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Original Article

Mass transfer coefficient augmentation in an electrolytic cell with rotating two-stage four-blade flat turbine promoter

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Abstract

The current experimental study looks at how the limiting current density is approached on using rotating 2-stage 4-blade flat turbine promoters to improve mass transfer coefficient in an open electrolytic cell. The mass transfer data are obtained at microelectrodes fixed on the cell wall and electrode support using an electrochemical method. The electrolyte was equimolal in potassium ferricyanide, potassium ferrocyanide and excess sodium hydroxide. The mass transfer coefficients were calculated using limiting current data from a diffusion-mediated electrode reduction reaction at the microelectrodes attached to the electrode supports. The limiting current technique has been particularly chosen in view of its accuracy, simplicity, negligible chemical polarization, and absence of any physical change to the reacting surface even after long exposure. The effects of geometric parameters such as turbine diameter (0.05-0.09 m), blade width (0.005-0.015m), turbine rotational speeds (250-1250 rpm) and electrolyte velocity ($0.567x10^{-3}$ to $7.93x10^{-3}$ m/s) were investigated. The mass transfer coefficients were increased by the turbulence created by rotation of the promoter turbines. The mass transfer correlation was formed in terms of dimensionless numbers: Schmidt number (Sc), Sherwood number (Sh_e), rotational Reynolds number (Re_r), and flow Reynolds number (Re_f).

Keywords: electrolytic cell, limiting current, mass transfer coefficient, turbine, electrode support

1. Introduction

The pursuit of heat and mass transfer process intensification/augmentation is never-ending (Yao, Zhao, & Chen, 2018). There has been improvements in the design and developments of electrolytic cells in the recent years, and many experiments have been directed toward electrolytic cell operation with the aim of raising current density by using various types of augmentation techniques (Leuaa, Priyadarshani, Choudhury, Maurya, & Neergat, 2020). Achieving appropriate product purity and high current output while the current density is kept low would result in significant savings in net expense and operating costs (Chandra, Rao, Kavitha, & Babu, 2018; Penta Rao, Rajendra Prasad, & Sujatha, 2018). Heat/mass transfer ratios in electrolytic processes have been steadily increasing (Kishore, Vijay, Reddy, & Ramesh, 2020; Penta Rao & Rajendra Prasad, 2018).

In electrochemical systems, the limiting current is an important parameter in assessing mass transfer rates. When an electrochemical system is run at its limiting current conditions, the reaction occurs at its optimum rate, and the hydrodynamic properties can be defined, allowing comparisons with other electrochemical systems (Naje, Ajeel,

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Mahdi, Alkhateeb, & Al-Zubaidi, 2020; Yaqub, Marappagounder, Rusli, Reddy, & Pendyala, 2020). The fundamental approach for increasing the transfer rates is to introduce turbulence into the flow. Several studies have attempted to increase current densities in electrolytic cells by using turbulence promoters (Krishna, 2001), vortex flow generators (H.A, & H.A, 2012), and by rotating the electrode / electrolytic cell (Kim, Kim, & Nam, 2019; Volgin, & Davydov, 2010). When improving the transfer coefficients, some augmentation techniques greatly complicate the process, but the use of such techniques aids in the completion of the mission more efficiently and effectively.

Prior studies have investigated the rotation of electrodes for increasing transfer coefficients. However, due to the difficulty in estimating transfer coefficients for complex rotating flow fields, the majority of the earlier experiments were carried out in relatively simple configurations such as with cones (Kappesser, Greif, & Cornet, 1973), disks (Ravi, Srinivasa Rao, Gopala Krishna, & Venkateswarlu, 1996), cylinders (Rao & Venkateswarlu, 2010), or coiled flow inverter (Sarma, Subramanyam, Murty, & Ramesh, 2019). Another sort of passive augmentation technology is to use impellers. The function of rotating impellers in enhancing the transfer coefficients is significant. A prior study (Bharathi, Kiran Appaji, Sanyasi Rao, Jagannadha Raju, & Venkateswarlu, 1997) examined the effects of spherical promoter vibration and rotation on mass transfer, both singly and in combination. The limiting current levels at the sphere's surface were calculated using an electrochemical method. The amplitude of vibration, frequency of vibration, rotation speed, and diameter of the sphere were all investigated. The values of the limiting current increased in direct proportion to the frequency, amplitude, and rotational speed. Venkateswarlu *et al*. (2010) investigated ionic mass transfer in an open cell using a rotating cone electrode made of copper. The limiting current measurements were gathered by altering the rotation speed and electrode seam diameter. On raising the rotating speed and lowering the seam diameter of the horizontal and vertical cone electrodes, mass transfer coefficients were enhanced. Naje *et al*. (2020) studied the effects of rotating impeller anodes on the ionic mass transfer coefficient in an electro coagulation reactor. The overall findings of this analysis show that as the rotational speed and anode diameter of the impeller increased, so did the limiting current density and mass transfer coefficient.

A recent study (Jagannadha Raju, Sarma, Ramesh, & Bhaskara Sarma, 2020) utilized a flow reactor with a coaxial inner cylindrical rod that revolved at various rates of rotations per minute (rpm). An increase in mass transfer coefficient k_L with liquid velocity was seen at all speeds, with the increase being more pronounced at low liquid velocities. The diffusion-controlled cathodic reaction was observed in an electrolytic cell equipped with a spinning radial flow 2-blade flat turbine (Estheru, Shrikanth, ChittiBabu, SubbaRao & Venkateswarlu, 2012). The mass transfer coefficient rose 3.3- to 16.7-fold with rotation, and 5.2- to 11-fold with rotation plus forced convection. The impact of a coaxially arranged entrance area twisted tape-disc assembly as a turbulence promoter for improving mass transfer rates in driven electrolyte convection was studied (Nageswara Rao, & Naga Rajini, 2016). The mass transfer coefficient rose with velocity, diameter of the disc, length of the tape, width of the tape, but dropped with pitch of the tape and tape-disc distance, according to the findings. The increases in mass transfer coefficients obtained throughout the spectrum of variables investigated was up to 5 times that of tube flow without a promoter.

The present work leads to useful information on mass transfer in a rectangular open electrolytic cell as concerns the effects of rotating 2-stage 4-blade flat turbine promoters in electrolyte flow. The objective of the study is to develop a transport correlation that will help design improvements of electrolytic cells. Mass transport data were obtained electrochemically at microelectrodes connected to the electrode support. The electrochemical method is accurate and convenient in the measurement of local mass transfer coefficients. The limiting current technique has been particularly chosen in view of its accuracy, simplicity, negligible chemical polarization and absence of any physical change to the reacting surface even after long exposure. For mass transfer observations utilizing limiting current measurements, a diffusion-mediated redox reaction involving potassium ferricyanide and potassium ferricyanide pair was employed. We have investigated the impacts of turbine diameter, turbine blade distance, turbine rotational speed, and electrolyte velocity on the mass transfer coefficient, using rotating 2-stage 4-blade flat turbine promoters, to create an adequate mass transfer correlation.

2. Experimental Setup and Methodology

The experimental setup for the investigation is illustrated in Figure 1 and has been utilized in previous studies (Chandra *et al*., 2018). Table 1 summarizes the ranges of variables studied in this investigation. As seen in Figure 2, sixteen microelectrodes were placed in four rows and four columns on the surface of the electrode support. The limiting currents for the reduction of ferricyanide ions were determined electrochemically at the microelectrodes. The electrode support is 0.04 m above the floor of the cell and 0.28 m from the cell entrance. The copper anode is placed 0.05 m from the cell's opposite end. The two-stage four-blade flat turbine promoter is securely attached to the motor's shaft, and the motor is safely mounted on a pedestal. The electrolyte had 0.01 N potassium ferricyanide, 0.01 N potassium ferricyanide, and 0.5 N sodium hydroxide. The electrolyte was pumped at the necessary flow rate from the storage tank. The motor rotates the 2-stage, 4-blade flat turbine promoter illustrated in Figure 3 at the appropriate speed. The turbine's rotating speed is regulated using a speed regulator, and the speed is monitored with a digital tachometer. Following the determination of the flow rate, a voltage is applied in tiny increments across the microelectrode and copper anode, and the current is measured for each increment. A small change in current for a large increase in potential indicates that the limiting current has been achieved. All the microelectrodes on the electrode support have their limiting current measurements collected. The trials were repeated with various electrolyte flow rates at a constant rotation speed. At various flow rates and rotational speeds, the effects of turbine blade width and diameter were investigated. The average mass transfer coefficient was determined as $k_{Le} = i_{de}/(nFC_i)$.

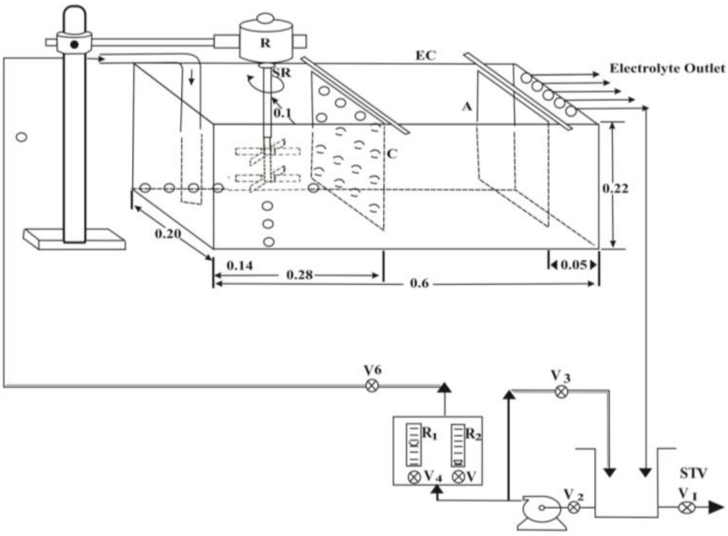

Figure 1. Schematic diagram of the experimental set-up (dimensions in 'm') EC – Electrolytic cell, T –Flat blade turbine promoter, C-Electrode support, CP-Centrifugal pump, A- Copper anode, M-Microelectrode, S-Stand, SR-Shaft rod, R – Motor, X- Flow inlet, and Y- Flow outlet

Table 1. The ranges of variables studied

Variable	Minimum	Maximum
Volumetric flow rate, Q, m^3/s	3.365×10^{-5}	47.117×10^{-5}
Width of the turbine blade, w, m	0.005	0.015
Diameter of the turbine, d, m	0.05	0.09
Rotational speed, N, rpm	250	1250
Flow Reynolds number, Re_f	189	2659

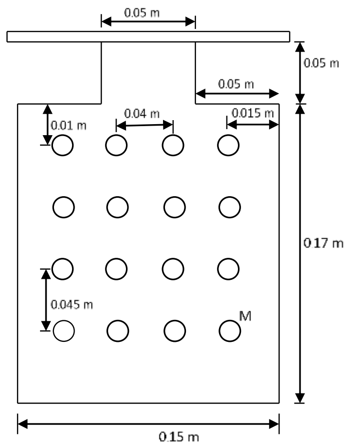

Figure 2. Details of the electrode support (M – Microelectrode)

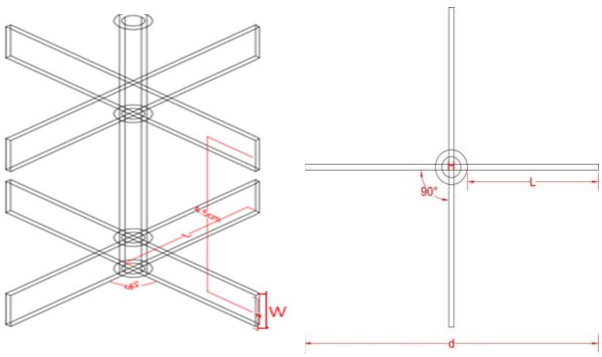

Figure 3. Two stage four blade flat turbine promoter

Figure 4. Experimental setup

3. Results and Discussion

The mass transfer coefficient is determined by the flow patterns created by turbulence inside the electrolytic cell. The flow pattern is determined by the geometry of the cell with its components, their sizes, and the rotating speed (Chandra *et al*., 2018). By spinning the 2-stage, 4-blade flat turbine promoters in an electrolytic cell at various operating conditions, mass transfer data were collected at all the microelectrodes on the electrode support.

3.1 Discussion on effects of operational parameters

The mass transfer coefficients were calculated using the limiting current density data.

3.1.1 Effect of the height of the turbine promoter

For a particular rotational speed and other relevant factors, the average mass transfer coefficient (k_{Le}) was computed as the simple arithmetic average of the local mass transfer coefficients at all microelectrodes on the electrode support. In Figure 5 (a), the average mass transfer coefficient is shown versus the height of the turbine promoter from the cell bottom. Even with different turbine diameters and blade widths, higher mass transfer coefficients are found at a turbine promoter height of 0.07 m. As a result, all further tests were conducted with 0.07 m height of the turbine promoter, in order to get greater mass transfer coefficients.

3.1.2 Effects of microelectrode position

Figure 5(b) depicts the influence of microelectrode height from cell bottom on local mass transfer coefficient. The mass transfer coefficients are found to be greater at microelectrodes set at heights of 0.08 m and 0.13 m, over the other heights. This is due to the promoter's placement covering both electrodes located at such heights.

3.1.3 Effects of electrolyte velocity

Graphs were plotted of average mass transfer coefficient (k_{Le}) versus electrolyte velocity with 'w' and 'd' as parameters, shown in Figure 5 (c) and (d) respectively, to assess the effects of individual parameters. From the plot in Figure 5 (c), it is observed that k_{Le} increased with electrolyte velocity. The cross-plot shown in Figure 5 (c) also indicates enhanced average mass transfer coefficient with increased turbine blade width. The increased turbulence produced by swirl formation decreases the film thickness on the microelectrode, leading to more diffusion and larger mass transfer coefficient. The higher the average mass transfer coefficient, the greater the swirl intensity due to the wide turbine width. As demonstrated in Figure 5 (d), increasing the diameter of the turbine increased the transfer coefficient k_{Le}. More turbulence was created by larger turbine diameters due to greater electrolyte movement, affecting the microelectrodes attached to the electrode support.

3.1.4 Effects of rotational speed

To avoid electrolyte overflow, the limiting current data of the two-stage four-blade flat turbine promoters were collected at various rotational speeds. Figure 6(a) shows a plot of k_{Le} against v_f for various rotational speeds to highlight the effects of the turbine promoter's rotating speed on k_{Le}. It has been observed that as the rotational speed rises, so does the value of k_{Le}. Figure 6 (b) is a plot of the average mass transfer coefficient versus rotational speed for a constant electrolyte flow rate using turbine blade width as a parameter. The graph illustrates that when the turbine promoter's rotational speed increases, so does the average mass transfer coefficient. Turbulence created by turbine rotation scours away the fluid boundary layer near the electrode support, lowering resistance and leading to greater mass transfer rates.

3.2 Augmentation of the mass transfer coefficient

Figure 6(c) shows the magnitudes of augmentation that may be accomplished in the presence of spinning flat blade turbine promoters over the electrolyte's induced convective flow. The mass transfer coefficient augmentation is represented as $(k_{Le}/k_{Lf})^{-1}$and displayed vs. v_f. The rotation of the two-stage four-blade flat turbine promoter increases the

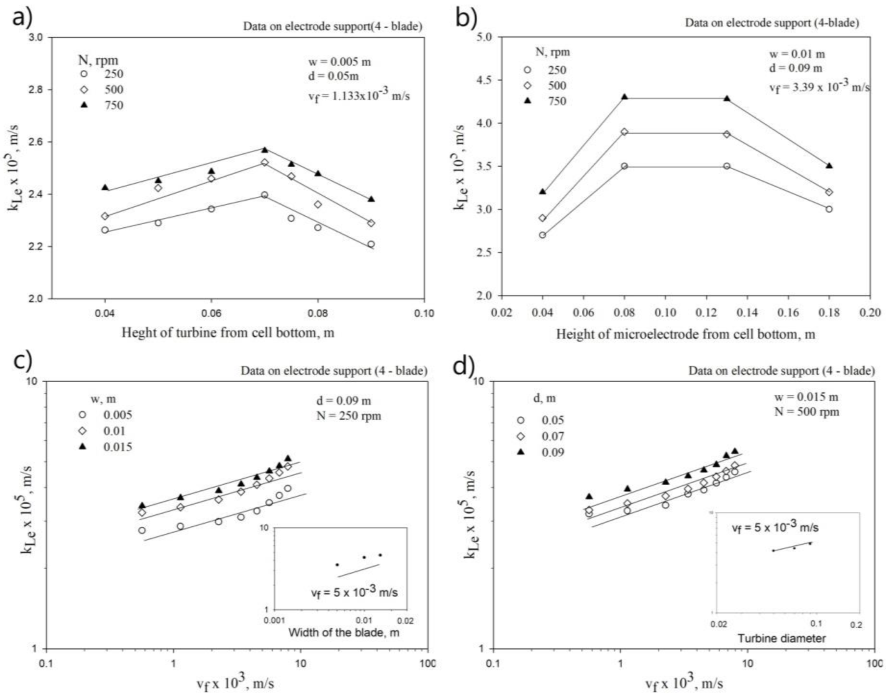

Figure 5. (a) Effect of height of two stage four blade flat turbine promoter from cell bottom on average mass transfer coefficient; (b) variation of mass transfer coefficient with electrode height; (c) effect of electrolyte velocity on average mass transfer coefficient with turbine blade width as parameter; and (d) effect of electrolyte velocity on average mass transfer coefficient with turbine blade width as parameter

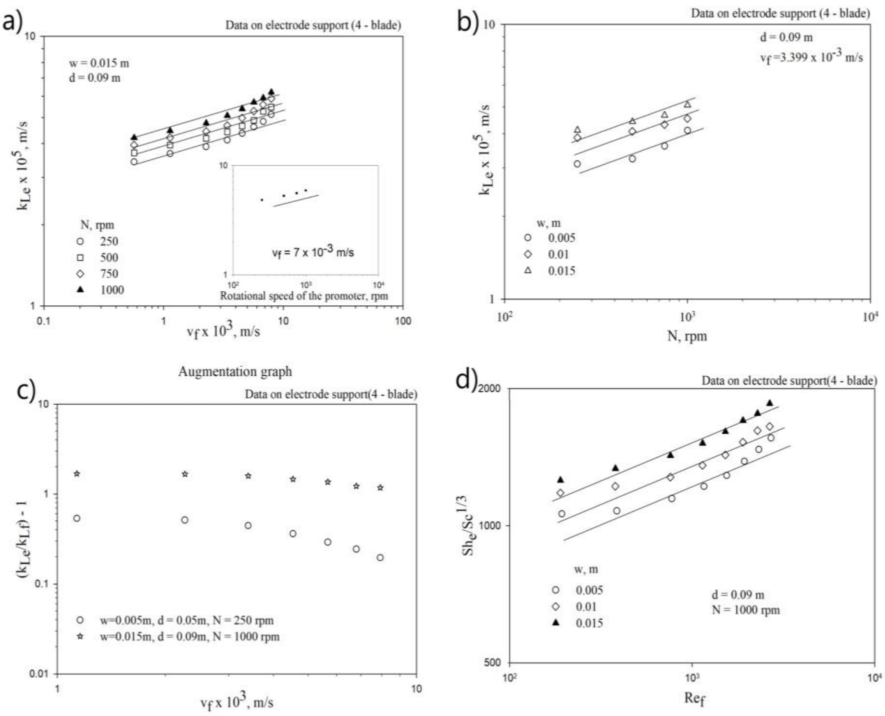

Figure 6. (a) Effect of electrolyte velocity on average mass transfer coefficient for different rotational speeds of turbine promoter; (b) the average mass transfer coefficient as a function of rotational speed with turbine blade width as parameter; (c) augmentation of average mass transfer coefficient due to rotation over forced convection flow; and (d) $Sh_e/Sc^{1/3}$ as a function of flow Reynolds number with turbine blade width as parameter

average mass transfer coefficient from 19.5% to 168.3% in the range of variables examined. In our earlier work (Chandra *et al.*, 2018), the mass transfer coefficient increased from 16.7% to 154.5% for a 2-stage 2-blade flat turbine promoter. The augmentation owing to turbine promoter rotation and forced convection flow over the stationary electrolyte ranges from 7.5- to 19.6-fold.

3.3 Correlation of the mass transfer data

The present mass transfer data were expressed as $Sh_e/Sc^{1/3}$. Plots of $Sh_e/Sc^{1/3}$ vs. flow Reynolds number (Re_f) are shown in Figure 6 (d) for different blade widths. This plot reveals the effects of the blade width as observed in also the plot between k_{Le} and v_f in Figure 5(c). Based on the above observations, the present data obtained on electrode support were used to fit $Sh_e/Sc^{1/3}$ as a function of Re_r and Re_f. The regression analysis of entire data yielded the equation $Sh_e/Sc^{1/3} = 53.95\ Re_r^{0.211}\ Re_f^{0.136}$. The average deviation was 7.55% and the standard deviation was 9.65%.

4. Conclusions

To better understand the improvement of mass transfer coefficient in an open electrolytic cell from spinning two-stage four-blade flat turbine promoters, an experimental study was carried out. The mass transfer coefficients were determined using limiting currents of microelectrodes connected to an electrode support, during a diffusion-controlled reduction process. The mass transfer coefficient was studied in relation to electrolyte velocity, turbine rotational speed, turbine diameter, and turbine blade width. The dimensionless factors Sherwood number, Schmidt number, flow Reynolds number, and rotational Reynolds number were used to create mass transfer correlations.

Here are the significant findings of the study.

- A turbine height of 0.07 m from the cell bottom yields the highest mass transfer coefficient.
- The electrode distance from the cell wall has no influence on the mass transfer coefficient.
- Rotation of the flat blade turbine promoter increases the mass transfer coefficient from 7.5- to 19.6-fold.
- In the range of variables examined, the mass transfer coefficients rise from 19.5% to 168.3% owing to turbine promoter rotation.
- The data are well fit by the equation: $Sh_e/Sc^{1/3} = 53.95\ Re_r^{0.211}\ Re_f^{0.136}$

As a consequence, the current investigation shows that augmentation of mass transfer coefficients in electrolytic cells using the promoters was successful.

This present investigation is encouraging and useful in the design of open electrolytic systems with enhanced mass transfer. There is an ample scope for research in the future to develop innovative electrolytic systems with augmented performance.

Nomenclature:

C_i	Concentration of ferri cyanide ions [kmol/m^3]
d	Diameter of the turbine [m]

d_e	Equivalent diameter of the cell [m]
F	Faraday's constant [Coulombs]
i_{de}	Average limiting current density [amp/m^2]
n	Number of electrons involved in reduction
N	Rotational speed of the turbine [rpm]
Q	Volumetric flow rate of electrolyte [m^3/min]
Re_f	Flow Reynolds number = $\rho d_e v_f / \mu$
Re_r	Rotational Reynolds number = $dvr/ \rho \mu$
Sc	Schmidt number = $k_{Le}\, d_e / D_L$
Sh_e	Sherwood number = $\mu/ (\rho\, DL)$
v_f	Velocity of the electrolyte [m/s]
v_r	Rotational velocity of turbine [m/s]
μ	Viscosity of the electrolyte [N-s/m^2]

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