Oscillating Electromagnetic Force Effect on Concentration Distribution near Liquid Solid Interface

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Abstract
Mass transfer near the reaction interface is often rate determining step in a high temperature process. Traditional agitation method reduces concentration boundary layer formed near the reaction interface from its outside by increasing the velocity in the bulk region. On the other hand, agitation in the concentration boundary layer is another way for intensification of the chemical reaction rate. For this purpose, excitation of flow in the concentration boundary layer is essential. Thus, effect of the static magnetic field on the solute concentration distribution near an electrode under the AC current imposition has been experimentally examined in this study. In the experiment, brightness near the interface between the copper electrode with the triangle shape and the mixed solution of 0.5mol/L CuSO₄ aqueous solution with 0.1mol/L H₂SO₄ aqueous solution was measured under the imposition of the AC electrical current of 4Vp-p and 0.5Hz. And the aqueous solution motion was estimated using polystyrene particles. As the results, the concentration boundary layer thickness decreased and the AC current concentrated around the top of the lower electrode by imposing the static magnetic field.

Keywords: oscillation, boundary layer, AC current, static magnetic field

Introduction
Rate determining step of a chemical reaction rate in industrial processes is reaction rate itself or mass transfer near the reaction interface, and the former increases with temperature increase. Thus, the mass transfer near the reaction interface is often the rate determining step in a high temperature process. The mass transfer is governed by diffusion and convection. Control of the diffusion is not easy, while the convection can be controlled through an external force. Therefore, agitation is a very common method for intensification of the chemical reaction rate. For example, not only mechanical force but also gas injection have been adopted for flow excitation in steel industry. However, strong agitation usually induces some defects such as slag entrainment [1], damage of refractory and so on. Because Schmidt number is usually larger than unity for a liquid, the concentration boundary layer thickness is thinner than the velocity boundary layer thickness. And increase in the velocity in the bulk region decreases the thickness of both the velocity and the concentration boundary layers. That is, traditional agitation method reduces the concentration boundary layer from its outside by increasing the velocity in the bulk region. However, the agitation near the interface is required for intensification of the chemical reaction rate. Thus, excitation of the flow in the concentration boundary layer is essential. On the other hand, agitation in the concentration boundary layer is another way for intensification of the chemical reaction rate. For this purpose, excitation of flow in the concentration boundary layer is essential. And, electromagnetic fields are a suitable tool since a local imposition of non-uniform force is possible. Based on this concept, some researches have been done. For example, the local agitation was observed by the superimposition of the AC current on the AC currents for dissolution of copper from a triangle shape copper electrode working as anode into an aqueous solution submerged in a static magnetic field [2]. The superimposition of the AC current on the DC current reduces the concentration boundary layer formed on a flat shape copper anode submerged in the static magnetic field [3].

These studies compared the local concentration distributions near the reaction interface formed under the imposition of the DC current and formed under the superimposition of the DC and the AC currents. However, effect of the static magnetic field on the concentration boundary layer under the AC current imposition has not been clarified until now. Thus, the effect of the static magnetic field on the solute concentration distribution near an electrode under the AC current imposition has been experimentally examined in this study.

Experimental Setup
Mixed solution of 0.5mol/L CuSO₄ aqueous solution with 0.1mol/L H₂SO₄ aqueous solution was used in this experiment. Copper electrodes was set at the top and bottom of the acrylic vessel, and the aqueous solution was filled
between them. The upper electrode was flat shape while the bottom one was four regular triangles lining up shape in which side length of each triangle was 4.3mm. The experimental setup was similar with that mentioned in reference [2]. Voltage and frequency of the AC electrical current in this experiment were 4V_p-p and 0.5Hz, respectively. Thus, the upper and lower electrodes periodically changed as anode and cathode with time, or deposition and dissolution occurred alternatively.

\[
\text{Anode } \quad \text{Cu} \rightarrow \text{Cu}^{2+} + 2e^- \quad (1)
\]

\[
\text{Cathode } \quad \text{Cu}^{2+} + 2e^- \rightarrow \text{Cu} \quad (2)
\]

Brightness of the aqueous solution changed by the chemical reaction expressed by equations (1) and (2). It increases with decrease of the copper ion concentration, and this relation can be expressed by the Lambert-Beer law. Thus, the concentration boundary layer can be estimated from the brightness measurement of the aqueous solution near the electrode. Polystyrene particles with diameter of 80 µm were used for fluid motion measurement. Their density of 1055kg/m³ was close to that of the aqueous solution of 1039kg/m³. Sedimentation velocity of the particles can be neglected because its calculated value of 5.6x10⁻⁵ m/s using the Stokes’s law was small enough. Both the brightness and the particle motion were observed from the side of the vessel using a camera. The static magnetic field was parallel to the observing direction in a horizontal plane.

**Experimental Results**

Time variation of the brightness measured at 198, 242, 264, 286 and 396 µm apart from the top of the lower electrode with the triangle shape is shown in Figures 1 and 2. The former indicates the results without the magnetic field imposition while the latter shows the results with the magnetic field imposition. The brightness at the 396 µm apart from the top roughly kept constant in the both cases of with and without the magnetic field imposition. This means that this position was in the bulk region and the concentration layer was less than 396 µm in the both cases. The brightness at the other four positions changed with 0.5Hz. This frequency was the same with the AC current frequency, and the Cu²⁺ ion concentration change was indirectly measured by the brightness. The magnetic field imposition increased the amplitude of the brightness oscillation. And this suggests that the current concentrated around the top of the lower electrode under the magnetic field imposition. Furthermore, the magnetic field imposition intensified the average value of the brightness at the positions of 242, 264 and 286 µm. This suggests that the concentration boundary layer thickness decreased by the magnetic field imposition.

![Fig.1 Brightness measured at 198, 242, 264, 286 and 396 µm apart from the top of the triangle shape lower electrode without the static magnetic field imposition.](image1)

![Fig.2 Brightness measured at 198, 242, 264, 286 and 396 µm apart from the top of the triangle shape lower electrode with the static magnetic field imposition.](image2)

Time variation of the brightness measured at 198, 242, 264, 286 and 396 µm apart from the valley point of the triangle shape lower electrode is shown in Figures 3 and 4. The former indicates the results without the magnetic field imposition while the latter shows the results with the magnetic field imposition. The amplitudes of the brightness oscillation with the frequency of 0.5Hz were smaller than those measured near the top of the electrode. This is because the AC current concentrated around the top of the electrode due to the relatively large electrical conductivity of solid copper than that of the aqueous solution. The periodical oscillation of the brightness in the case of the magnetic field imposition was not clear. This corresponds to the increase in the amplitude near the top of the lower electrode by
imposing the magnetic field, and this was caused by the concentration of the AC current around the top of the electrode as mentioned above.

![Graph showing brightness versus time](image1)

**Fig.3** Brightness measured at 198, 242, 264, 286 and 396 µm apart from the valley point of the triangle shape lower electrode without the static magnetic field imposition.

![Graph showing brightness versus time](image2)

**Fig.4** Brightness measured at 198, 242, 264, 286 and 396 µm apart from the valley point of the triangle shape lower electrode with the static magnetic field imposition.

The aqueous solution motion estimated from the polystyrene particles under the magnetic field imposition condition is shown in Figure 5. Horizontal oscillation was observed near the upper electrode and central region of the vessel, and its amplitude decreased as the observed position became lower. Around the top of the triangle shape lower electrode, curved oscillation surrounding the top was observed. On the other hand, the aqueous solution was almost static near the valley point of the lower electrode. Therefore, the aqueous solution near the top of the lower electrode must be agitated by imposing the static magnetic field, and this leads to the decrease of the concentration boundary layer and the concentration of the AC current around the top of the lower electrode.

![Aqueous solution motion](image3)

**Fig.5** Aqueous solution motion estimated from the polystyrene particles under the magnetic field imposition condition

**Conclusions**

Effect of the static magnetic field on the solute concentration distribution near the electrode under the AC current imposition has been experimentally examined in this study. In the experiment, brightness near the interface between the copper electrode with the triangle shape and the mixed solution of 0.5mol/L CuSO₄ aqueous solution with 0.1mol/L H₂SO₄ aqueous solution was measured under the imposition of the AC current of 4V peak-to-peak and 0.5Hz. And the aqueous solution motion was estimated using polystyrene particles.

The obtained results are as follows.
* The thickness of the concentration boundary layer in this experiment was less than 396 µm around the top of the lower electrode in both cases that with and without the magnetic field imposition.
* The aqueous solution was almost static near the valley point of the lower electrode.
* The amplitudes of the brightness oscillation with frequency of 0.5Hz near the valley point of the triangle shape lower electrode were smaller than those measured near the top of the lower electrode.
* The magnetic field imposition increased the amplitude of the brightness oscillation around the top of the lower electrode.
* The concentration boundary layer thickness around the top of the lower electrode decreased by the magnetic field imposition.
* The aqueous solution near the top of the lower electrode must be agitated by imposing the static magnetic field because the oscillating motion of the aqueous solution was observed.

**References**

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