CHARACTERISTICS OF CONVECTIVE MASS TRANSFER UNDER INFLUENCE OF TURBULENCE CONTROL WITH WALL-RECESS IN A PARALLEL PLATE ELECTROCHEMICAL FLOW CELL

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ABSTRACTS
This research investigated the characteristics of convective mass transfer in a parallel plate electrochemical flow cell under the influence of turbulence induced by a wall-recess that produce a separating-reattached flow field. Wall-recess was in the form of a 5 mm rearward-facing step contoured-channel which was placed upstream of the electrochemical cell to serve as a control device for turbulence level. Experimental work was done to elucidate the effect of fluid dynamical parameters to the rate of mass transfer between cell electrodes made of copper plates. The experimental set-up consisted of closed loop flow channel equipped with flow rate control and solution of CuSO$_4$ of 0.5M was used as electrolyte fluid. The measurement of rate of mass transfer was done using the limiting diffusion current technique in which local limiting current measured at micro cathodes placed in the electrochemical cell would indicate the local mass transfer coefficient ($K_m$). The current measurement was done with a precision digital multimeter interfaced by a data acquisition system to a personal computer. Some results shows that the convective mass transfer is proportionally influenced by the increase of Reynolds numbers of main flow velocity. Within the range of Re = 300 – 3000, the mass transfer coefficient increase to $K_m = 3.299 \times 10^{-4} - 3.89 \times 10^{-4}$ (m/s) which give some improvement up to 25.5 % of mass transfer rate compare to the case of electrochemical process with no flow condition. Furthermore, some correlations between Sherwood and Reynolds number are also discussed.

Keyword: wall recess, turbulence control, separating-reattached flow, convective mass transfer, electrochemical cell

1. INTRODUCTION
An abrupt change of wall contour in flow passages will change the characteristics of the flow near the wall and sometimes causes flow separation and reattachment. A typical case is the existence of wall recess in the solid boundary of a flow channel in the form of a backward facing-step. The flow separation, recirculation and reattachment such those occur behind the backstep has applications in a wide range of engineering practices. Examples include its utilizations in heat exchangers, chemical process reactors, energy system equipments, combustors, and so on. It is the alteration of the turbulence caused by the occurrence of some complex flow structure that gives significant effects to the fundamentals of transport demonstrated that the occurrence of significant change in heat transfer coefficient along the channel. Then, Yang and Kuo [5] continued the work by developing numerical analysis. Both studies suggested that the amount of injected mass will alter the turbulence characteristics which responsible to the properties in the flow field. Eventually, the effects result in a drastic change in the performance of various fluid machinery, heat transfer devices and chemical reactors and so on. Since pioneering works on the backward-facing step flow focusing on the various fundamental features of fluid dynamics involved [1]-[3], research works on the characteristic of flow passage with turbulence control using a backstep as a kind of wall recess had been made by many researchers with various flow configurations, parameters, and objective of interests both experimentally and computationally. Yang and Tsai [4] utilized a secondary fluid injection from the base wall of channel with a backstep in the upstream position and heattransfer in the whole recirculation zone. Studies on local mass transfer rates had been done by Chouikhi et al. [6] at the wall of a pipe downstream of a constricting nozzle in turbulent pipe flow at various Schmidt numbers and Oduoza et al. [7] at rectangular channel with wall obstruction. Chun and
Sung [8] and Yoshioka et al. [9] conducted researches on recirculation flow behind a backward facing step in channel with expansion ratio of 1.5 under influence of a periodical slot jet excitation with high frequency. The results showed a significant decrease of average length of recirculation zone. This decrease was found to be sensitive to injection frequency. Harinaldi, et al. [10] showed that mixing process in the recirculation zone was effectively occurred in within the region of three to five times of step height along the flow direction. Dejoan et al.[11] used Large eddy simulation (LES) and statistical turbulence closures to study the unsteady effect of external excitation from a 45° slot jet that showed a decrease in of recirculation zone length. Despite of various achievements in fundamentals understanding as well as practical issues previously mentioned, there still exist a lot of details that needs more investigations, especially to further elaborate some possibilities to enhance transport properties in the flow for practical applications. This work is part of a broader study of industrial electroplating equipment involving complex geometries and complex flows. This research investigated the characteristics of convective mass transfer in a parallel plate electrochemical flow cell under the influence of turbulence induced by a wall-recess that produce a separating-reattached flow field. Wall-recess was in the form of a backward-facing step contoured-channel which was placed upstream of the electrochemical cell to serve as a control device for turbulence level. Computational as well as experimental works were done to elucidate the effect of fluid dynamical parameters to the rate of mass transfer between electrodes.

2. EXPERIMENTAL SET UP

2.1 Flow system and Parallel Plate Electrochemical Cells

The experiment was conducted in a closed-loop electrolyte flow system as shown in Fig. 1. The flow system was design to enable electrolyte fluid to flow through a 1000 mm vertical channel made of acrylic plates. The electrolyte flow was driven by a pump and the control of flow rate entering the channel was done by-pass valve, control valve and a flow meter.

![Figure 1. Schematics of Experimental Setup](image)

The inlet section length was 300 mm and the exit section length was 250 mm. Following the inlet section, a test section of flow channel was constructed of an acrylic plate (length 100 mm; width 40 mm and thickness 5 mm) rectangular flow channel with area of 40 x 10 mm². The cathode was equipped with 32 surface flush copper mini-electrodes (diameter, 1.5 mm) arranged in two axially oriented rows in the middle of the plate. In this case, the entire cathode plate with all of its mini-electrodes lay downstream of the step. The assembly of the copper mini-electrodes on the copper macro-electrode was tedious, and was performed carefully using Araldite epoxy to secure them in position, whilst ensuring complete electrical insulation from the macro-cathode. The diagrammatic plan to serve as backstep plate and two flat plates of made of copper (length 370 mm; width 40 mm). The plates installed in parallel at a distance of 10 mm to function as electrochemical electrodes (cathode and anode). Hence, the electrodes and the side walls formed a view of the test section and electrodes arrangements is shown in Fig. 2. The electrochemical reaction was powered by a precision DC power supplied. Data acquisition system of local electrical current measurement in the mini-cathodes was constructed of a high precision digital multimeter which was connected to a personal computer via an USB connection-and-controlled with DMM data acquisition software. In each mini-cathode about 400 individual data of local current were sampled to ensure a sufficient
2.2 Limiting Diffusion Current Method

In this experimental work, the determination of local mass transfer coefficient was done by limiting diffusion current method following Chouikhi et al. [6] and Oduoza et al. [7]. Electrochemical reaction takes place between anode and cathode in the electrolyte of copper sulphate, CuSO\(_4\) (0.5 M). The local mass transfer was determined by measuring the local limiting diffusion current for the cathodic reduction of copper ion

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

Table 1. Physical properties of the electrolyte at 20°C

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>CuSO(_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, (\rho) (kg/m(^3))</td>
<td>1.072</td>
</tr>
<tr>
<td>Viscosity, (\mu) (kg/m.s)</td>
<td>0.001149</td>
</tr>
<tr>
<td>Molecular weight, (M_r) (gr/mol)</td>
<td>250</td>
</tr>
<tr>
<td>Concentration, (C) (mol/m(^3))</td>
<td>500</td>
</tr>
<tr>
<td>Diffusivity of ion, (D) (m(^2)/s)</td>
<td>(4.43 \times 10^{-10})</td>
</tr>
<tr>
<td>Schmidt number, (S_c)</td>
<td>2418</td>
</tr>
</tbody>
</table>

Prior to each experiment, the cathode surface was cleaned and polished using different grades of wet or dry paper. Voltage was then applied beyond the limiting current region of 1.2 V for about 5 min to liberate hydrogen. This had the effect of removing surface oxides. By applying a potential of 800 mV between anode and macro-cathodes, i.e. the mid-plateau region of the current-potential curves, limiting current values for each mini-electrode for a range of Reynolds numbers were determined. Local mass transfer coefficients were then calculated using the equation

\[
K_m = \frac{I}{zFAC} \quad (2)
\]

where \(I\) is the mini-electrode limiting current, \(z\) is the number of electrons exchanged (\(z = 2\)), \(F\) is the Faraday number (96 487 C mol\(^{-1}\)), \(A\) is the exposed mini-electrode area and \(C\) is the bulk CuSO\(_4\) concentration. Data from the mini-electrodes were collected and processed using the data acquisition system described above. The raw and average data values for each mini-electrode were saved to disk and accessed and processed off-line. The experiment was done in a various condition of electrolyte flow rate and the corresponding Reynolds number, \(R_e\) based on hydraulic diameter of cross section of flow passage upstream of the step are shown in Table 2.
3. RESULTS AND DISCUSSION

3.1. Characteristics of rate of mass transfer

The effect of wall recess in the form of a backstep as a turbulent control to the convective mass transfer in the electrolyte flow is indicated in Fig. 3 showing the mass transfer distributions at different Reynolds numbers along axial distance from the step in the stream wise location.

It can be seen that the distributions demonstrate a similar characteristics for every condition of $R_e$. Typically, the mass transfer coefficient, $K_m$, steeply increases just after the step to reach its maximum (peak) value and then gradually decreases up to some axial distance of about ten step height.

The mass transfer then increase again to reach another high value at far location from the step. However, compared to the case of no flow condition, the rate of mass transfer is higher only at the location of less than ten times of step height of every flow condition.

This results suggest that enhancement of the convective mass transfer seems to occurs mainly within the recirculation zone up to the average location of reattachment point. Around and after the reattachment, the fluid particles experience a highly random motion due to reattachment process.

Therefore, even though the local flow still maintain high turbulence intensity, it seems that the random motions of the fluid flow causes more significant suppression effect to the mass transfer rate.

3.2 Effect of Electrolyte Flow Rate

The effect free stream flow rate of the electrolyte to the convective mass transfer rate is presented in Fig. 4 which shows the relation between peak mass transfer coefficients (Peak $K_m$) to the Reynolds number of the electrolyte flow.

<table>
<thead>
<tr>
<th>Flow rate (liter/min)</th>
<th>$R_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>404.8</td>
</tr>
<tr>
<td>1</td>
<td>551.4</td>
</tr>
<tr>
<td>2</td>
<td>1513.2</td>
</tr>
<tr>
<td>3</td>
<td>2856.5</td>
</tr>
</tbody>
</table>

Table 2. Test condition of electrolyte flow
It can be seen from the figure that the peak mass transfer coefficient increases as the Reynolds number increases. The increase shows a tendency to be linear, at least within the range of Reynolds number in the present investigation. If compared with the value of no flow condition as previously shown in Fig. 3, the maximum peak \( K_m \) indicates as much as 25.5\% increase of mass transfer rate obtained at Re of 2856. Current results show an agreement to those of Tagg [13] which showed an enhancement of mass transfer rate in turbulent flow in the downstream of a nozzle with a sudden expansion.

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4. CONCLUDING REMARKS
This research work has investigated the characteristics of convective mass transfer in a parallel plate electrochemical flow cell under the influence of turbulence induced by a wall-recess in the form of a backstep that produce a separating-reattached flow field. Some results shows that the peak mass transfer downstream of the step is dependent on the Reynolds number, and lies between the flow recirculation and reattachment zones. The convective mass transfer is proportionally influenced by the increase of Reynolds numbers of main flow velocity. Within the range of Re = 300 – 3000, the mass transfer coefficient increase to \( K_m = 3.299 \times 10^{-4} - 3.89 \times 10^{-4} \) (m/s) which give some improvement up to 25.5\% of mass transfer rate compare to the case of electrochemical process with no flow condition.

Acknowledgements
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Nomenclature
\( A \) cross sectional area of mini-cathode (m\(^2\))
\( C \) electrolyte concentration (mole/m\(^3\))
\( D \) mass diffusivity coefficient (m\(^2\)/s)
\( d \) hydraulic diameter (m)
\( F \) Faraday constant (A.s/mol)
\( I \) Limiting diffusion current (A)
\( K_m \) mass transfer coefficient (m/s)
\( M_r \) molecular weight (g/mol)
\( Re \) Reynolds number
\( Sc \) Schmidt number
\( Sh \) Sherwood number
\( z \) electrons exchanged in electrode reaction

\[ \text{Figure 4. Peak mass transfer coefficient against Reynolds number} \]

\[ \text{Figure 5. Log scale plot of peak Sh/Sc}^{0.33} \text{against Reynolds number at the cathode,} \]

\[ \text{Figure 5 shows a log plot of Sherwood number (peak) } \text{Sh/Sc}^{0.33} \text{against the jet Reynolds number, averaged over four experiments. Here the Sherwood number is based on the hydraulic diameter of cross section of flow passage upstream of the step. This plot achieves a successful correlation of the data. The equation through the points is } \text{Sh} = 315.0 \text{Re}^{0.67} \text{Sc}^{0.33}. \text{The correlation of Tagg et al. [13] in turbulent flow with an axisymmetrical cell is also shown in this plot (Sh = 0.27Re}^{0.67} \text{Sc}^{0.33}, \text{and is seen to lie lower than the present data for Re less than about 2000 and seems to be higher for Re more than 2000.} \]
μ  dynamic viscosity (kg/ms)
ρ  density (kg/m³)

REFERENCES