

The Reduction of TDS, COD, and Oil-and-Fats in Produced Water by Pre-Treatment Process Using Electrocoagulants in the Oil and Gas Industry of South Sumatra, Indonesia

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Abstract—Produced water is one of the largest wastes generated by the oil and gas industry. Produced water is waste with a mixture of several organic and inorganic compounds. The increasing volume of wastewater produced in several countries this decade impacts the environment, creating its problems. Some of the produced water is treated conventionally and modernly, including physical, chemical, and biological treatment. This study uses the electrocoagulation method in treating produced water in the Talang Jimar structure of the oil and gas industry in South Sumatra, Indonesia. This study aims to determine the factors of surface area, voltage, and time of electrocoagulation in reducing COD, TDS, and oil-and-fats levels in produced water under the quality standards required by the government. The results of this study indicate the electrocoagulation process in producing the obtained water. The efficiency of electrode reduction with a surface area of 38.4 mm² is the best COD reduction occurs at a voltage of 9 conditions of 90 minutes, reaching 88.07%. The best decrease in TDS at a voltage of 9 conditions of 90 minutes reached 31.29%. The best reduction in oil and fat occurred at a voltage of 12 of 30 minutes, reaching 96.98%. Meanwhile, the reduced efficiency of the electrode decreased with a surface area of 78 mm²; the best COD reduction occurred at a voltage of 9 conditions of 90 minutes, reaching 92.95%. The best decrease in TDS occurred at a voltage of 9 conditions of 90 minutes, reaching 36.25%. The best reduction in oil and fats occurred at voltage 12 for 90 minutes or 98.56%.

Keywords—Electrocoagulation; produced water; oil-and-gas; COD; TDS; oil-and-fats; electrodes; surface area.

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I. INTRODUCTION

The oil and gas industry is an industry that lifts oil and gas reserves (hydrocarbons) under the earth to the surface. The nature of the oil and gas industry is that it is expensive, global, and full of risks. The current oil and gas industry increases the amount of waste generated from oil and gas production. Waste generated from the oil and gas industry contains various organic and inorganic compounds. In 2019, according to the APBN target, Indonesia projected the oil production lifting target of 775 Mbopd and gas of 7,000 MMscfd. Increased production impacts the amount of waste in the form of produced water resulting from oil and gas exploration and production activities. Indonesia has set production water quality standards such as the oil and fat content of produced water of 25 mg/L (milligrams per liter), Chemical Oxygen Demand (COD) of 300 (milligrams per liter), and Total

Dissolved Solids (TDS) of 4,000 (milligrams per liter). The technology used in the treatment of produced water in the oil and gas industry is reinjecting water into injection wells to prevent the water from being discharged into the environment, which can cause pollution. The reinjection process aims as pressure maintenance in increasing oil and gas production. In addition to the reinjection method, the produced water treatment is carried out by adding chemicals to remove the content that causes scale in the injection circuit [1]. Another method used in the treatment of produced water is to use electrocoagulation technology. This technology has been developed as an alternative treatment for treating produced water because of its ability to reduce compounds contained in produced water. Electrocoagulation is also used in treating textile industrial waste [2] [3], dyes [4], pesticides [5], heavy metals [6], pharmaceutical industry [7], pulp and paper [8].

The aims of this research are: To determine the effect of voltage, time, and surface area of the electrode on the decrease

in the content of TDS, COD, and oil-and-fats produced in water. To determine the characteristics of the water produced by electrocoagulation treatment. To explore and discover the advantages of using electrocoagulation in the treatment of produced water.

A. Produced Water of Global Offshore dan Onshore

The total amount of water produced is estimated at around 250 million in one day from the data obtained. Meanwhile, oil revenues are estimated at around 80 million barrels per day. At least, the water to oil ratio is 3:1, where the water content is about 70%. In the last ten years ago, the amount of water produced has been increasing every year. In recent years the trend of the amount of produced water has decreased. This is due to good management methods for managing Production wells and discovering new oil fields [9], [10].

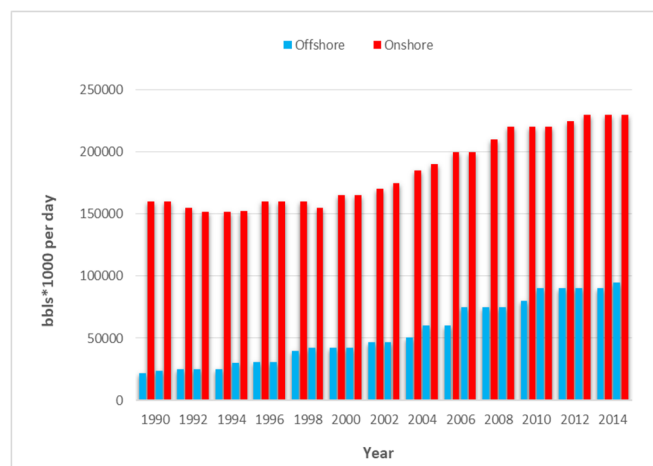


Fig. 1 The estimation of onshore and offshore produced water production since 1990 and estimates for 2015

Several factors that are evaluated and can affect the total amount of water produced on the sustainability of the well, have been described by Reynolds and Kiker [11]:

- Well drilling method: a horizontal well can produce at a higher rate than a vertical well with the same draw, or it can produce the same production rate with a lower draw.
- Located in wells with homogeneous or heterogeneous reservoirs: Inhomogeneous reservoirs, horizontal wells can reduce the water produced. The increase in water produced in horizontal wells compared to unstimulated vertical wells depends on the reservoir area connected to the wellbore
- Various types of finishes: open hole method allows testing of drilling zones and avoids drilling into water. On the other hand, the perforated finishing method offers a much higher level of control because the intervals can be punched and tested.
- Single and mixed zone: most of the wells are initially completed in one zone. As the level of oil production decreases due to the condition of the well, other zones can be opened to maintain the level of oil production; consequently, water production also increases.
- Types of water separation technology: different methods are used to reduce the cost of lifting and/or handling water for wells that produce large quantities

of brine. This method is a water cover treatment using a gel polymer, reducing the cost of lifting the pump beam, power options to reduce electricity costs, and separation technology.

- Water injection or waterlogging to improve oil recovery: the purpose of waterlogging is to bring the well-treated water to the oil level to increase the production rate. Due to stagnant water, the percentage of water produced is higher. As flooding progresses, the volume of water required for injection increases. In this case, dressing water with suitable chemical characteristics is required. The poor quality of the treated produced water or makeup allows sealing, swelling of the clay, and saltwater incompatibility.
- Poor mechanical integrity: the volume of water ingress caused by mechanical problems of the casing hole caused by corrosion or wear and splitting caused by excessive flow and pressure can allow unwanted reservoir fluid to enter the casing and increase water production.
- Improper mechanical integrity: the amount of water produced is caused by mechanical problems such as cracks in the casing walls of production wells that occur due to corrosion which causes inward flow. Excessive pressure can cause unwanted reservoir fluid to enter the casing and increase the water produced

B. Produced Water Characteristics

Rocks in formations are generally absorbed by underground fluids such as oil, gas, and saltwater. Previously hydrocarbon compounds entered rock cavities, hydrocarbons with lower density migrated and removed some saltwater from the formation layer. Reservoir rocks absorb brine and hydrocarbons (oil and gas). The sources of brine are as follows:

- Flow from above or below the hydrocarbon zone.
- Flow from within the hydrocarbon zone.
- The flow of liquid injected liquid and the addition of additives in the production process.

These three brine sources are formation water and will become production water when brine and hydrocarbons meet at the surface [12].

1) *Dissolved solid*: Produced water contains dissolved solids, but the amount varies from less than 100 mg/l to more than 300,000 mg/l, depending on geographic location, age and reservoir type. The water produced by Gas production is condensed water vapor with little dissolved solids with very low salinity. Aquifer water produced with gas or oil will be much higher in dissolved solids. Water produced from hot reservoirs tends to have higher TDS concentrations, while cooler reservoirs tend to have lower TDS levels. Dissolved solids are inorganic constituents that are dominated by sodium cations (Na⁺) and chloride anions (Cl⁻). Other common cations are iron (Fe²⁺), Magnesium (Mg²⁺) & also Calcium (Ca²⁺). While the cations that are rarely encountered are potassium (K⁺), barium (Ba²⁺), strontium (Sr⁺), lithium (Li⁺), aluminum (Al³⁺). For anions, there are carbonate (CO₃), bicarbonate (HCO₂) sulfate (SO₂). All produced water treatment facilities must have water analysis data for each reservoir layer [13].

2) *Dissolved gas*: Natural gases such as (CH₄, C₂H₄, C₃H₈, and C₄H₁₀), hydrogen sulfide, carbon dioxide is usually found in produced water. In hydrocarbon liquids, water is saturated with gases that have high-pressure activity. When the resulting water flows into the well, most gas will be wasted during the separation process. Most of these gases ignite at high vapor phase pressures where the temperature of the resulting water is separated from the oil. Quality effect of the dissolved gas content in the resulting water stream flowing into the water treatment facility. The higher the quantity of dissolved gas, the higher the pressure and temperature. The separation resulted in a lower dissolved gas quantity [13]. The resulting water usually contains carbon dioxide compounds. CO₂ in the liquid is corrosive. This can also cause CaCO₂ scale, an increase in pH occurs due to the removal of H₂S and CO₂ content. It is not found naturally in the produced water. When the resulting water is brought to the surface, it will be released into the atmosphere, and oxygen will be absorbed into the water [13].

3) *Dissolved oil*: Polar constituents are organic compounds dissolved in produced water. Within these constituents, there is a division between the low and medium carbon ranges. This can be illustrated as formic acid and propionic acid present in the temperature of the produced water (organic acid). The pH also increases the dissolved organic matter in the produced water. This pressure slightly increases the concentration of dissolved organic compounds. Temperature changes the relative ratio of the range of carbon in the water. Dissolved compounds cannot increase the amount of dissolved organic matter in the produced water. In addition, the level of salinity does not directly affect the dissolved organic compounds in the produced water [14].

The amount of water-soluble oil produced depends on the type of water production volume [15]. Aromatic compounds, which are the most important chemicals that contribute to the toxicity of the natural environment, cannot be efficiently removed using water or oil separation techniques. In addition, there was an increase in the alkalization component, the concentration of phenanthrene, naphthalene, alkylated, C₁-C₃ alkyl homologs, dibenzothiophene, and alkylated phenols decreased. Sometimes, the concentration of these components is relatively high. Phenol and BTEX were the most water-soluble compounds produced [16].

This type of gravity separation equipment has an impaired function to remove dissolved oil. For example, produced water sources contain significant amounts of dissolved oil to remove high amounts of oil and grease. As a result of the produced water stream containing a high concentration of dissolved oil can be recycled into a separator to help minimize the amount of dissolved oil in the water. Other technologies are currently under review, and their applications are not yet commercially available [17].

4) *Oil Spread*: Oil ranges from about 0.5-200 microns. The size distribution of this oil is important because it is one of the main parameters affecting the performance of the produced water treatment. "The velocity of an oil droplet rises is proportional to the square of the droplet diameter" is a statement of Stoke's law. The diameter of the oil droplet greatly influences the separation and removal of the oil droplet from the water. This condition is for equipment that

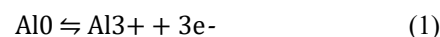
operates according to the principles of Stoke's law [17]. The oil droplet size distribution is a fundamental characteristic of produced water. This is also considered when designing and measuring regulatory standard treatment systems for wastewater compliance. The oil droplet diameter has a maximum of 250 to 500 microns. The oil content has a content of 1000 to 2000 mg/L for the first phase fat removal equipment. The size of the oil droplet diameter starts from 30 microns with a total oil inlet rate of less than 100 mg/l so it can be assumed for the feed water produced to the final treatment equipment [13].

5) *Heavy Metal*: The content of heavy metals in the produced water has various concentrations. The water produced depends on the age of the well and the geological formation sequence [18]. The resulting produced water contains small amounts of various types of heavy metals; Cd, Cr, Cu, lead, Hydrargyrum, Ni, Ag, and Fe [19].

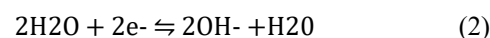
C. Mechanism of Electrocoagulation

Electrocoagulation is a type of wastewater and electrochemical treatment that uses electrochemical cells. The voltage current at the electrodes is generally iron or aluminum [20]. Generally, electrocoagulation can occur when there is an electrochemical reaction at the cathode and anode. However, the solution reaction also has an important role in this process, as seen in the reaction equation (1), (2), and (3) [20].

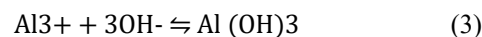
Anode reaction:



Cathodic reaction:



Solution reaction:



Then the steps taken are as follows:

- Anode oxidation will produce metal cations (Al or Fe);
- The water is electrolyzed at the cathode will produce small hydrogen and hydroxide bubbles.
- Solution reaction, where the ions in the metal react with hydroxy, will absorb pollutants from the coagulant, then separated by coagulation or flocculation [21].

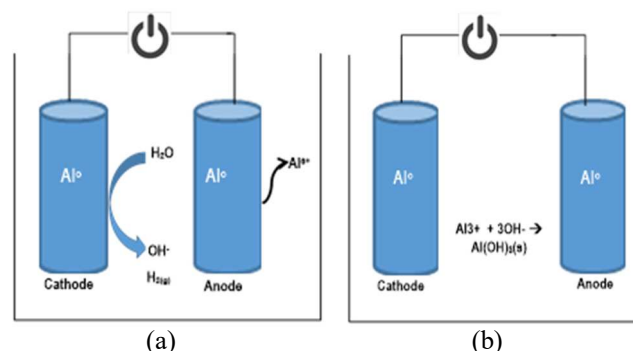


Fig. 2 (a) Electrolytic reaction and (b) solution reaction in the electrocoagulation process

The electrocoagulation reactor can function as an electrochemical reactor where the addition of Fe or Al must be controlled. Ions in the metal will result in colloidal

aggregation, which increases the size and floc formation. If the applied current is higher, the bubbles will increase. The combination of increased production and increased aggregation makes disposal a major flotation [22].

pH or acidity also affects the resulting bubble size. The range of the enhanced form in electrocoagulation is 20-70µm. The resulting bubbles are smaller when viewed from under conventional air-assisted flotation. Several conditions must be provided, such as a sufficiently large surface for the gas-liquid and solid interface and mixing efficiency to support small and unstable particles. If seen in other experiments, the hydrogen accumulation will usually follow a normal floc size distribution known as neutral pH [23]. EC has several advantages, such as being versatile and relatively inexpensive to process various industrial fuels and wastewater [5]-[24]. This advantage comes from the nature of the process because it does not involve other compounds or chemicals but only uses iron or aluminum electrodes that are soluble in ion-generating solutions. The mechanism of EC has been thoroughly discussed in previous studies [25].

D. Al Electrode

Specifications on aluminum can be deduced based on the Pourbaix E-pH diagram. The reaction will work thermodynamically. It can be concluded that the constant has a balance for reacting acids and a standard reduction potential, as shown in Table 1. Simply put, the dissolved Al³⁺ cation occurs when the pH is below four, the soluble aluminate anion occurs when the pH is above 10, while the insoluble form of al(OH)₃ dominates in reverse. Polymer formation is reported:

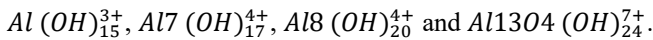


TABLE I
EQUILIBRIUM CONSTANT AND STANDARD REDUCTION POTENTIAL
OF ALUMINUM SPECIES

Reaction	pK
$Al_{(aq)}^{3+} + H_2O \rightleftharpoons Al(OH)_{(aq)}^{2+} + H_{(aq)}^+$	4.997
$Al_{(aq)}^{3+} + 2H_2O \rightleftharpoons Al(OH)_{2(aq)}^+ + 2H_{(aq)}^+$	10.094
$Al_{(aq)}^{3+} + 3H_2O \rightleftharpoons Al(OH)_{3(aq)} + 3H_{(aq)}^+$	16.791
$Al_{(aq)}^{3+} + 3H_2O \rightleftharpoons Al(OH)_{3(s)} + 3H_{(aq)}^+$ (amorphous)	8.578
$Al_{(aq)}^{3+} + 2H_2O \rightleftharpoons Al(OH)_{(s)} + 3H_{(aq)}^+$ (boehmite)	10.800
$Al_{(aq)}^{3+} + 4H_2O \rightleftharpoons Al(OH)_{4(aq)}^- + 4H_{(aq)}^+$	22.688
Reaction	E° (V)
$Al_{(aq)}^{3+} + 3e^- \rightleftharpoons Al_{(s)}$	-0.41
$Fe_{(aq)}^{3+} + 3e^- \rightleftharpoons Fe_{(s)}$	-0.04
$Fe_{(aq)}^{3+} + 2e^- \rightleftharpoons Fe_{4(aq)}^{2+}$	+0.77
$FeO_{4(aq)}^{2-} + 3e^- + 8H^+ \rightleftharpoons Fe_{4(aq)}^{3+} + 4H_2O$	+2.20

According to the Lewis equation, aluminum offsets the formation of OH⁻ anions present at the cathode and induces and leads to a final acidity (pH) and buffer solution effect between 7-8. This is very different from conventional chemical coagulation using Al salts [26]. The conclusion that can be drawn is that polymers and monomers will eventually induce the formation of al(OH)₂. The floc has a large surface area to accelerate the participatory absorption of colloids and dissolved organic compounds [16].

Faraday's law describes the consequences of the amount of dissolved Al that will be released when electrocoagulation

exceeds a set concentration limit. Faradic results can be higher than 100% and can also be up to 200%. The main problem with electrocoagulation is cathode passivation, as it increases energy consumption as well as cell voltage. The passivation mechanism can also be avoided by adding sodium chloride (NaCl) to increase the corrosion reaction between Cl⁻ adsorbed on the aluminum oxide film. Al³⁺ species in oxide or current inversion frequency optimization/in the chemical corrosion rate of dissolved aluminum anodes. It mainly depends on two mechanisms [22] as follows:

- Subsequent partial destruction of this layer through pitting and
- Formation and deposition of a passive aluminum-oxide layer.

II. MATERIALS AND METHOD

A. Materials

Produced wastewater is taken from the Talang Jimar structure. The Talangjimar structure produces the highest average produced air compared to other structures in the Prabumulih area. In addition, the water structure produced by Talang Jimar contains the highest TDS content compared to other structures.

This study uses an electrochemical device, as shown in Figure 3. The reactor tube has dimensions of A length of 23 cm, the width of 3 cm, the thickness of 2 mm, and dimensions of B length of 23 cm, a width of 6 cm, the thickness of 2 mm. The electrodes used are aluminum electrodes with a surface area of 38.4 mm² and 78 mm². Electrochemical equipment is equipped with an adapter with an adjustable voltage from 3-24 volts.

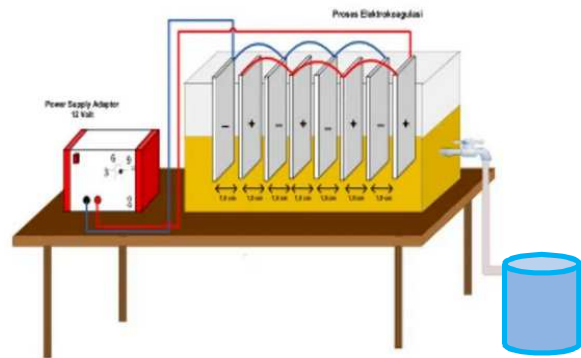


Fig. 3 Produced water treatment electrochemical equipment series

B. Method

Wastewater produced from the oil and gas industry in South Sumatra from the Talang Jimar structure is taken from a holding tank in one of the production facilities. The produced water is put into the reactor bath, which has been equipped with aluminum electrodes and is followed by the following steps:

- Produced water is put into an electrocoagulant reactor which has been equipped with aluminum electrodes, with each electrode having a cross-sectional area of 38.4 mm² and 78 mm². Electricity with a voltage of 3V is supplied at a current of 35A for 15 minutes. The flow of electricity was stopped for 10 minutes while waiting for floc to form and a precipitate to form. Then samples

of the produced water were taken to analyze the pH, COD, oil-and-fats results.

- Step number 1 is again carried out with time parameters of 15, 30, 45, 60, 75, and 90 minutes. The voltage parameters at this stage are 6, 7.5, 9, and 12 volts.

C. Results Analysis

Analysis of the results carried out in this study were COD, TDS, and oil-and-fats. COD was measured using a COD reactor and a HACH spectrophotometer with a wavelength of 420 nm. Oils and fats were measured using a HACH brand spectrophotometer with a wavelength of 450 nm.

III. RESULT AND DISCUSSION

A. Produced Water Characteristics

Table 2 shows that the characteristics of the produced water waste taken from the Talangjimar structure are waste with the content of TDS, COD, and oil-and-fats exceeding the threshold value required by the Regulation of the Minister of the Environment of the Republic of Indonesia No. 19 of 2010 concerning Quality Standards for Oil and Gas Exploration and Production Activities. from Onshore Facilities, as presented in Table 2.

TABLE II
RESULTS OF ANALYSIS OF WATER PRODUCED TALANGJIMAR STRUCTURE

Parameter	Unit	Hasil	Threshold Limit Value
pH	-	7.56	6 – 9
Temperature	°C	27.1	45
Amonia (NH ₃ -N)	mg/l	17.71	10
COD	mg/l	430.25	300
Oil & Grease	mg/l	377	25
Phenol	mg/l	1.30	2
Sulfide (H ₂ S)	mg/l	0.14	1
TDS	mg/l	1,6010	4,000

Table 2 shows the results of several water parameters produced by the Talangjimar structure before the processing. The parameters above the threshold value are under government regulations. Minister of Environment Regulation No. 19 of 2010 concerning Standards for Exploration and Quality of Oil and Gas Production from Onshore Facilities stipulates the COD value of 737.57 mg/L (COD quality standard 300 mg/L), TDS value 16010 mg/L (TDS quality standard 4000 mg/L) and the value of oil & fat content is 364.2 mg/L (standard oil & fat quality is 25 mg/L).

B. The Effect of Surrounding Electrodes on Contaminant Reduction

Reduction of contaminants becomes the benchmark criteria for selecting the electrode material to be selected as the main material. The electrodes used are aluminum plates and tested in electrocoagulation filtration experiments. All water samples were treated and analyzed to determine COD, oil, grease, and TDS. In Figure 5, it has been explained that aluminum electrodes will be much more effective in reducing COD, oil, grease, and TDS contaminants.

The decrease in IR increases as the distance between the electrodes increases. Energy consumption is minimized by reducing the distance between the indicated electrodes [27], [28]. The effect of the electrode surface area on the resulting

electrocoagulant process can be seen in the decrease in COD. As presented in Figure 4 below:

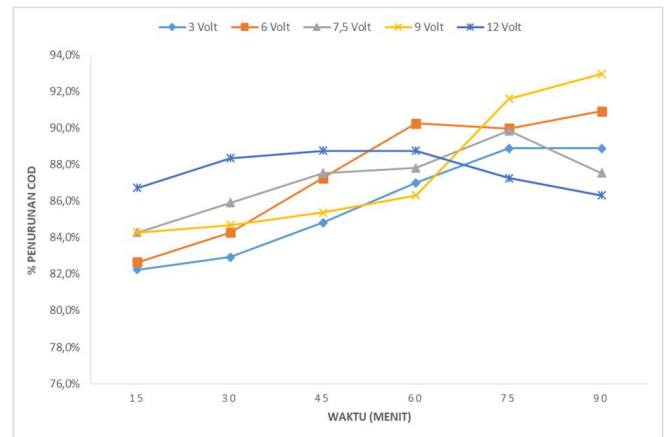


Fig. 4 The relationship between time and COD reduction with a variable voltage around the electrode circumference of 78 mm²

The lower the distance between the electrodes, the more gas bubbles will be produced electrochemically. This can lead to turbulent hydrodynamics leading to high mass transfer and high reaction rates between coagulants and pollutants [29]. In the inter-electrode distance determines the time between cathode and anode for the continuous system as well as the maintenance time of the batch reactor to achieve the desired electrocoagulation efficiency. Therefore, the arrangement of the block and complex electrodes and the distance between the electrodes also determine the number of electrodes placed in the electrocoagulation cell if the volume has been determined [30].

The effect of the electrode surface area on the COD reduction can also be seen in Figure 5. The effect of the electrode surface area affects the COD reduction of the produced water. Several compounds that cause high COD in produced water are bacteria contained in sewage. Bacteria will consume pollutants as a source of nutrients in produced water and form biomass which can cause high COD concentrations [13].

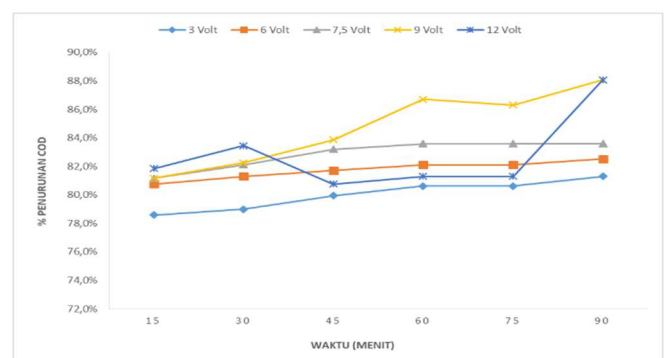


Fig. 5 The relationship between time and COD reduction with a variable voltage on the circumference of the electrode 38.4 mm²

In this case, the researchers conducted a study on an eight-plate electrode configuration, using an iron or aluminum plate as an anode and a stainless-steel plate as a cathode. The results of Gadd *et al.* [31] showed that there was a brief increase or efficiency in the treatment associated with an increase in the

electrode area, which was associated with bubble formation and coagulant electro generation.

Fig. 4 and 5, show the effect of electrode surface area on COD reduction. The best COD reduction electrode occurred at a voltage of 9 volts in 90 minutes at 92.95% at an electrode surface area of 78 mm². The best COD reduction occurred at a voltage of 9 volts in 90 minutes at 88.07% at an electrode surface area of 38.4 mm². The surface of the Al electrode will oxidize its electrons to Al³⁺, which then binds OH⁻ to form Al (OH)₃, which functions as a coagulant. The formation of oxygen and hydrogen gas affects the decrease in COD. Hydrogen (H) helps contaminants lift or float. This causes dissolved or dissolved organic matter, including floc Al (OH)₃ to bind organic waste and capture some organic waste that is not deposited on the cathode electrode. The production of H₂ resulting from the redox reaction causes the organic matter to be reduced. Some of the molecules contained in the effluent are captured by Al (OH)₃ ions and then removed by H₂ as organic compounds to form bubbles which can reduce COD [32].

The rate of mass transfer of dissolved gas will determine the formation of bubbles on the electrode surface. In this case there are two processes. The first process is when dissolved gas molecules are formed from a chemical reaction on the electrode's surface. The second is the diffusion or transfer of molecules into a bulk solution. This process comprises a density variation with a dissolved gas concentration on the electrode surface and an examination of the effect of nucleation time. Previous studies have predicted the supersaturation concentration of dissolved gas until the initiation of bubble nucleation on the electrode surface, called heterogeneous nucleation [33]. The following Equation estimates the average concentration of H₂ contained in the diffusion layer:

$$C_i(\bar{t}) = \frac{1}{\delta} \int_0^\delta C_i(x,t) dx \cong \frac{0.247 J_s}{\sqrt{D_{H_2}}} \sqrt{t} + C_i^\infty \quad (3)$$

The symbol of \bar{C}_i is the average content concentration in the diffusion flow layer. δ is the thickness of the diffusion layer, while the symbol repeats the flux produced on the electrode surface, also D_i is the diffusion coefficient of species i . This is explained in the first law in Fick, states that the mass of the molar flux over the entire area A is given in Equal (2), I is the current $F =$ Faraday constant and z alone is the courage number for the ionic species.

$$-J_s = -J_i(0,t) = \frac{1}{zFA} = D_i \left(\frac{\partial C_i(x,t)}{\partial x} \right)_{x=0} \quad (4)$$

Thus, the higher the density, the higher the dissolved gas flux (at the electrode surface) [34].

Thus, the resulting concentration of the average dissolved gas in the diffusion layer increases and results in a shorter nucleation time, favoring a smaller bubble size [33]. Nagai *et al.* [35] have also conducted research on the effect of electrode spacing (0-20 mm). If the electrodes are too close to each other and 1 or 2 mm apart, the voltage may increase depending on the applied density. This can happen because the volume of hydrogen and oxygen bubbles increases, which increases the solution's electrical resistance. In the case studied, there was also an observed increase in stress when the density was above 0.6 A cm⁻² caused by a large bubble layer created when the density was high. The voltage decreases at

lower current densities, ranging from 0.1-0.5 A cm⁻² as the electrode spacing becomes smaller in the 1-2 mm range.

Consequently, the optimal range of studied current densities ranging from 0.1 to 0.9 A cm² is from the 1-2 mm mark at 0.5 A cm⁻². There is a reduction in energy consumption when applying electrolytes in high conductivity. It should be borne in mind that the limit for reducing vapor consumption is reached if we increase the conductivity to more than 1.5 μS cm⁻¹ [36].

C. Voltage Effect

Electrocoagulation is often designed as a function of current density. The continuity equation enforces the conservation of current between the cathode and anode. The evolutionary, gradual change process of hydrogen gas (H₂) at the cathode can be found in Faraday's law as well as the current density that determines the coagulant dose at the anode. The density present in the bubble affects the hydrodynamic system. The density of the coagulant and gas microbubbles affects the mass transfer between pollutants. These conditions ultimately determine the degree of collision of the solidified particles resulting in the formation of a liquid [37]. Density also affects the hydrolyzed metal species through the evolution of pH during the EC process. The EC process functions as the alkalinity of the water create a chemical or dynamic environment that can directly regulate the graft coagulation mechanism, causing currents to appear [38], [26]. This makes the stress on the electrocoagulation process of the resulting water can be expressed in the reduction of TDS which is shown in figures 6 and 7 below:

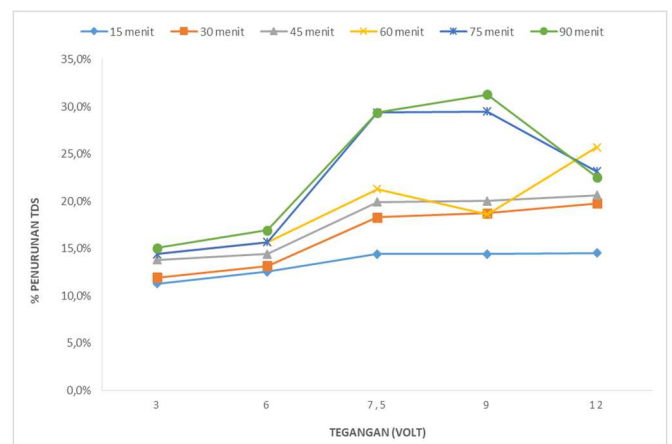


Fig. 6 The relationship between voltage and TDS drop with time variable on the electrode circumference 38.4 mm²

The greater the voltage applied, the greater the aluminum ion (Al³⁺) produced by the anode and hydroxide ion (OH⁻) produced by the cathode, which functions as a coagulant [39]. In Figure 6 above, the efficiency of reducing TDS occurs at a voltage of 9 volts in 90 minutes with a decrease of 31.29%. The effect of voltage on the decrease in TDS is also seen at the 38.4 mm² electrode surface area as shown in Figure 7.

Some of the compounds contained in the produced water that cause high TDS concentrations [40] include:

- Reservoir layer. The higher the temperature in the reservoir layer, the higher the TDS content.
- Cl⁻ & Na
- Mg²⁺, (Ca²⁺), Iron (Fe²⁺)

- Bicarbonate (HCO₃), Carbonate (CO₃)

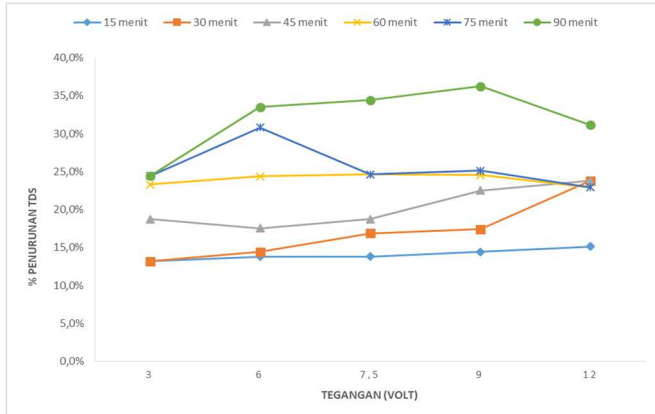


Fig. 7 The relationship between voltage and TDS drop with time-variable around the electrode circumference of 78 mm²

Figure 7 shows that the best TDS reduction efficiency in the electrode surface area of 78 mm² occurs at a voltage of 9 volts in 90 minutes with a decrease of 36.25%. As for the cell, voltage can be considered a function of the potential having equilibrium, both cathode and anode excess, as previously described. We can conclude as the objective of the operation t (time) with Equation (5) below:

$$P = \int_0^t V.I. dt \quad (5)$$

Several things are needed to process electrocoagulation, which we will connect with an electric current and function as electric potential energy [41]. Electrocoagulation here can serve as a potentiostatic mode driven under galvanostatic. The electrocoagulation process can be carried out by controlling or distorting the current flowing through the electrodes. For the Galvanostatic potentiostatic mode, the applied cell voltage will be controlled as a function of the amount of coagulant required for release in the electrocoagulation reactor. It is also frequently used in other electrochemical methods, for example, electro-reduction and electro-oxidation, when the sacrificial electrode is not used, and the potentiostatic mode is rarely used for EC [42], [43].

$$R = \frac{l i}{S K} \quad (6)$$

Where l represents the distance between the electrodes. K is the water's conductivity. As i increases and U tends to IR the drop term RI concludes at *Eq.* [1], which means that the electric power varies as RI^2 . Therefore, the power input can increase the electrode surface area and the water/wastewater conductivity and reduce the distance between the electrodes [44].

The most common application for electrolysis treatments in electrical construction is energy sources having a continuous electric current. In electro flocculation, the placement or installation of the electrode wire and the mass wire to the positive-negative pole (electrode polarity) can be reversed. Its function is to reduce the passive effect on the cathode. The electro flocculation system can be set up and controlled in various electrode configurations creating continuous maintenance or plug flow. Thus, the electrodes can be arranged in a monopolar or bipolar configuration [45], [33].

At present, the cell voltage is easily controlled, and the electro-flocculation is processed. The operational flow in the electro-flocculation cell must exceed the equilibrium potential, excess cathode and anode, and the required amount of potential. This is to overcome the resistance experienced by the ions moving towards the anode or cathode (ohmic potential) of the solution to enhance the electrochemical reaction, which is shown in Eq. (6) [46].

$$E_{cell} = E_{eq} + n_{a,a} + n_{a,c} + n_{a,p} + |n_{c,a}| + |n_{c,c}| + n_{ohm} \quad (7)$$

E_{cell} is known as electrolysis voltage (V), E_{eq} is the breakdown of water molecules (V), and the difference between the balance. η_a , a is known as overpotential anode activation (V), a, c itself is known as anode concentration overpotential (V), η_c , a is often known as the cathode activation overpotential (V), a, p is the passive anode potential (V), n_c, c is the potential cathode concentration (V), and ohms is the ohmic resistance.

The voltage can be seen in Equation [47]. If the estimation is done directly, it will not be easy [48]. In the majority, the potential gain (overvoltage) is the range of activation and concentration associated with some of the electrochemical properties of the electrode, applied current density, and acidity pH of the solution. Thus, the voltage required to carry out the electro-flocculation process is generally given by the potential for decreasing the ohmic resistance of the solution. Research like this has been done by Merzouk et al., who investigated the gap between the electrodes by eliminating the turbidity efficiency [49]. It is clear that when the distance of the two aluminum electrodes varies from 1 to 3 cm, the density varies from 11.55 - 91.5 mA cm⁻², respectively. The degreasing efficiency can reach 89% with the smallest distance and decreases with the increasing gap between the electrodes.

Research like this is by Alam [50], who has developed an electrochemical model to calculate the total stress that would be required during electrolysis while in tie media using electro flocculation under different conditions. It was found that the variation of the electrode distance was studied and analyzed in the experiment changing the distance from 2.0 – 9.5 cm in the center of the tie with a conductivity of 2100 S cm⁻¹. At the end of the conclusion, what can be drawn is that the resistance occurs with increasing linearity with increasing electrode distance.

D. Effect of Electrocoagulation Time

The effect of time on reducing the contaminated water produced in the electrocoagulation process can be seen in the reduction in the surface area of oil and grease electrodes of 38.4 mm² and 78 mm², respectively. Oils and fats are organic compounds of natural origin and are insoluble in water but soluble in non-polar organic solvents. Oils and fats are soluble because they have the same polarity as non-polar organic solvents, such as diethyl ether (C₂H₅OC₂H₅), chloroform (CHCl₃), and benzene [51]. Based on their physical properties, oils and fats are water-insoluble compounds extracted from living organisms using weak solvents or non-polar solvents [46]. Oils and fats are lipid mixtures consisting of 95% triacylglycerols, and the remainder is diacylglycerols, monoacylglycerols, and free fatty acids (FFA) [52].

The effect of time on decreasing oil and fat content on the electrode surface area of 38.4 mm² can be presented in Figure 8. The greatest reduction efficiency was at a 12-volt voltage in 30 minutes with a decrease of 96.98%. Nur and Jatnika [16] studied wastewater from hotels in Bandung, where the batch electrocoagulation treatment method reduced the oil and fats content by 77.50%. Waste treatment with an electrocoagulation method with a sustainable system reduced the oil and fats content by 89.79%. Sutanto [38] conducted a study on domestic liquid waste reveals that the electrocoagulation method was able to reduce domestic liquid waste's oil and fat content by 0.02 mg/L. This result is under the quality standard of the Regulation of the State Minister of Environment Number 19 the Year 2010 about Waste Water Quality Standards for Business and/or Activities Oil and Gas and Geothermal.

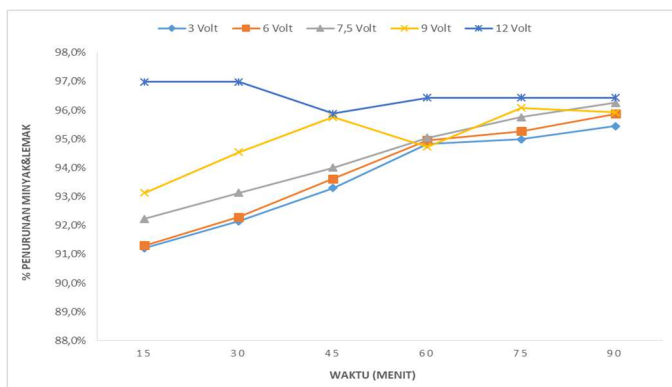


Fig. 8 Relationship of time with oil & grease reduction with variable voltage at the circumference of the electrode 38.4 mm²

In contrast, with an electrode surface area of 78 mm², the effect of time on the reduction of oil and fat after electrocoagulation of produced water is presented in Figure 9. This figure shows that the longer the electrocoagulation process, the oil and fat content of the produced water decreases. The oil and fat content efficiency decreased at a voltage of 12 volts within 90 minutes with a decrease of 98.56%.

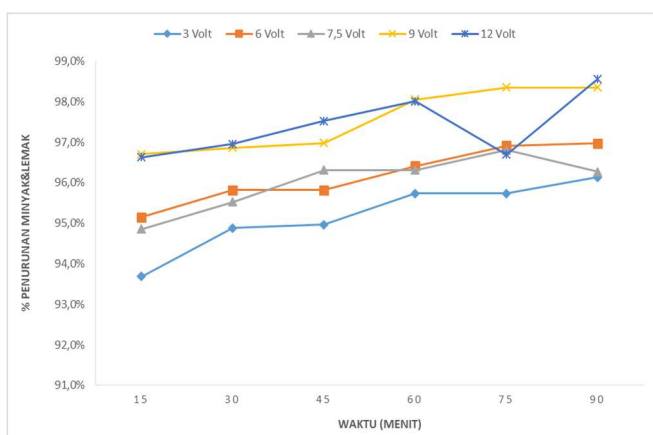


Fig. 9 Relationship of time with oil & grease reduction with variable voltage on electrode circumference 78 mm²

The liquid (sub-set of object phases) generated during the electro-flocculation process must be presented in some basic features, such as a certain conductivity. To avoid increasing

the number of electrolytes and materials suspended in the liquid, it must float. Otherwise, when it does not float, additional coagulation steps have to be performed. This is meant to be the activation of the electro-flocculation process [39], [49]. If it is seen from most of the EF studies, which behave as a first-order kinetic model, except at the initial time, this can be illustrated in Equation (8).

$$\ln\left(\frac{C}{C_0}\right) = -kt \quad (8)$$

The symbol C is known as the concentration-time $t = t$, K represents the coefficient of the flotation rate, and C₀ is known as the concentration at $t = 0$.

Although the process, manner, and behavior of electro flocculation are similar to flotation, this process of electro flocculation helps in an additional (definite) advantage over other flotation techniques. Under some operating conditions, it can be checked quickly and relatively and is easy to control. The ionic strength of the effluent solution (slurry) to be treated is not an important parameter, for example, in other flotation techniques. The equipment is reliable and relatively safe in operation. For product recovery is a potentially helpful and useful aspect (EF), so is the acquisition of proteins, fats, organics, and oils, along with toxic or precious metals. Repair and maintenance of waste streams can be carried out and maintained, especially in the absence of reagents. Other chemicals (surfactants) are added to aid in the separation of pollutants [39].

The electrocoagulation process is strongly influenced by the contact time caused by the release of Al³⁺ as a coagulant [15]. The mechanism of reducing the oil and fat content in the waste is binding by the coagulant core. Dissolved organic matter is involved by forming colloidal Al³⁺ to disrupt the emulsified oil in the effluent [22].

IV. CONCLUSION

The results showed that the electrodes' voltage, time, and surface area in the electrocoagulation process produced water had an effect on reducing COD, oil, fat, and TDS contaminants. The efficiency of electrode reduction with a surface area of 38.4 mm² is the best COD reduction that occurs in a voltage condition of 9 volts 90 minutes at 88.07%. The best decrease in TDS occurred at a voltage of 9 volts for 90 minutes by 31.29% and the best decrease in oil and grease occurred at a voltage of 12 volts for 30 minutes for 96.98%. Meanwhile, the electrode surface area of 78 mm² is the best COD reduction in a voltage condition of 9 volts 90 minutes at 92.95%. The best decrease in TDS occurs at a voltage of 9 volts for 90 minutes by 36.25%, and the best decrease in oil & grease occurs at a voltage of 12 volts for 90 minutes for 98.56%.

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