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Mass Transfer Enhancement Using Extensions as Turbulence Promoters

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Abstract

Mass transfer was studied using a rotating cylinder electrode with different lengths of legs acting as turbulence promoters. Two types of rotating cylinder ,made of brass, were examined : an enhanced cylinder one, with four rectangular extensions 10 mm long, 10 mm wide, and 1mm thick, and an enhanced cylinder two with four longitudes 30 mm long,10 mm wide, and 1mm thick. The best performance was obtained for enhanced cylinder two at low rotation speeds while enhanced cylinder one was realized at high rotation speeds. The mass transfer enhancement as compared with a normal rotating cylinder electrode, devoid of promoters, is 53% or 58% higher. The enhancement percentage decreased as rotation speeds increased further, since, seemingly, full turbulence has been reached practically by means of rotation and turbulence promoters.

Key Words: electrochemical reactors, mass transfer, rotating cylinder electrode, limit current, turbulence promoter.

Introduction

The legal limitations for environmental protection require the development of reliable and cost-effective processes for the treatment of effluents with small concentrations of dangerous species. The electrochemical treatment of effluents can be efficiently achieved by the use of rotating cylinder electrode. The advantages of the rotating cylinder electrode (RCE) may be summarized in terms of high mass transfer in turbulent flow at low rotation rates, an equipotential surface for potentiostatic control, good solution mixing in a relatively low volume cell, and versatility of design for continuous cascade reactor usage[1-3]. However, in order to further increase the space time yield the incorporation of turbulence promoters has been suggested.

Therefore; Kappesser et al. [4] performed mass-transfer investigations at rotating cylinders with staggered diamond knurls machined on their surfaces. Sedahmed et al. [5] studied mass-transfer at rotating finned cylinders. The fins were made by cutting longitudinal rectangular grooves on the cylinder surface. Makanjuola and Gabe [6] reported mass transfer studies at V-grooved cylinders and the investigation was extended to pyramidal knurling and wires or meshes wound to the cylindrical rotating electrode [7]. Further mass-transfer works as a function of the roughness factor are discussed by Gabe et al. [8]. Nahle´ et al. [9] studied Mass transport to rotating cylinder electrodes fabricated from reticulated vitreous carbon of different porosities. Using copper deposition as test reaction they reported that the Sherwood number was dependent upon the Reynolds number to the power 0.63, both defined in terms of the cylinder diameter. It was also concluded that the mass transfer coefficients are comparable to those at a smooth rotating disk electrode (RDE) and rotating cylinder electrode (RCE) of the same diameter. Thus, enhancements are mainly due to the large electro-active area of the three-dimensional matrix. The performance of electrochemical reactors with rotating cylinder electrodes of expanded metal was studied by Grau and Bisang [10, 11]. It was found that the mass transfer coefficients, using the reduction of ferricyanide, for rotating cylinder electrodes of woven-wire meshes are about three times higher than those obtained with smooth electrodes, because of the turbulence promoting action of the meshes. Furthermore, Reade, Ponce-de-León, and Walsh found that the introduction of baffles in the electrochemical cell has little effect on the behavior of a reticulated vitreous carbon rotating cylinder electrode, and a jet electrolyte flow towards the electrode can enhance the mass transfer rate by a factor ranging from 1.03 to 1.46, depending on the electrode type[12]. Grau and Bisang studied the mass transfer at a rotating cylinder electrode with different turbulence promoters using the reduction of ferricyanide as a test reaction. Four types of turbulence promoters were examined: expanded plastic meshes, Teflon structures, a plastic woven mesh and a plastic perforated net, which were rotated together with the electrode. They concluded that the best performance was obtained for the Teflon structures at low rotation speeds and for the plastic woven mesh at high rotation speeds. The mass-transfer enhancement factor related to a smooth rotating cylinder electrode was found twice as large [13]. The aim of present work is enhancement of mass transfer of dissolved oxygen using turbulent promoters in 0.1N NaCl solution at various temperatures under flow conditions and to compare the mass-transfer characteristics with rotating cylinder without extensions.

Experimental Work

The experimental rig which was used for performing the present work is shown in Fig 1.

The experimental apparatus was composed of water bath to obtain different solution temperatures, mechanical agitator to obtain different rotational velocities, power supply to apply the current , variable resistance (rheostat) to control the current flow, digital ammeter to measure the current, digital voltmeter to measure the potential, graphite electrode as auxiliary electrode (anode) of an immersed area which was three times larger than the area of cathode (working electrode) to make sure that the limiting current density occurs on cathode. The reference electrode was a saturated calomel electrode (SCE) in order to measure the cathode potential using a Luggin capillary placed midway of the rotating electrode surface at a distance 1-2 mm from it. The electrical connection of cathode (working electrode) was achieved using brush.

The working electrode (cathode) was a rotating cylinder 25 mm in diameter, 27 mm long with four extended rectangular legs 1 and 3 cm long, 1 cm wide , and 1 mm thick, made of brass to generate additional turbulence. The lower and upper surfaces of the electrode were insulated. The experimental details are shown in figure 2 .

Before each experimental run, the metal specimen was cleaned by emery paper and washed by tap water followed by distilled water, dried with clean tissue, degreased with annular ethanol, and dried with clean tissue. The specimens were then stored in a desiccator over highly active silica gel for overnight before use, and then directly exposed to the solution for cathodic scanning of limiting current [14].The test solution was 0.1M NaCl of PH = 6.

When the constant temperature bath attained the required temperature, the working electrode was immersed and the electrical circuit was switched on. The power supply was set at 5 V (applied voltage). The specimen (working electrode) was cathodically polarized from a particular potentials (-1.5 to -1.9 V) to the corrosion potential (where $i_{app.} = 0$) by changing the applied current using rheostat. The potential was recorded galvanostatically for step changes in current. One minute was allowed for steady state to be reached after each current increment. Then the polarization curve can be drawn and the limiting current can be obtained.

In a set of experiments the above procedure was repeated for five values of rotation speeds 200,400,600,800, and 1000 rpm at different temperatures (35, 45 and 55 °C).

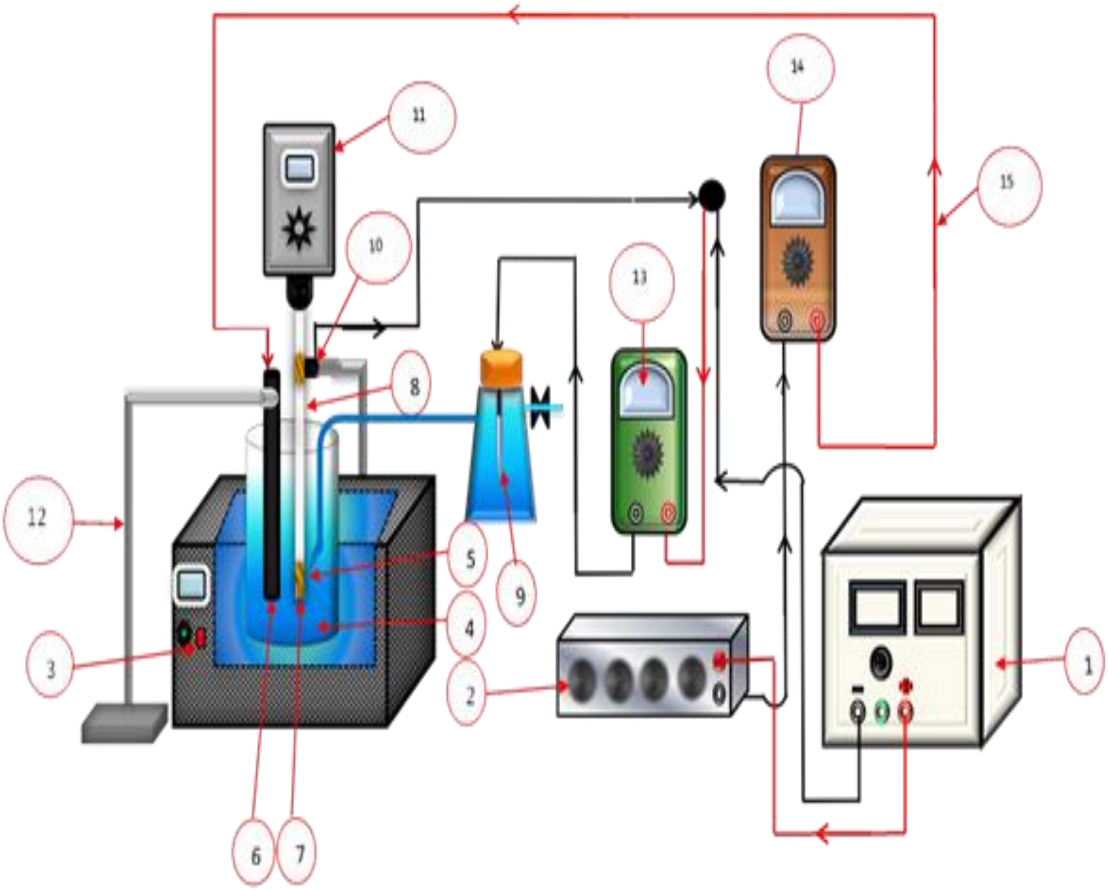
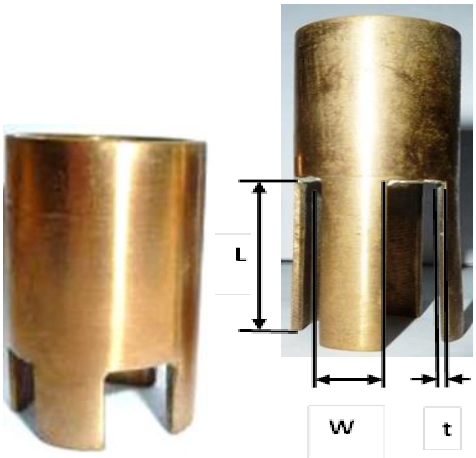
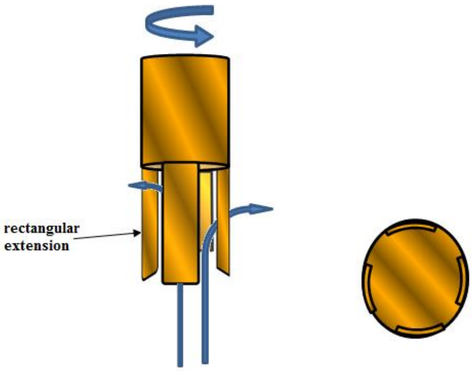


Fig. 1, Experimental apparatus: 1) Power supply,2) Resistance box ,3)Water bath , 4)0.1M NaCl, 5) Luggin capillary tip, 6) Graphite electrode (anode) ,7) Working electrode ,8) Rotating shaft ,9)Reference Saturated Calomel Electrode (SCE), 10) Carbon brush ,11) Stirrer ,12) Stand ,13) Voltmeter ,14) Ammeter ,15) Electrical wires



(a) Enhanced cylinder 1

(b) Enhanced cylinder 2



(c) Electrolyte flow rate produced by the electrode rotation

(d) Top view of working electrode

Fig. 2, Schematic view of the working electrode

Results and Discussion

The limiting current density i_L is obtained from polarization curves for smooth rotating cylinder under similar conditions.

The limiting current plateau is not well defined, thus the method given by Gabe and Makanjoula [15] will be Adopted to find the limiting current density values as in Fig.3

$$i_L = \frac{i_1 + i_2}{2} \qquad \dots (1)$$

Where i_1 and i_2 are the currents associated with E_1 and E_2 respectively.

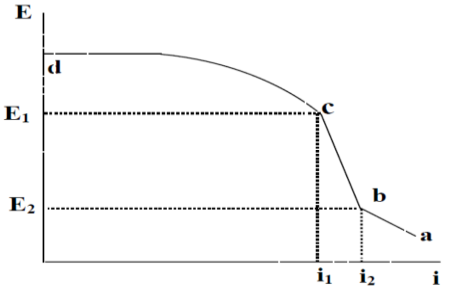
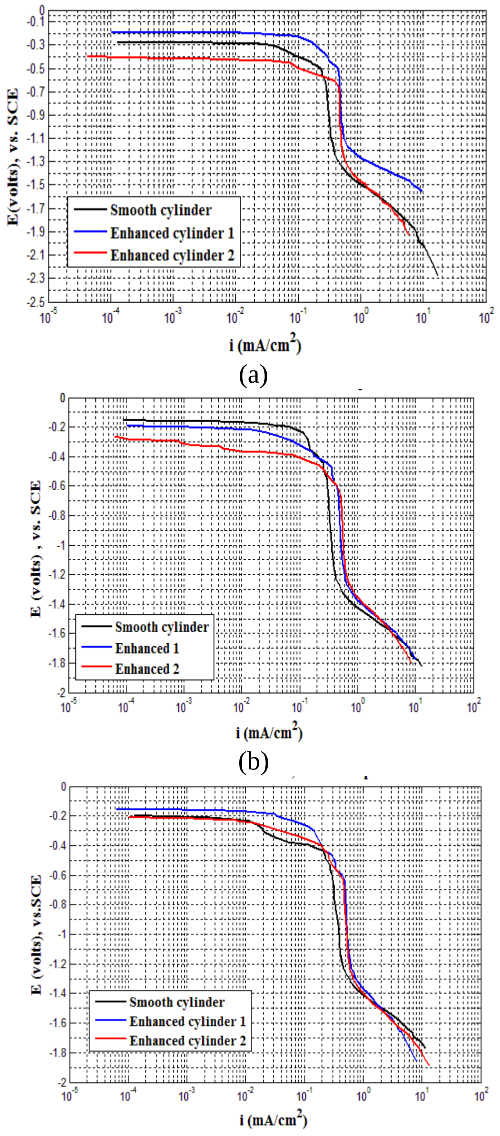


Fig. 3, Typical polarization curve of dissolved 0_2

Fig.4 shows the cathodic polarization curves in 0.1 M NaCl for smooth, enhanced one and two rotating cylinder at 200 rpm for 35, 45, and 55 °C.



(c)

Fig. 4, Cathodic polarization curves in 0.1 M NaCl for smooth, enhanced one and two rotating cylinder at 200 rpm for (a) 35°C, (b) 45°C, and (c) 55 °C

Also, the limiting current density was calculated for smooth cylinder of geometrical characteristics (25mm diameter, 27mm long), Enhanced cylinder one, and Enhanced two including areas of extensions as listed in table1.

Table 1, Experimental limit current density as a function of velocity at different temperature

Temperature	Rotation rate **ω** (RPM)	limiting current density, i_L (mA/cm^2) of smooth cylinder	limiting current density , i_L (mA/cm^2) of Enhanced cylinder one	limiting current density , i_L (mA/cm^2) of Enhanced cylinder two
35 ºC	200	0.3134	0.4815	0.49523
	400	0.5041	0.70845	0.7243
	600	0.61715	0.8068	0.8367
	800	0.8956	1.0855	1.138
	1000	1.137	1.271	1.286
45 ºC	200	0.3543	0.53175	0.56535
	400	0.5443	0.7454	0.7543
	600	0.7194	0.894	0.9223
	800	1.0012	1.14715	1.1455
	1000	1.236	1.3645	1.3515
55 ºC	200	0.371	0.54765	0.566
	400	0.66855	0.8509	0.8656
	600	0.80865	0.9586	0.96835
	800	1.146	1.308	1.302
	1000	1.3965	1.5325	1.469

The mass transfer coefficient, k is calculated from the following equation,

$$k = i_L/n_e F C_b \qquad \ldots(2)$$

Where n_e =charge number of the electrode reaction, F= Faradays constant (96487 columb/equivalent), and C_b = bulk concentration$(mole/m^3)$, for system under mass transfer control C_b =Co_2 which is the concentration of O_2 in the solution bulk.

Table 2, shows the oxygen solubility and concentration for different temperatures [19]

T (ºC)	Solubility (mg/l) 0.1NaCl	C_b $(mole/m^3)$
35	5.9445	0.21718
45	4.894	0.18718
55	4.9445	0.154515

Figure 5 shows the mass transfer coefficient, k, as a function of Reynolds number for enhanced one, and enhanced two rotating cylinder electrodes at different temperatures. The experimental mass-transfer coefficients for a similar smooth rotating cylinder electrode are also reported in this figure, which provides a baseline for performance comparison.

It can be seen that as Reynolds number increases k is increased. This can be attributed to the increase in oxygen supply from the bulk of the solution to the metal surface leading to higher i_L [16] according to equation (2), thus k will be increased. This is because of leg extensions, which present a higher specific area and promote additional turbulence in the electrolyte flowing over the cylinder surface. The k values for enhanced one and two cylinders are higher than dictated by the additional cylinder area only as displayed in Fig.5.

Figure 6 shows the mass transfer coefficient, k, as a function of the temperature for smooth, enhanced one, and two rotating cylinder electrodes at different Re numbers. It is clear that as the temperature increases k increases. This is due to the fact that increasing temperature accelerates the reaction rate as dictated by Arrhenius equation. Likewise, increasing temperature will increase the rate of oxygen diffusion to the metal surface and decrease the viscosity of water which will aid the oxygen diffusion. Moreover, as the temperature increases, the oxygen solubility decreases. The k values are still higher showing that the diffusion has a higher degree of effect than O_2 solubility [18].

In order to determine the efficiency of enhancement due to extensions a Percentage (EP) can be defined as:

$$EP\% = \frac{K_{for\ Enhanced\ cylinder} - K_{for\ Smooth\ cylinder}}{K_{for\ smooth\ cylinder}} * 100 \qquad \ldots(3)$$

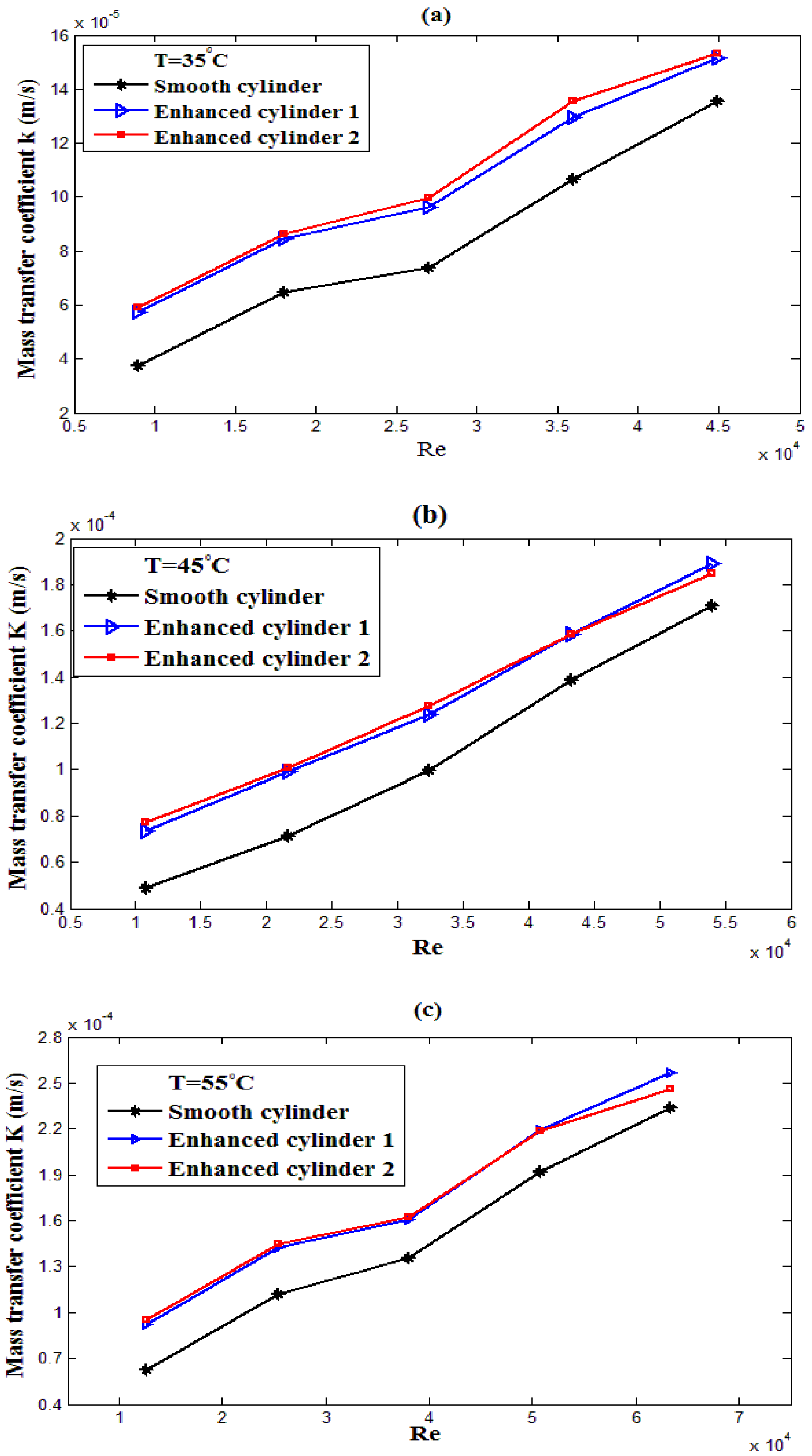


Fig. 5, Mass transfer coefficient k vs. Re for the three temperatures (a) 35°C (b) 45°C (c) 55°C

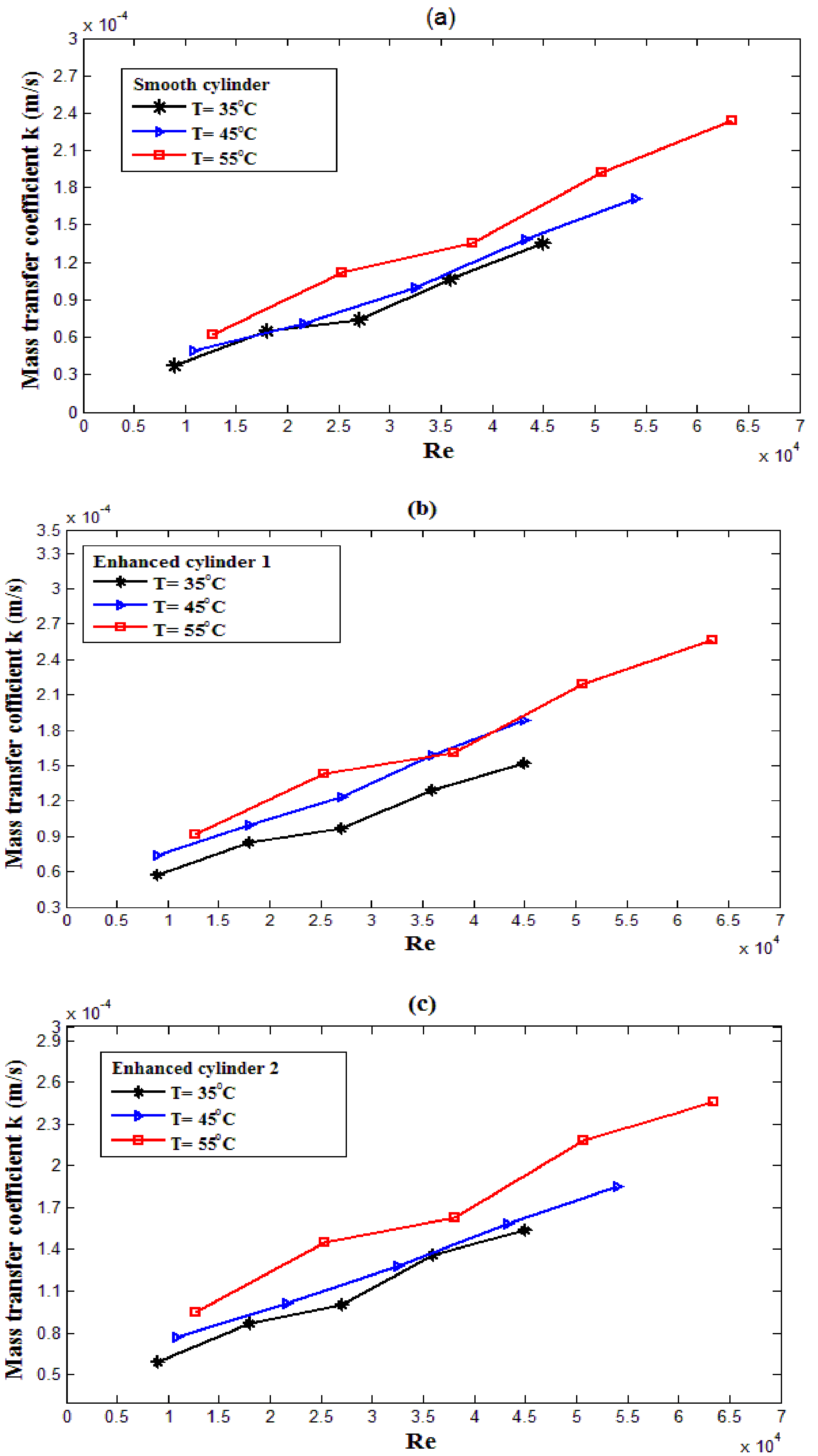


Fig. 6, Mass transfer coefficient vs. Re (a) Smooth cylinder, (b) Enhanced cylinder1, and (c) Enhanced cylinder 2

Fig.7 shows the enhancement percentage as function of the Re number for enhanced cylinder one, and two in terms of temperature.

The enhancement percentage ranges from 58% to 5% depending mainly on rotation speed; the greater Re the smaller is the enhancement percentage for a given temperature. This may be attributed to the fact that the effect of extensions which act as turbulence promoters is practically limited, since full turbulence had already been achieved by means of rotation, i.e, Re.

Also, Fig.7 compares enhancement percentages for enhanced cylinder one and two. As shown for the lower Re values enhanced cylinder two is more efficient than one. This indicates that the transition to turbulence occurs earlier due to promoters. However, the reverse, is, apparently indicated at higher Re.

Moreover, it is to be noticed from Fig.7 that at high temperature the percentage of enhancement is lower. This can be explain as the temperature increase the mass transfer coefficient increase for smooth and enhanced cylinder electrode and the effect of extensions which acting as turbulent promoter will be diminish this lead to the values of K approximately close to each other and enhancement percentage reduce.

Although, the effect of extensions length on the enhancement factor can be considered as few.

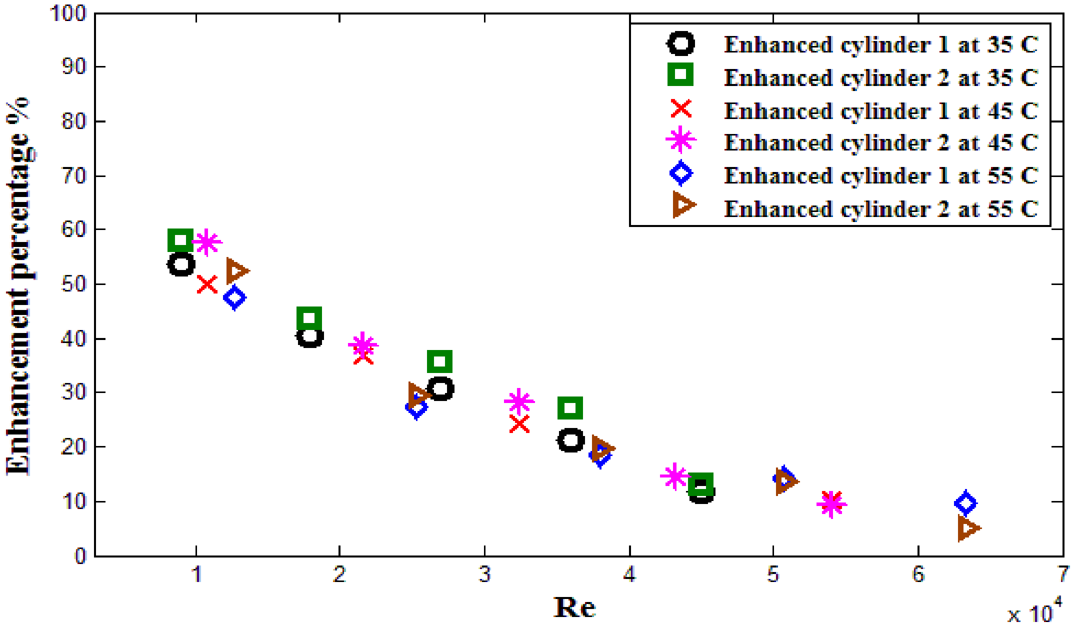


Fig. 7, Comparison of mass transfer enhancement using rotating cylinder electrodes with extensions

Conclusions

1. Mass transfer coefficients for enhanced rotating cylinder electrode are, in general, about 53% or 58% higher those obtained with smooth electrode without extensions.
2. The mass transfer enhancements are due in the main to leg extensions, which present a higher specific area and promote additional turbulence in the electrolyte flowing over the cylinder surface.
3. The enhancement percentage decreases as Re increased by the average 47.26%. This may be attributed to the fact that the effect of extensions which act as turbulence promoters is practically limited, since full turbulence had already been achieved by means of rotation, i.e, Re.

4. The enhancement percentage decreases as the temperature increased the average 33.727%. This can be explain as the temperature increase the mass transfer coefficient increase for smooth and enhancement cylinder electrode and the effect of extensions which acting as turbulent promoter will be diminish this lead to the values of K approximately close to each other and enhancement percentage reduce.

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