

CONTROL OF TURBULENT MASS TRANSFER IN BACKWARD-FACING STEP FLOW USING ACOUSTIC EXCITATION

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ABSTRACT

An acoustic excitation serves as a mean of turbulent control of an electrolyte flow in a backward-facing step channel equipped with electrochemical cells to improve convective mass transfer of an electrochemical process. Comprehensive experimental works were done on the effects of fluid dynamical and acoustics excitation parameters on the rate of mass transfer between electrodes. The solution of CuSO_4 of 0.5 M (mol/l) was used as the electrolyte fluid. The rate of mass transfer was determined by measuring the local limiting current at mini cathodes placed in the electrochemical cell. Some results showed that the acoustic excitation altered the rate of mass transfer in the flow field. As the Reynolds number increases the influence of acoustics excitation on the enhancement of mass transfer rate becomes less significant and the maximum mass transfer coefficients tend to converge into a single value. Furthermore, there exists an optimum Strouhal number of excitation that will support an optimum rate of mass transfer which may be attributed to the existence of optimum effective forcing frequency to support the production of large scale vertical structure in the shear layer and vortex amalgamation process in a separating-reattached flow.

Keywords : *Backward-facing step, turbulent control, acoustic excitation, mass transfer*

1.0 INTRODUCTION

A fluid flow experiencing separation and reattachment has long been a subject of fundamental fluid dynamics research. The presence of these two mechanisms gives rise to increased unsteadiness, pressure fluctuations, structure vibrations and noise. Also, they enhance heat and mass transfer and augment mixing [1]. An important technological outcome of the basic research on separated flows is thus related to studies about methods aimed at controlling the unsteadiness around the separated region. In this context, the backward facing step flow is an appropriate test case for real-life separated flows because of several reasons. It shows essentially all the flow features of the practical engineering applications where separation and reattachment occur; moreover, the geometry is very simple and easily reproducible [2].

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Review on some past studies reveals that there have been many attempts to control or lessen the unfavorable behavior associated with separated and reattaching flows. One of the early attempts of flow control by periodic perturbation was made by Bhattacharjee, et.al [3]. They applied an acoustic perturbation to a flow behind a backward-facing step, and revealed that the enhancement of the spread of the shear layer occurred due to the production of large scale vertical structures in the shear layer, enabling the promotion of the reattachment. Chun and Sung [4] mentioned that vortex amalgamation process could be captured at the effective forcing frequency for laminar separation. This vortex merging process enhances flow mixing, which leads to the shortening of the reattachment length. In a study of periodically perturbed separated flow over backward-facing step, Yoshioka et.al [5] showed that there existed an optimum frequency for the promotion of reattachment. When the perturbation at the optimum frequency was applied, Reynolds stress markedly increased near the reattachment and enhanced the momentum transfer across the shear layer. Another study by Sigurdson [6] also concluded the existence of an optimum frequency for the promotion of vortex merging process.

Meanwhile, some other researches focusing on the alteration of rate of mass transport properties in a separating-reattached flow configuration has been done since the pioneering works by Krall and Sparrow [7], and Runchall [8]. In those works they utilized controlled electrolysis by diffusion and reported rate of mass transfer in a relatively wide range of Schmidt and Reynolds number in the separation region and redeveloping layer in the downstream of a sudden expansion flow. In typical kind of studies, Hung and Lin [9] and Oduoza and Wragg [10] also showed that an installation of turbulence promoter could improve heat and mass transfer in the flow channel. Furthermore, a study to obtain fundamental understanding of mass transfer improvement with hydrodynamics turbulence control had been conducted by Harinaldi [11] for an electrodeposition process.

This research investigated the characteristics of convective mass transfer in a parallel plate electrochemical flow cell under the influence of acoustics excitation in a backward-facing step contoured-channel. The acoustics source was placed upstream of the electrochemical cell to serve as a control device for turbulence level. An experimental work based on the limiting diffusion current method to measure local convective mass transfer rate [12] was done to elucidate the effect of fluid dynamical and acoustics excitation parameters to the rate of mass transfer between electrodes.

2.0 EXPERIMENTAL METHOD

2.1 Flow System Arrangement

The characteristics of the turbulent control on the mass transfer by an acoustics forcing was experimentally investigated in an electrodeposition facility. Main purpose of the experimentation was to determine the coefficient of mass transfer and to visualize the electrodes condition after the electrodeposition process. The experiment was done in a closed-loop electrolyte flow system as schematically shown in Figure 1.

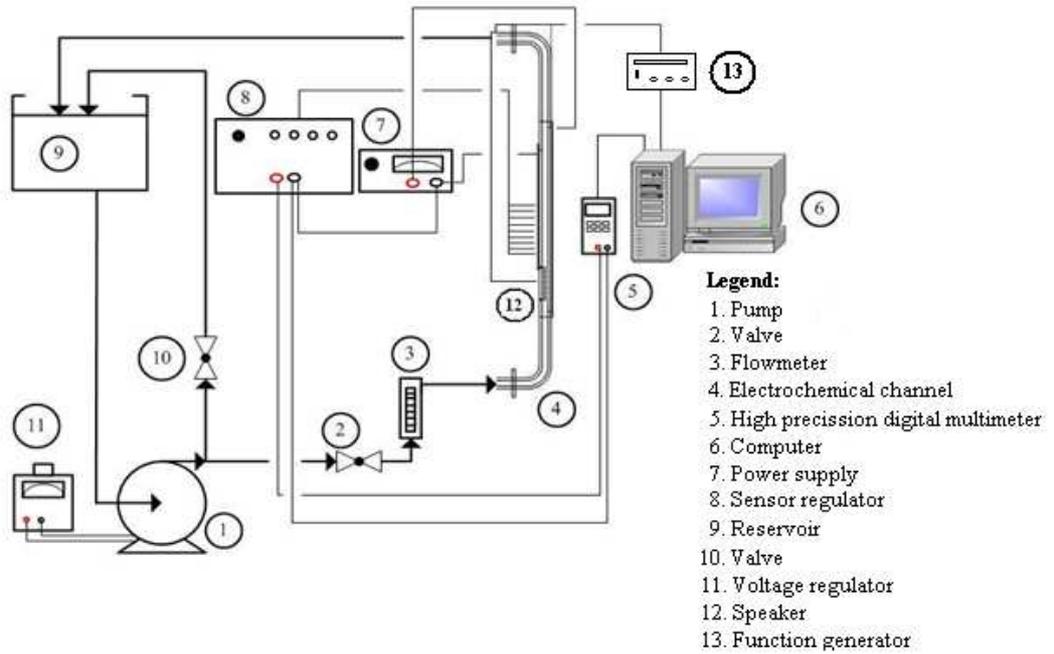


Figure 1: A closed loop electrolyte flow system

The flow system was designed to enable electrolyte fluid initially placed in the reservoir to run through a vertical channel made of acrylic plate of 1000 mm long. The flow was driven by a pump and the flow rate control was done by some valves and a flow meter. The length of inlet prior to the test section was 200 mm. As shown in Figure 2, at the upstream of the test section channel was constructed from an acrylic box of 100 mm long, 40 mm wide and 5 mm high to provide a backstep contour in the channel base wall with step height, $h = 5$ mm. Furthermore, inside the box a loud speaker was installed to provide an acoustic excitation force generated from a function generator and controlled by a computer. After the step edge, the test section was 300 mm long and two copper plates of 250 mm long and 40 mm wide was connected to the lower and upper base walls. The two plates were arranged parallel with separation distance of 10 mm and served as electrodes (anode and cathode) for electrochemical reaction.

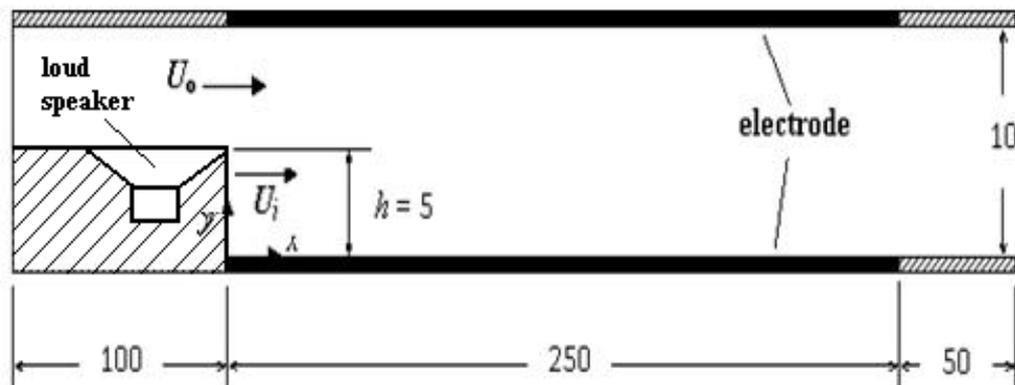


Figure 2 : Test section of backward facing-step with acoustic excitator

The arrangement of electrodes and side walls made of acrylic plates formed a rectangular channel with cross sectional area of 40 mm x 10 mm. The cathode plate was equipped with 48 mini electrodes, each having diameter of 1.5 mm and placed in flush surface to the cathode plate in two axial rows at the center of the cathode. These mini electrodes were isolated from the cathode plate with insulation made of epoxy. Figure 3 shows the arrangement of mini electrode in the cathode plate.

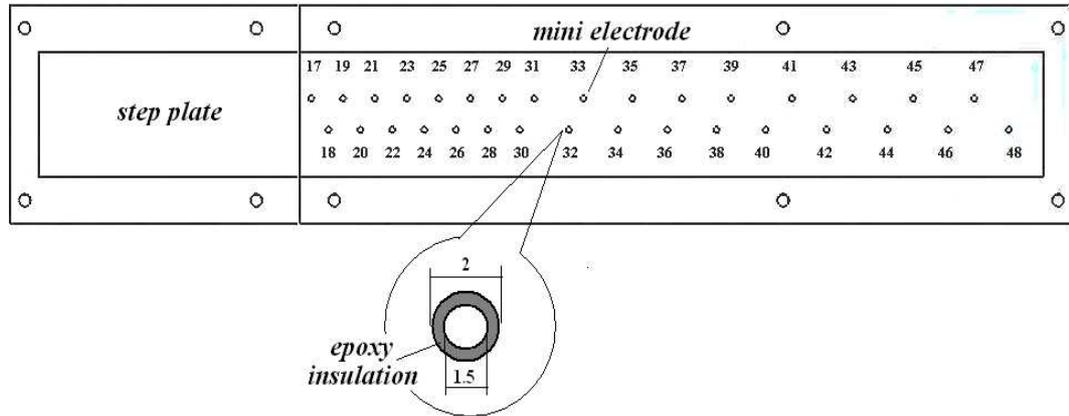


Figure 3: Arrangement of mini electrodes in the cathode plate

The chemical reaction was driven by electricity from a DC power supply. The data acquisition system for local current measurement in the mini electrodes was configured from a high precision digital multimeter connected to a computer via a USB data cable and controlled by DMM[®] data acquisition software. In each mini electrode 400 data of local current were measured to confirm sufficient number of data to make statistical averaging in the highly fluctuated flow condition. Preliminary assessment resulted in a statistical uncertainty of less than 1 % for the local current measurement.

2.2 Limiting Diffusion Current Method

In the experiment, the determination of local mass transfer coefficient was conducted by a limiting diffusion current method following the principles described by Quiroz et al. [12]. The chemical reaction occurred between anode and cathode in electrolyte fluid 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:



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 within the mid-plateau region of the current-potential curves between anode and macro-cathodes, limiting current values for each mini-electrode were determined. Local mass transfer coefficient, K_m was then calculated using Equation (2).

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

where I is the mini-electrode limiting current, z is the number of electrons exchanged ($z = 2$), F is the Faraday number (96487 C mol^{-1}), A is the exposed mini-electrode area and C is the bulk CuSO_4 concentration. More detail of the measurement procedure can be referred to another report [11].

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 various conditions of electrolyte flow rate and various excitation frequencies and intensities of sinusoidal acoustic wave. The corresponding Reynolds number, Re based on hydraulic diameter of cross section of flow passage upstream of the step ($d_h = 8.9 \text{ mm}$) and some other experimental conditions are shown in Table 1.

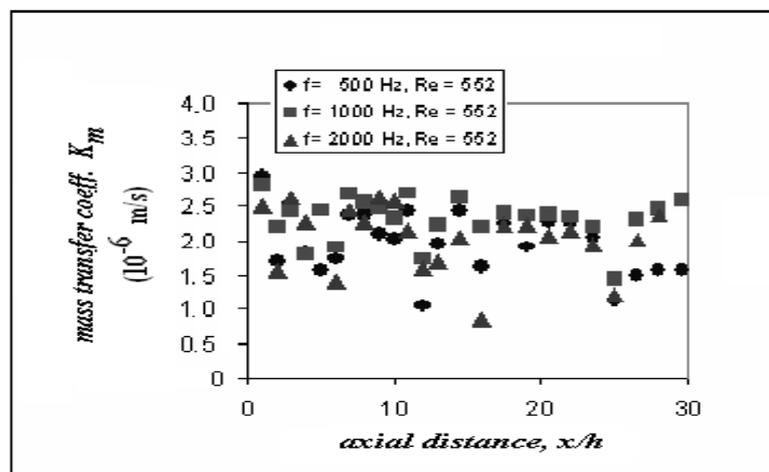
Table 1: Experimental Conditions

Density CuSO_4	1072	kg/m^3
Viscosity CuSO_4	1.7×10^{-6}	m^2/s
Concentration CuSO_4	0.5	M
Channel Area	0.0004	m^2
Step Height	5	mm
Microelectrode Area	1.5×10^{-6}	m^2
Main flow, Re	400-5000	
Excitation Intensity, I	48, 95	dB
Excitation freq, f	500-2000	Hz
Excitation Strouhal, St	10-150	

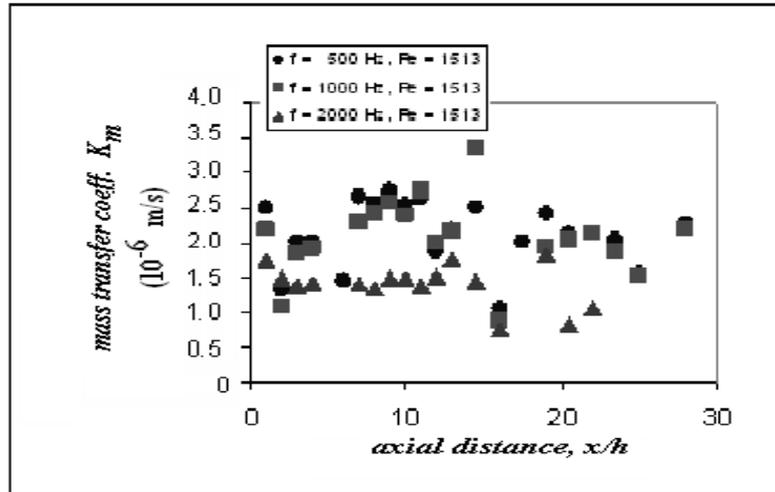
3.0 RESULTS AND DISCUSSION

3.1 Distribution of Mass Transfer Coefficient

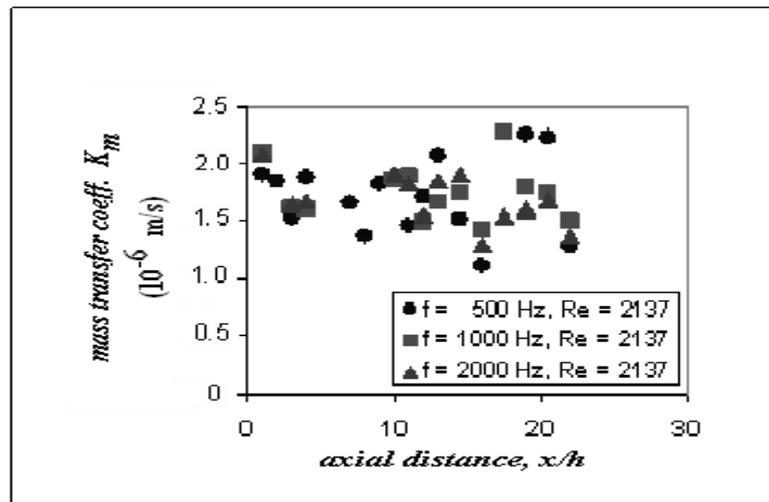
The distribution of convective mass transfer coefficient, K_m along axial direction ($x/h = 0-30$) obtained from experimental measurement is shown in Figure 4. The distributions are for the case of flow with (a) $Re = 552$, (b) $Re = 1513$ and (c) $Re = 2137$ excited at 95 dB, each with various excitation frequency. For every case of Reynolds number, the distribution indicates that within the most part of the region of flow field downstream of the step edge, the increase of excitation frequency will make the convective mass transfer coefficient decreases. Besides, it is also observable that with lower Re , the distribution of mass transfer coefficient along axial direction covers higher range values compare to that of higher Re .



(a) $Re = 552$



(b) $Re = 1513$



(c) $Re = 2137$

Figure 4: Distribution of convective mass transfer coefficient, K_m along axial direction (x/h) at various excitation frequency at Reynolds number (a) $Re = 552$, (b) $Re = 1513$ and (c) $Re = 2137$

3.2 Effect of Reynolds Number

One of the important aspects related to the mass transfer characteristics which become the main interest in this research is the maximum rate of mass transfer represented by maximum mass transfer coefficient that can be obtained by acoustics control of turbulence. Figure 5 shows the graphs of relation between the maximum mass transfer coefficient ($K_{m,max}$) and the Reynolds number of the electrolyte flow at various frequency of acoustics excitation. For all cases the excitation intensities are 95 dB.

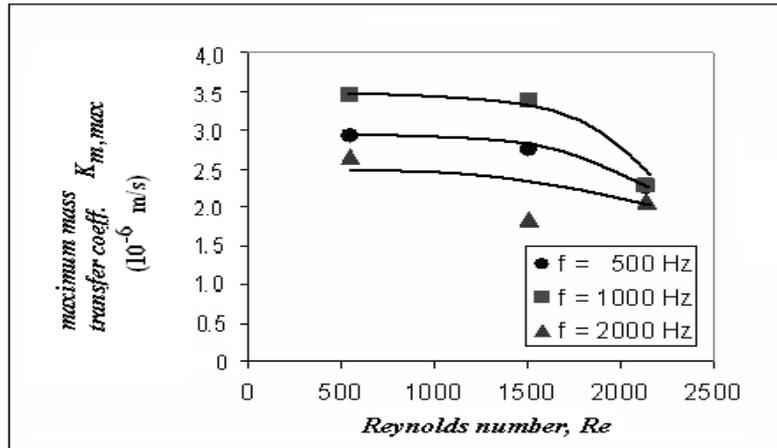


Figure 5: Effect of Reynolds number on the maximum mass transfer coefficient, $K_{m,max}$ at various frequency of excitation

From Figure 5 it can be understood that under acoustics excitation for a certain frequency, the increase of Reynolds number of the electrolyte flow will suppress the rate of convective mass transfer indicated by the decrease of maximum mass transfer coefficient. It seems that the promotion of the transport properties across the shear layer by the enhancement of vortex merging under an acoustics forcing such those mentioned in past studies [3 - 6] become less remarkable when the upstream flow is faster. Another indication that can be observed from Figure 5 is that at the highest Reynolds number of the present experiment, the maximum mass transfer coefficients tend to converge into a certain value under all excitation frequencies. Furthermore, this tendency is also observed for the case of excitation at 48 dB.

3.3 Effect of Frequency of Excitation

The effect of frequency of acoustics excitation to the rate of convective mass transfer is shown in Figure 6. Here, the excitation frequency is expressed as non-dimensional Strouhal number, St based on the upstream main flow velocity (U_o) and the step height (h) as $St = f h/U_o$. Meanwhile, the rate of convective mass transfer is represented by the maximum mass transfer coefficient ($K_{m,max}$). For all cases the excitation intensities are 95 dB.

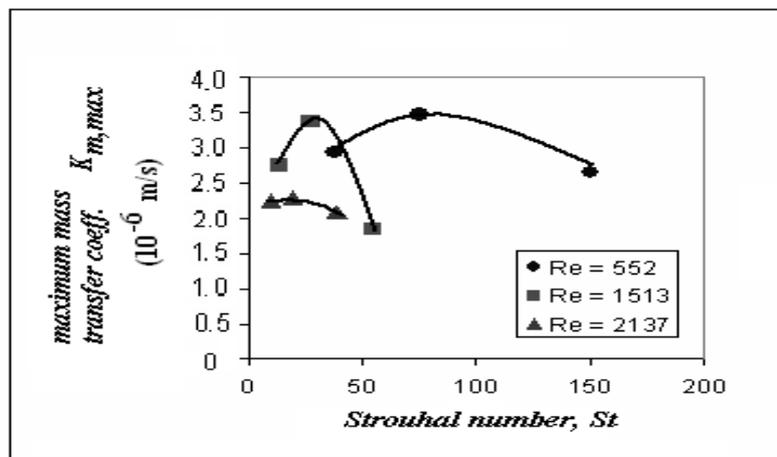


Figure 6: Effect of Strouhal number, St on the maximum mass transfer coefficient, $K_{m,max}$ at various Reynolds number

From Figure 6 it can be seen observed that for every flow condition with acoustics excitation there exists an optimum Strouhal number of excitation that will support an optimum rate of mass transfer presented by maximum value of $K_{m,max}$. This result may be attributed to the past findings of the existence of optimum effective forcing frequency to support the production of large scale vertical structure in the shear layer and vortex amalgamation process in a separating-reattached flow such that in a backward-facing step flow configuration [3 - 6]. This study postulates that the resonance mechanism between the frequency of acoustics excitation and the frequency of vortex shedding responsible for the enhancement of the vortex growth in the separated shear layer which eventually increase the turbulent transport properties. Moreover, the figure also indicates a less significant influence of acoustics excitation to the enhancement of mass transfer rate in case of flow with high Reynolds number.

3.4 Effect of Intensity of Excitation

Figure 7 shows the effect of intensity of acoustic excitation on the rate of convective mass transfer. In the figure, two series of values of maximum mass transfer coefficient, $K_{m,max}$ for various acoustic excitation Strouhal number obtained at intensities of 48 dB and 95 dB are compared. In general, it can be clearly observed that acoustic excitation with higher intensity will increase the rate of mass transfer for the same Strouhal number. This result is not surprising since higher intensity of excitation will cause higher turbulence intensity which support transport properties in the flow field.

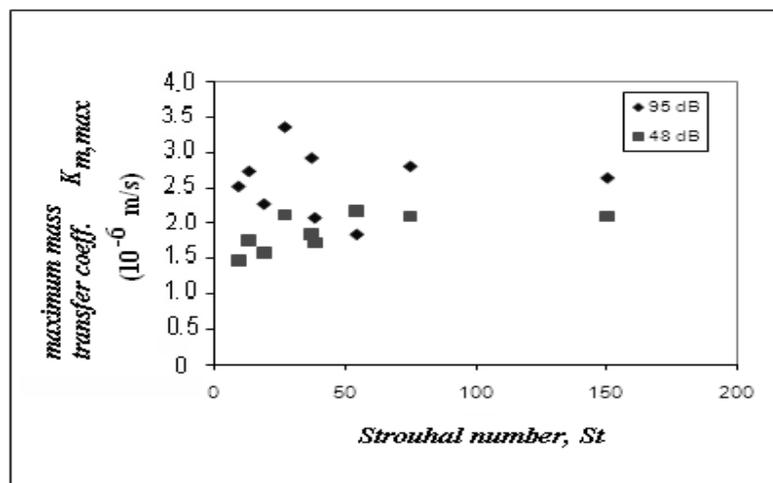


Figure 7: The maximum mass transfer coefficient, $K_{m,max}$ for excitation intensity at 95 and 48 dB

3.5 Appearance of Deposition in Cathode Surface

Considering the possible future application of mass transfer enhancement in manufacturing field especially in electroplating industry, visual observation to the surface of electrodes after the electrochemical process was done to get a qualitative description about the effect of acoustic turbulence control to the deposition characteristics. Figure 8 shows the photographs of electrodes surface after an electrochemical reactions under the turbulent control by the acoustic excitation of present experiments. The process generated a sufficiently uniform thickness distribution of deposition in the whole cathode surface from the upstream to the downstream part.

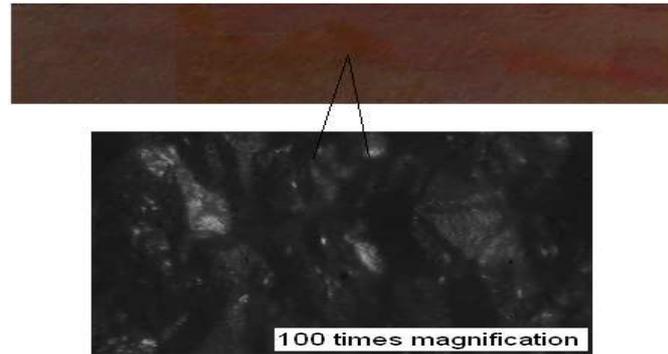


Figure 8: Photographs of cathode surface

4.0 CONCLUSIONS

An investigation on the effects of an acoustics excitation as a method of turbulent mass transfer control behind a backward facing step flow of electrochemical cell has been done comprehensively through an experimental work based on limiting diffusion current technique. Some conclusions obtained are as follow:

- i. As the Reynolds number increases the influence of acoustics excitation on the enhancement of mass transfer rate becomes less significant indicated by the maximum mass transfer coefficients which tend to converge into a certain value under all excitation condition at higher Reynolds number.
- ii. An acoustic excitation with higher intensity will increase the rate of mass transfer for the same Strouhal number
- iii. There exists an optimum Strouhal number of excitation that will support an optimum rate of mass transfer which may be attributed to the existence of optimum effective forcing frequency to support the production of large scale vortical structure in the shear layer and vortex amalgamation process in a separating-reattached flow

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REFERENCES

1. Vogel, J.C and Eaton, J.K., 1985. Combined Heat Transfer and Fluid Dynamic Measurements Downstream of a Backward-facing Step. *ASME Journal. Heat Transfer*, 107, 922-929
2. Spazzini, P.G., Iuso, G., Zurlo, N., Di Cicca, G.M and Onorato, M., 2000. Flow Control Downstream of a Backward-Facing Step, *Proceeding of 22nd International Congress of Aeronautical Sciences*, Herrogate-UK, 2102.1-10
3. Bhattacharjee, S., Scheelke, B. and Troutt, T.R., 1986. Modification of Vortex Interaction in a Reattaching Separated Flow. *AIAA Journal*, 24, 623-629
4. Chun, K.B. and Sung, H.J., 1998. Visualization of a Locally Forced Separated Flow Over a Backward-Facing Step. *Experiments in Fluids*, 25, 133-142

5. Yoshioka, S., Obi, S. and Masuda, S., 2001. Turbulence Statistics of Periodically Perturbed Separated Flow Over Backward-Facing Step. *International J. Heat and Fluid Flow*, 22, 393-401
6. Sigurdson, L.W., 1995. The Structure and Control of a Turbulent Reattaching Flow. *Journal of Fluid Mechanics*, 298, 139-165.
7. Krall, K.M. and Sparrow, E.M., 1966. Turbulent Heat Motion and Turbulence Downstream of a Rough Circular Tube. *Journal of Heat Transfer*, 88, 131-136
8. Runchall, A.K., 1971. Mass Transfer Investigation in Turbulent Flow Downstream of Sudden Enlargement of a Circular Pipe for Very High Schmidt Numbers. *International J. Heat and Mass Transfer*, 14, 781-792
9. Hung, Y.H. and Lin, H.H., 1992. An Effective Installation of Turbulence Promoters for Heat Transfer Augmentation in a Vertical Rib-Heated Channel. *International J. Heat and Mass Transfer*, 35, 29-42
10. Oduoza, C.F and Wragg, A.A., 2000. Effects of Baffle Size on Mass Transfer in a 3-D Rectangular Cell. *J. of Applied Electrochemistry*, 30, 1439-1444
11. Harinaldi, 2011. On the Hydrodynamics Turbulent Control of Mass Transfer in Electrodeposition Process. *International J.Mechanical & Mechatronics Engineering - IJENS*, 11(01), 1-7
12. Quiroz, M.A., Martinez-Huitel, U.A. and Martinez-Huitel, C.A., 2005. Mass Transfer Measurements in a Parallel Disk Cell Using the Limiting Current Technique. *J. Mex .Chem. Soc.*, 49(3), 279-283