Examining the Flocs Rise Velocity of Electrocoagulation with Intensified Microbubbles

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Abstract. The rising pollution from household and industrial waste has exacerbated the leachate issue, necessitating effective treatment methods like electrocoagulation (EC). The role of vibrated electrode plates (VEPs) is to enhance floc formation during EC that improve the interaction between pollutant particles and coagulant ions, leading to better floc formation. Flocs' hydrodynamic performance can be evaluated by determining the mean rise velocity (RV) during the process. In the present study, the RV of flocs under different current intensity (CI) levels during EC employing VEPs and stationary electrode plates (SEPs) was investigated using particle image velocimetry (PIV). The results showed that, at CI=4.5A, the flocs' RV during EC with VEPs was 12.77 mm/s compared to 8.65 mm/s with SEPs. Moreover, flocs had higher RV when CI was higher (4.5A); it varied from 0.74 mm/s at 0.5A to 8.65 mm/s during EC with SEPs. The changes in RV closely correlate with the introduction of an agitation mechanism that improves the ionic transfer between particles and bubbles in the wastewater solution.

1 Introduction

Wastewater is produced as effluent with plenty of organic and inorganic contaminants, which can pollute the environment and seriously affect human health. Landfills are typically used as the last destination for the disposal of urban solid waste in various countries. Landfill wastewater is known as leachate which consists of water contaminants that percolate through the ground; hence, they must be treated prior to discharge in rivers. Leachate is difficult to treat because of high pollutant load and complex structure in it. Electrocoagulation (EC) is one of the physicochemical treatment methods that researchers widely use in leachate wastewater treatment because of its advantages with easy operation. Studies has shown that EC also has been used to eliminate fluoride in water [1], removal of nitrate concentration from groundwater [2] and effective for arsenic reduction in short treatment time [3]. Several

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parameters were studied to attain significant result, such as current density, electrode plate materials, electrode distance and reaction time.

Iron (Fe), aluminium (Al) and stainless steel (SS) are the most effective materials used as coagulant aids in solution [4], [5], [6], [7]. This approach effectively removes contaminants from leachate by destabilising and removing suspended particles and pollutants. Unfortunately, some issues may reduce pollutant removal efficiency due to less bubble detachment from the electrode plate and the upward movement of the pollutants.

The introduction of vibrated electrode plates (VEPs) to treat landfill leachate showed successful results regarding microbubble detachment from electrode plates and helped maximise pollutant-bubble adsorption [8]. Microbubbles have significance for floc movement and flotation in EC processes, and may influence floc aggregation performance [9]. The particle-bubble aggregate becomes less dense than the surrounding water when microbubbles adhere to the flocs, lowering the aggregate's effective density. The aggregation of particle and bubble then rises to the water's surface due to buoyant force. As the destabilised pollutant aggregate moves upward, it carries along other flocs and floating particles, which makes faster for them to separate from the water. Effective removal of pollutants during EC depends on the floc aggregate's rising motion, which is caused by the buoyant force that the microbubbles exert.

To date, there is a lack of information about flocs' mean rise velocity (RV) during EC using VEPs for wastewater treatment. In this study, particle image velocimetry (PIV) was used to compare flocs' RV when VEPs and stationary Al electrode plates (SEPs) were implemented.

2 Materials and Methods

2.1 Collection of Raw Leachate

The raw leachate sample was taken from Padang Cina Sanitary Landfill, Kulim, Kedah, Malaysia, an old leachate retention pond. The sample was transferred into clean high-density polyethylene (HDPE) containers, which were instantly transferred to the laboratory for preservation. The samples were stored in a refrigerator at 4ºC to avoid contamination. Before tests, the sample was defrosted to reach room temperature.

2.2 Experiment Apparatus

A 5000ml clear glass reactor was used as the reaction vessel for the leachate sample experiment. A working volume of 2000ml of untreated leachate sample was added in the reactor after introducing the pH level to 5 using 1M of hydrochloric acid. Throughout each run, the experiment was conducted in batch mode. Two Al electrode plates were set up as cathode-anode connection, and they were fitted with vibration motors to induce vibration during the experiment. The electrodes were 200mm tall, 50mm wide, and 1mm thick, yielding a total surface area of 120 cm^2. The distance of electrodes was remained unchanged at 2cm apart and installed opposite each other. After that, a digital direct current (DC) power supply (QJE PS3005, China) was connected to both electrode plates to provide current intensity (CI) ranging from 0.5-4.5A.

2.3 Determining the Flocs' Rise Velocity (RV) using PIVlab

The flocculation-flotation characteristics of floc movement during the experiment were recorded using PIV to determine the flocs' RV. A high-speed camera (Canon EOS 1300D) was used to focus on the specific zone of the reactor and capture images of floc displacement during the flocculation-flotation process. The speedy camera was set up perpendicular to the reactor and Al plates. A continuous sequence of 100 photos was taken at a frame rate of 300 frames per second (fps). All images were processed using IrfanView and PhotoFiltre to enhance the image quality. The images were interpreted in MATLAB® with embedded PIVLab Tools to determine flocs' RV. Data collection was started at the 20th minute and was carried out until the 50th minute for each parameter.

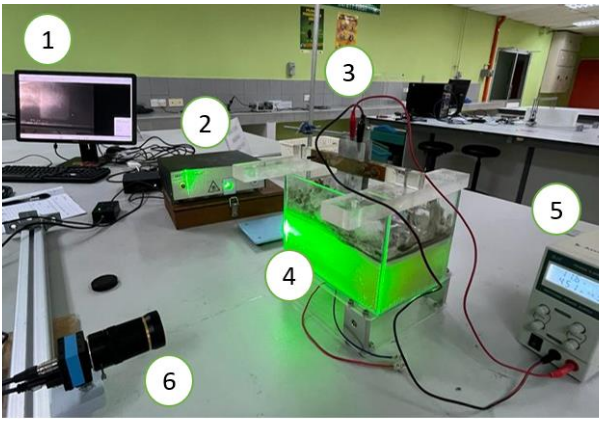

Fig. 1. The PIV setup for EC with SEPs: 1) image processor, 2) LED illuminator, 3) electrode plates, 4) glass reactor, 5) DC power supply, and 6) CANON EOS 1300D camera.

3 Results and Discussions

3.1 Effect of Current Intensity (CI) on the Flocs' Rise Velocity (RV) during Electrocoagulation (EC) with Vibrated Electrode Plates (VEPs)

Flocs' RV during batch EC may be affected by the hydrodynamics of bubbles in the solution. Microbubbles are generated by the introduction of air or gases such as hydrogen (H_2) and oxygen (O_2), and they help facilitate the coagulation process, where the nucleation is followed by their rise to the liquid surface. The bubbles carry destabilised pollutants and coagulant particles and adhere together to form flocs that float to the water surface, forming stable sludge. It represents the efficiency of the electro-flotation technique, as the pollutant particle-bubble interaction and attachment depend on flocs' RV. Based on Figure 2, the flocs' mean RV increased at CIs of 0.5-4.5A for VEPs and SEPs. An increase in CI resulted in higher coagulant ion generation from electrode plates; thus, the amount of precipitate is greater for the removal of pollutants [10]. The flocs' mean RV for VEPs was higher than that of SEPs.

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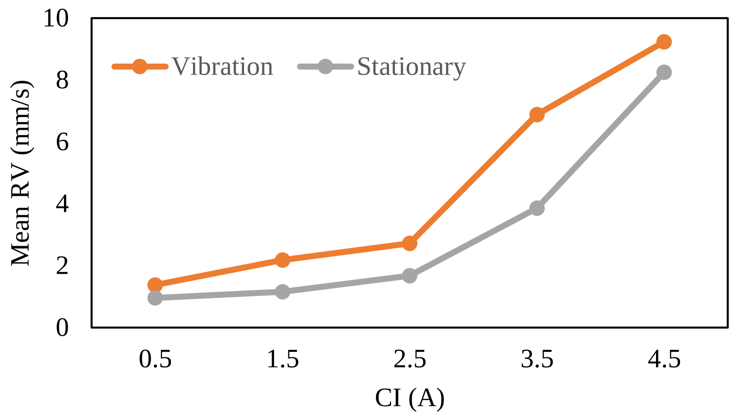

Fig. 2. The effect of CI on the mean RV of EC with VEPs and SEPs.

The floc aggregate RV may also be influenced by the presence of other particles and flocs in the water, as well as any turbulence or mixing in the systems [11]. Overall, the movement of the floc aggregates for higher CIs is typically characterised by faster upward motion towards the water surface compared to low CIs, aiding the separation and removal of contaminants from the system. As depicted in Figure 3, at higher CI (3.5A-4.5A), a slight decrease in flocs' RV is observed starting at the 30th minute. At low CI (0.5A-2.5A), the flocs' mean RV increased slowly until the end of the experiment. A high CI facilitates more dissolution of coagulant ions from the anode to react with stabilised pollutant particles compared to a low CI [12]. A layer of sludge that develops at the surface of the solution impacts the upward movement of flocs due to repulsion. Furthermore, prolonging the experiment allows more microbubble dispersion until particle RV reduces due to the generation of a metal oxide layer on the electrodes during high CIs [13].

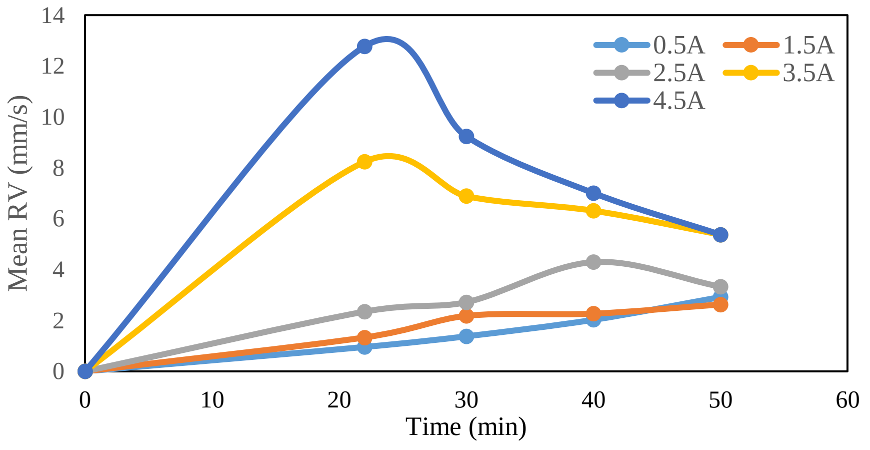

Fig. 3. The effect of varying CIs on EC with VEPs.

3.2 Effect of Current Intensity (CI) on the Flocs' Rise Velocity (RV) during Electrocoagulation (EC) with Stationary Electrode Plates (SEPs)

During EC, the anode material dissolved due to the impact of CI, which also affects the generated flocs' mass transfer mechanism. While at the cathode, the hydrolysis reaction takes place during the EC operation produces H_2. This gas (microbubbles) helps to precipitate suspended impurities and flocs upward to the leachate surface. According to Faraday's law, the amount of flocs formed is proportional to the amount of electrode material released in the solution, and it is dependent on the CI [14]. Figure 4 shows the effect of flocs' mean RV at a CI of 0.5-4.5 A at the 50th minute. The highest mean RV of 8.65 mm/s was achieved at the 20th minute when CI was 4.5A; at 0.5A CI, the mean RV was 0.74 mm/s.

The increasing RV could be caused by the lower bubble coverage on the electrode plate and the detached bubbles reacting with flocs. With SEPs, there is no mechanical agitation. Thus, the flotation phase of the flocs was attained from the continuous leachate flow which performed by the production of *in-situ* H_2 bubbles. During SEPs condition, the displacement of H_2 bubbles from Al electrode plates is least in consequence to lack of agitation movement [15]. Furthermore, a high CI also produces massive gas bubbles that benefit bubble RV, which enhances the flow around the electrode plates. Moreover, the RV at high CIs shows a fair reduction at the 30th minute due to the presence of a sludge layer at the surface of the solution, which hindered the flocs' upward movement. In contrast, a low CI causes the flocs' RV to remain stable until the end of the experiment, which might be due to the low dispersion of microbubbles into the solution, leading to a slower reaction with destabilised particles [16].

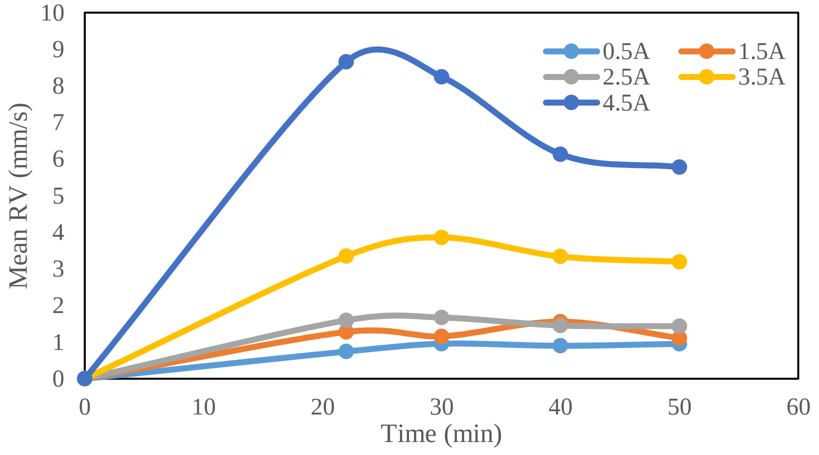

Fig. 4. The effect of varying CIs on EC with SEPs.

3.3 Comparison of the Flocs' Rise Velocity (RV) during Electrocoagulation with Vibrated (VEPs) and Stationary Electrode Plates (SEPs) throughout the Reaction Time

The condition of a solution with a soft floc mix relies on the CI utilised during EC. The *in-situ* evolution of O_2 and H_2 gas bubbles at the anode-cathode plates polarity is known as electro-flotation, which helps attract pollutants that flocculate and rise to the solution surface.

Figure 5 shows the result of a comparison between VEPs and SEPs at CI=4.5A. The mean RV of VEPs was 12.77 mm/s; it was higher than the SEPs' 8.65 mm/s at the 20th minute. For SEPs, the H_2 gas build up surrounding the electrode top layer had enhanced the electrical resistance and reducing ionic transfer across both of the electrodes [17]. Furthermore, the agitation by VEPs enhanced the movement between microbubbles and destabilised particles. For SEPs, an applied current produced a flow that only facilitated slow microbubble movement to trap pollutant particles during upward movement, leading to slow RV during flocculation-flotation. The use of vibrating electrode plates during EC for wastewater treatment has a positive impact as it reduces colour and COD by > 90% and 35%, respectively [15].

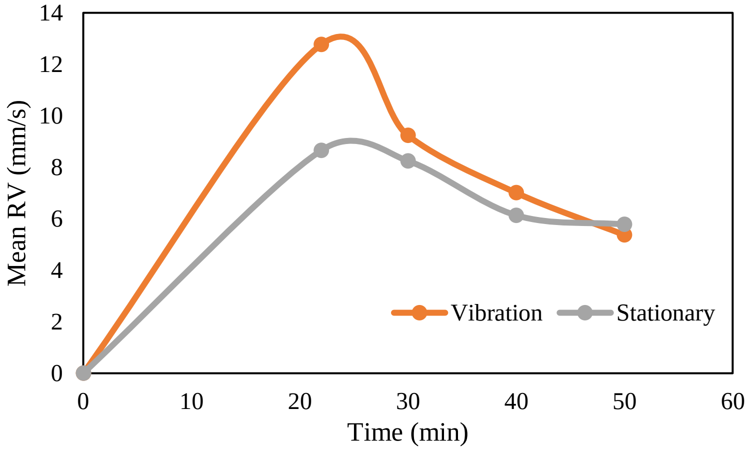

Fig. 5. The effect of reaction time on the flocs' RV between VEPs and SEPs at CI=4.5A.

4 Conclusion

Using VEPs for EC, which influence the flocs' upward movement, yields a higher mean RV of 12.77 mm/s than 8.65 mm/s for SEPs. The flocs' RV increases due to additional mixing produced by agitation, resulting in lower electrical resistance concerning ionic transfer between electrode plates. A 4.5A CI with VEPs and SEPs yields the highest mean RV. A high CI dissolves more metal ions that destabilise the flocculate particles, leading to the formation of larger flocs, while more microbubbles facilitate electro-flotation during the experiment.

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