. When the electric field intensity is large, the droplet undergoes polarization, resulting in a change in the distribution of the internal charges. Figure 3 shows the internal charge distribution of the polarized droplet. The electrohydrodynamic (EHD) force [20] acting on the droplet can be described as follows:

$$ F_e = qE - \frac{1}{2} \rho \frac{\partial E}{\partial T} $$

where \( q \) is the free charge density, \( E \) is the electric field intensity, \( \epsilon \) is the dielectric constant, \( \rho \) is the density of the droplet, and \( T \) is the temperature. The first term represents the Coulomb force caused by free charges, which is the interaction of free charges in the conducting fluid under the action of the electric field. Under the influence of a positively charged needle electrode, negative charges concentrate on the upper surface of the droplet, resulting in a negative charge on the upper surface of the droplet. In this case, the droplet surface is distributed with a large amount of charge, and the free charge density cannot be ignored. Therefore, the Coulomb force plays a dominant role in the electric field force, and its direction is from the droplet to the needle electrode. The second term is the dielectrophoretic force caused by the difference in dielectric constant. Under the action of a non-uniform electric field, the charged droplet tends to move towards the region of lower electric field intensity, indicating that the direction of the dielectrophoretic force is opposite
to that of the Coulomb force. The third term represents the electrostriction force, which is caused by the spatial inhomogeneity of the electric field intensity and dielectric constant. In addition to the above-mentioned EHD force, there is surface tension on the liquid surface. When the voltage is low, the generated field strength is small, and the current environment is a single electrode without an effective current loop, so the free charges generated by the electrode struggle to migrate to the surface of the liquid droplet, and the EHD force on the liquid droplet will not change. At this time, the droplet is in a relatively static equilibrium state. When the voltage increases, the EHD force increases, breaking the balance with the surface tension, causing the droplet to stretch, and increasing the surface charge of the droplet. When the charge reaches its maximum value, the change in electric field strength between the droplet and the electrode is small, causing the vibration to weaken. This phenomenon has been reported in [21]. In this paper, the process of this phenomenon is used to explain the effect of the electric field on the evaporation of droplets. Therefore, the detailed mechanism of the electric field’s effect on the liquid surface is only briefly described. In addition, because the liquid-carrying substrate is an insulating material, the high-voltage electrode is not in contact with the droplet, so it can be considered that the thermal effect of the electric field on the droplet in the current environment is negligible.

Figure 3. Charge distribution of base droplet in electric field.

In order to reflect the repeatability of the experiment in this paper, repeated experiments were carried out for each group of working conditions five times, and experimental errors were obtained through these repeated experimental data.

The amplitude and frequency of droplet oscillations within 30 s were measured and are depicted in Figure 4. The oscillation amplitude is defined as the difference in height (Δx) between the top of the droplet and the substrate at the extreme positions during the oscillation process. Combining Figures 2 and 4a, the results indicate that at 4 kV voltage, the droplet does not oscillate. However, the droplet height increases and the contact angle decreases at this current voltage value; the liquid surface is polarized, but there is no instability of the gas–liquid interface of the droplets. When the voltage reaches 6 kV, intermittent oscillations become evident. Within the first 10 s, the oscillation amplitude of the droplet’s upper-surface center point fluctuates between 0.11 and 0.32 mm. Afterward, the amplitude starts to decay. At 8 kV voltage, the droplet oscillations become more intense. Within the first 10 s, the oscillation amplitude ranges from 0.39 to 0.72 mm. After that, the amplitude begins to decay and almost stops after 1 min. This shows that when the voltage value is higher, the amplitude of droplet vibration is greater and the phenomenon of droplet instability becomes more obvious, which can also promote the escape of water at the gas–liquid boundary surface. Figure 4b shows the droplet’s oscillation frequency curves at different voltages (the oscillation frequency is the number of droplet oscillations reaching the extreme positions per second, calculated within a 2 s interval). The results indicate that in the first 12 s, the vibration frequency fluctuates significantly when the voltage is 8 kV, and the extreme value of the frequency fluctuation is close to that of 6 kV. However, after 12 s, the vibration frequency value of 6 kV is significantly higher than that of 8 kV, indicating that when gas–liquid interface instability occurs, higher voltage values
lead to more significant vibration frequency attenuation and a shorter time is required for the droplet to stabilize in the later stages.

![Amplitude and frequency of droplet in electric field.](image)

**Figure 4.** Amplitude and frequency of droplet in electric field.

### 3.2. Effect of Voltage Variation on the Evaporation Mode of Wall Droplets

The evaporation process of liquid droplets on a wall surface can generally be divided into three modes: Constant Contact Radius (CCR) mode, Constant Contact Angle (CCA) mode, and Slippy-Slidy (SS) mode [22–24]. In order to study the effect of an electric field on the evaporation mode of wall surface droplets, the spreading radius and contact angle of pure water droplets and a 5% KCl solution were investigated under different voltage values. The temperature was set at 25 °C, and the evaporation process of droplets was experimentally observed under no-electric-field conditions as well as under the application of 4 kV and 8 kV voltages. The experimental results are shown in Figures 5 and 6. The results indicate that the evaporation process of the droplets studied in this paper includes the three modes mentioned, with each stage corresponding to a specific evaporation mode. Among them, the CCA stage occupies approximately half of the entire evaporation time, followed by the CCR stage, which is slightly longer than the SS stage. As the voltage intensity increases, the spreading radius of the droplets increases while the solid–liquid contact angle decreases. However, the change in voltage does not affect the rate of contact angle decrease in the CCR stage or the rate of spreading radius reduction in the CCA stage. The positive charge on the needle tip attracts the negative charge on the gas–liquid interface, causing the droplet to have an upward trend and form a conical shape, resulting in a decrease in the contact angle. In addition, the CCA stage of both the pure water droplets and the KCl solution occurs earlier with increasing voltage intensity, thereby reducing the duration of the CCR stage.

In order to study the differences in the evaporation times of droplets in an electric field environment with different salt concentrations, this section compares the survival times of pure water (0% KCl), 5% KCl, and 10% KCl droplets. The volume of the experimental droplets is 10 µL, and the results are shown in Figures 7 and 8. The results show that the higher the concentration, the longer the survival time of the droplets and the longer the required evaporation time. Combined with the analysis results included in Section 3.1, it is found that when the droplets vibrate in an electric field, the enhancement of evaporation by the electric field is more significant. The average evaporation time of pure water droplets under natural evaporation conditions is about 2640 s, and the evaporation time decreases with increasing voltage. When a voltage of 8 kV is applied, the average evaporation time of the droplets is about 2500 s, with an increase in evaporation efficiency of about 5.3%. The evaporation time of 5% concentration KCl solution droplets under natural evaporation conditions is 2820 s, and under an 8 kV electric field intensity, it is 2700 s, representing an
increase of about 4.3%. The average evaporation time of 10% concentration KCl solution droplets under natural evaporation conditions is 3000 s, and under an 8 kV electric field intensity, it is 2880 s, representing an increase of about 4%. It can be seen that as the salt concentration increases, the promotion effect of the electric field on evaporation weakens, suggesting that the evaporation process of a salt solution is a process that involves increasing the solute concentration. Therefore, as the evaporation progresses, the phenomenon of enhanced evaporation by the electric field will weaken or even disappear. The main reason for this phenomenon is that when the concentration of salt solution is high, the water is more constrained by the surface tension when it escapes the gas–liquid interface. At the same time, according to Coulomb’s law, the charge of charged ions in a salt solution is much higher than that of water molecules. The effect of an electric field on charged ions in a salt solution is stronger than that of water molecules, thus weakening the power of water migration from the droplet to the gas–liquid interface.

Figure 5. Spreading radius and contact angle of pure water droplets.

Figure 6. Spreading radius and contact angle of 5% KCl droplet.
process that involves increasing the solute concentration. Therefore, as the evaporation progresses, the phenomenon of enhanced evaporation by the electric field will weaken or even disappear. The main reason for this phenomenon is that when the concentration of salt solution is high, the water is more constrained by the surface tension when it escapes the gas–liquid interface. At the same time, according to Coulomb’s law, the charge of charged ions in a salt solution is much higher than that of water molecules. The effect of an electric field on charged ions in a salt solution is stronger than that of water molecules, thus weakening the power of water migration from the droplet to the gas–liquid interface.

Figure 7. Survival time of pure water and KCl droplets at different voltages.

Figure 8. Survival time of droplets with different KCl concentrations.

3.3. Effect of Voltage and Temperature Field Variation on Droplet Evaporation Characteristics

Figures 9 and 10 show the influence of electric field strength and ambient temperature on the survival time of droplets. The results indicate that as the ambient temperature gradually increases, the survival time of the droplets exhibits a non-linear decrease, which is due to the reduction in droplet surface area and a subsequent decrease in evaporation rate. When the ambient temperature increases from the initial temperature of 25 °C to 40 °C, the droplet survival time decreases rapidly. However, as the ambient temperature continues to increase, the decrease in droplet survival time slows down. The variation in electric field strength has a greater impact on droplet survival time at lower temperatures compared to higher temperatures. As the ambient temperature increases, the effect of electric field strength variation on the droplet evaporation rate decreases. Taking pure water as an example, as shown in Figure 9, when the ambient temperature $T = 25 \, ^\circ C$, the droplet survival time at 8 kV voltage is 5.3% shorter than at 0 kV, whereas when the
temperature rises to 55 °C, the survival time is essentially unaffected by voltage variation. This indicates that as the ambient temperature increases, the effect of electric field strength variation on droplet survival time gradually diminishes. It is evident that a single-electrode high-voltage electric field environment is more suitable for enhanced evaporation in low-temperature environments, and this pattern also applies to the droplet evaporation process in KCl. In addition, when the droplet is in KCl, the survival time of the droplet varies with the evaporation time, which is due to the change in solute concentration during the evaporation of the KCl solution, resulting in a change in solution density and surface tension, thus changing the evaporation rate. This process involves the correlation of many factors. The evaporation process of salt solution in an electric field is different from that of pure water droplets.

Figure 9. Survival time of droplets of pure water at different temperatures.

Figure 10. KCl droplet survival time at different temperatures.
4. Conclusions

Our experiment found that the high-voltage electrostatic field formed by a single electrode has a certain enhancing effect on the evaporation of liquid droplets. Around this new phenomenon, experimental studies on the evaporation process of liquid droplets under different conditions were conducted. This article elaborated on the influence of the electric field on the morphology of the liquid surface and the evaporation mode and analyzed the influence of droplet salt concentration, environmental temperature, and voltage on the evaporation of liquid droplets. This provides a reference for the development of low-energy-consumption sewage evaporation systems in the future. The main research conclusions are as follows:

(1) When a high voltage is applied to a single electrode, the top of the liquid surface approaches the needle electrode, the contact angle decreases, and the liquid droplet tends to be conical. When the voltage value increases, the liquid surface becomes unstable, exhibiting deformation and vertical oscillation phenomena, at which point the electric field significantly promotes evaporation.

(2) In the electrostatic field environment, the CCA stage occurs earlier as the voltage intensity increases, but the voltage change does not alter the contact angle reduction rate in the CCR stage or the radius reduction rate in the CCA stage.

(3) For a KCl solution, the electrostatic field has a more pronounced enhancing effect on the evaporation of low-concentration salt solutions. A 5% KCl solution under 8 kV voltage exhibits an approximately 5.3% increase in evaporation efficiency. However, as evaporation progresses, the phenomenon of electric field-enhanced evaporation weakens and even disappears. Additionally, as the environmental temperature increases, the effect of electric-field intensity changes on the survival time of liquid droplets gradually diminishes.

Author Contributions: Conceptualization and Methodology, H.L. and Z.X.; Post-processing of numerical calculation results and data extraction, H.L. and J.Z.; Geometric modeling, Analysis of data results, Paper writing, Result analysis, and Calculation result checking, H.L. and J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Jilin Province, grant number 20230101329JC And The APC was funded by the Natural Science Foundation of Jilin Province.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

4. Mato, F.A. Analysis of the Energy Flow in a Municipal Wastewater Treatment Plant Based on a Supercritical Water Oxidation Reactor Coupled to a Gas Turbine. Processes 2021, 9, 1237. [CrossRef]
5. Asakawa, Y. Promotion and retardation of heat transfer by electric fields. Nature 1976, 261, 220–221. [CrossRef]


15. Wang, Y. Experimental Study on High-Pressure Electrostatic Field Gas-Liquid Contact Multi-Effect Evaporation High-Salt Wastewater; University of South China: Hengyang, China, 2019.


18. Zhang, X.D. Dynamic spreading of a water nanodroplet on a nanostructured surface in the presence of an electric field. *J. Mol. Liq.* 2021, 333, 116039. [CrossRef]


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.