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Variation in the Mass Transfer Coefficients in the Radial Direction for Submerged Impinging Multi-Jet Flow of Fluid Electrolyte

Shaik FEROZ
M & IE Department, Caledonian College Of Engineering-OMAN
e-mail: feroz@caledonian.edu.om
V. S. R. K. PRASAD
Chemical Engineering Department, Andhra University, Visakhapatanam-INDIA

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Abstract

This paper presents the second part of experimental results for the mass transfer coefficients in the radial direction from the stagnation point of a multi-jet flow. Two more regions are identified on the target surface, beside the stagnation point/impingement region. One is the region in which the coefficients fall rapidly and the other is the region in which the fall in the coefficients is gradual and smooth as the impinging jet-flow is fully transformed into wall-jet flow. In view of the smooth transition of this fall from the transition region to the wall-jet region, these 2 regions are treated as a single region in the radial direction from the stagnation point. The mass transfer coefficients in this region showed similar trends of stagnation point with variation in nozzle hole and disc distributor, cell size, and height of the disc distributor from the target surface. Correlations of the mass transfer coefficient with a typical flow Reynolds number are also proposed for the region in the radial direction from the stagnation point.

Key words: Multi-jets, Disc distributor, Nozzle-hole, Electrolytic cell, Stagnation point.

Introduction

Engineering practice and research emphasize the exploitation of different ways of augmenting the transfer rates. Several techniques are reported in the literature (Gardon and Cobonpue, 1962; Gardon and Akfirat, 1965; Korger and Krizek, 1966; Koopman and Sparrow, 1976; Chang et al., 1995; Chattopadhyay and Saha, 2002) and many of them are in practice in various industrial operations. A majority of studies are directed to probe into the techniques or methods to enhance the intensity of turbulence. Several industrial operations, viz. annealing of metal and plastic sheets, the tampering of glass, drying of textiles etc., involve heat and mass transfer between surface and jets impinging on it. Impinging jet flows are widely used in situations where localized and controlled surface transfer is desirable. High specific productivities and near uniform distribution of mass transfer coefficients over electrodes having larger dimensions can be achieved only with impinging multi-jets.

The jets are basically classified as (i) free jets, and (ii) submerged jets. Jets issuing out from nozzles impinge perpendicular to the target surface in a non-striated flow, resulting in increases in heat and mass rates due to large inertia differences. Investigations (Martin, 1977) carried out so far revealed that the coefficients of heat and mass transfer and the resultant radial flow were enhanced multifold by the impinging jet flow on the target surface. The essential dynamic parameter, which influences the intensity of turbulence, is the mass flow rate. Among the other variables that affect the performance of an impinging jet are the geometric parameters such as shape, size, position of nozzle-holes and size, location of nozzle-hole assembly relative to the target surface, orientation of the jet/jets, combination of multiple nozzles on a disc distributor, and size of the cell. Investigations reported in the present study thus essentially deal with ionic mass transfer in a forced convection flow of an electrolyte through submerged multi-jets issuing from circular holes, which serve as nozzles, onto a target surface placed at the bottom of the cell normal to the jet flow. The electro-chemical technique, using diffusion controlled redox reactions between ferri-ferro cyanide couple, has been chosen for mass transfer studies through limiting current measurements. The limiting current technique for mass transfer studies has been explicitly preferred over other techniques like dissolution and sublimation in view of its simplicity, accuracy, negligible chemical polarization, and absence of any physical changes in the reacting surface even after long exposure. The ionic mass transfer rates at the electrodes were obtained, in the present case, by measuring the limiting currents for the case of reduction of the ferric ion. The experimental data have been initially analyzed graphically and finally by regression analysis. Plots of limiting current densities/mass transfer coefficients against average radial distance of electrode from the center of the target surface at various velocities show the existence of 2 regions on the target plate area: (i) the impingement region/the stagnation point, and (ii) the region in the radial direction from the stagnation point. The analysis of data on impingement region/stagnation point was discussed in part 1 (Feroz and Prasad, 2006) and in this paper the analysis in the radial direction from the stagnation point is presented.

Experimental Set-up and Procedure

The experimental apparatus and procedure were described in part 1 of this work (Feroz and Prasad, 2006). Limiting currents were measured for reduction of ferri-cyanide ion, once the flow rate and temperature had stabilized. For any individual run the temperature remained constant within ± 0.1 °C and if the temperature varied more than ± 0.1 °C the run was repeated. The electrolyte was analyzed for each and every run and the reproducibility of data was tested from time to time by repeating one of the previous runs under identical conditions. Mass transfer rates were evaluated at the central electrode and at concentric ring electrodes, placed normal to the jet flow, employing the limiting current technique (Lin et al., 1951).

Results and Discussion

The experiments covered a wide range of geometric parameters such as diameter of nozzle-hole (d_j), height of the nozzle-hole assembly from the target surface (h), diameter of disc distributor (D_d), diameter of the cell (D_c), and the dynamic variable- the jet velocity (v_n). In the case of multi-jet flow, the effective velocity/mean exit velocity (v_{ef}) of the flow flowing through all the nozzle-holes has been evaluated from the analytic expression reported by Seung-Tae Koh et al. (1991). In all these cases, the effects/improvements were expressed in terms of mass transfer coefficients computed from limiting current data (with an accuracy level of ± 0.001) similar to earlier studies (Rao et al., 1971; Venkateswarlu and Raju, 1979; Nanzer et al., 1984; Nanzer and Coeuret, 1984; Bensmaili and Coeuret, 1990a, 1990b; Bensmaili and Coeuret, 1995). Plots of limiting current densities/mass transfer coefficients against average radial distance of electrode from the center of the target surface at various velocities show the existence of 2 regions on the target plate area: (i) the impingement region/the stagnation point, and (ii) the region in the radial direction from the stagnation point. The earlier investigations on mass transfer with single jets (Martin, 1977) reported the existence of 4 regions: (i) the transition jet region, (ii) the fully developed jet region, (iii) the impingement region/the stagnation point, and (iv) the wall jet region. Regions (i) and (ii) refer to flow characteristics of the jet while regions (iii) and (iv) refer to the flow on the target area. However, other studies (Chin and Tsang, 1978; Prasad, 1994; Bensmaili and Coeuret, 1995) on single submerged jets reported 3 regions on the target surface: (1) the impingement region/the stagnation point, (2) the transition wall jet region, and (3) the fully developed turbulent wall jet region. In the present case, the transition wall-jet and fully developed turbulent wall jet regions have been merged into one single region, in view of systematic and gradual fall of coefficients at any flow rate with radial distance as shown in Figure 1, and a similar observation was made by Prasad (1994) in the case of a single submerged jet. The mass transfer coefficients were found to be maximum in the impingement region/stagnation point comprising of a central electrode (E_1, at x = 0 or $x/D_c = 0$) and decreased gradually in the radial direction from the stagnation point (E_2 to E_{11}, x/D_c = from 0.07 to 0.5833). The schematic diagram of the arrangement of concentric ring electrodes on the target plate is shown in Figure 2.

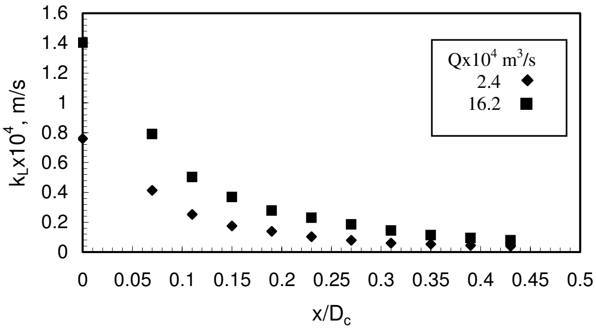

Figure 1. Variation in mass transfer coefficients with x/D_c from the center for different flow rates.

Effect of disc distributor height (h) from the target surface

The variation in mass transfer coefficients with mean velocity for a given $D_c = 0.25$ m, $D_d = 0.08$ m, and $d_j = 0.0015$ m and heights of jets 'h' varying from 0.01 to 0.25 m for $x/D_c = 0.11$ (E_3) are shown in Figure 3. It was observed that the trends are similar to that of stagnation point (Feroz and Prasad, 2006). The increase in coefficients is gradual up to certain velocity and then it is rapid. This change is found to be dependent on geometric variables. The coefficients decrease with the increase in the height of the disc distributor as jets lose their impact on the target surface.

Effect of diameter of disc distributor (D_d)

Figure 4 shows the effect of disc distributor size on mass transfer coefficients. An increase in D_d, for a given flow rate or velocity keeping the other geometric variables, d_{jef}, D_c, and h constant, showed an increasing trend of coefficients due to large area swept by the jets on the target surface and it is similar to the observation made at the stagnation point (Feroz and Prasad, 2006).

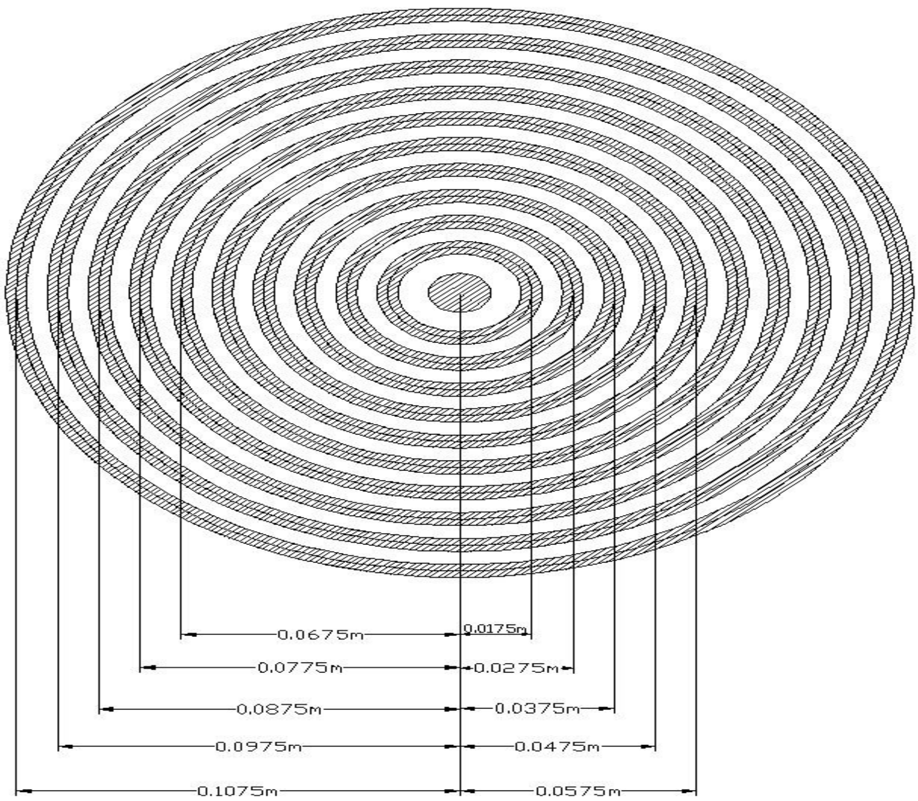

Figure 2. The schematic diagram of concentric ring electrodes on the target surface.

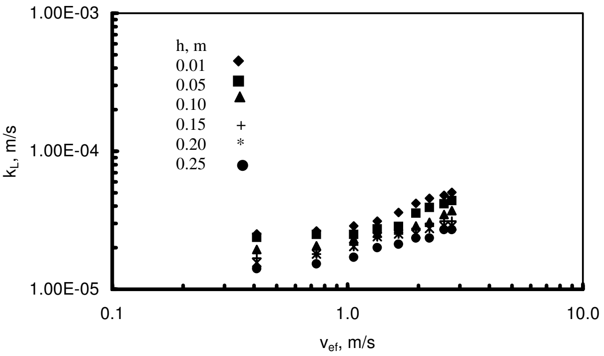

Figure 3. Variation in mass transfer coefficients with effective velocity in the region of radial direction from stagnation point (E_3) at different heights of disc distributor.

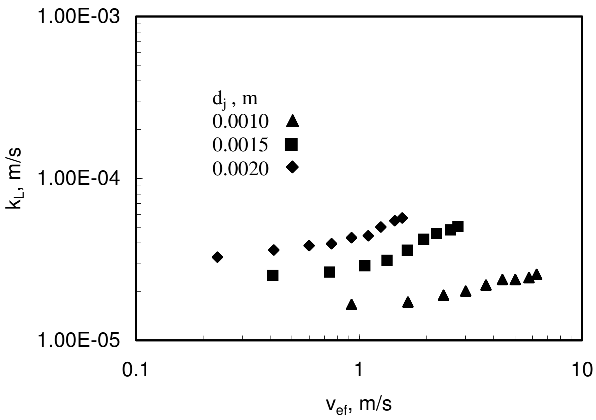

Figure 5. Variation in mass transfer coefficients with effective velocity in the region of radial direction from stagnation point (E_3) for different nozzle-hole diameters.

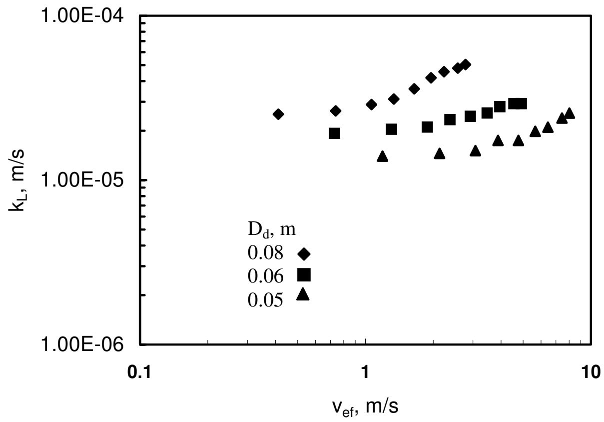

Figure 4. Variation of mass transfer coefficients with effective velocity in the region of radial direction from stagnation point (E_3) with different diameters of disc distributor.

Effect of nozzle-hole diameter (d_j)

The plots of the data on mass transfer coefficients in Figure 5 demonstrate the effect of nozzle-hole size on mass transfer coefficients. The plots of the data revealed the same trends of the stagnation point (Feroz and Prasad, 2006); the coefficients increased with an increase in the nozzle size due to large eddy turbulence created by collisions of wall jets at given velocity.

Effect of cell diameter (D_c)

Figure 6 demonstrates the effect of D_c on the transfer coefficients at a given flow rate, keeping the other geometric variables, d_{jef},D_d, and h, constant. The coefficients showed a decreasing trend with an increase in cell size, similar to that at the stagnation point (Feroz and Prasad, 2006). As cell size increases, the bulk average velocity decreases, which results in the decreasing trend in coefficients.

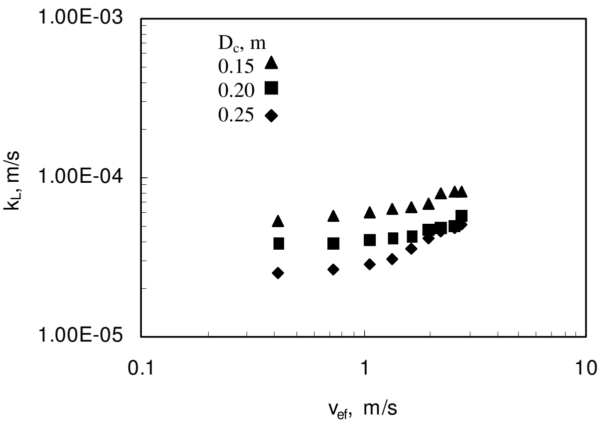

Figure 6. Variation in mass transfer coefficients with effective velocity in the region of radial direction from stagnation point (E_3) for different cell diameters.

Mass transfer coefficients at the stagnation point and in the radial direction from the stagnation point

The coefficient data of stagnation point/impingement region and in the region of radial direction from stagnation point are plotted and are shown in Figure 7. Plot A refers to the data in the impingement region ($x/D_c = 0$), while plots B, C, and D give the data in the region of the radial direction from the stagnation point. The coefficients in the impingement region were found to be in the range 3.2- to 18-fold over those in the region of the radial direction from the stagnation point. The data are drawn for 3 electrodes, $E_3, E_5, E_8 (x/D_c = 0.11, 0.19, 0.31)$, respectively, and the data revealed a decreasing trend in the coefficients with increasing x/D$_c$. The jet flow was assumed to be transforming into radial flow, the intensity of which is gradually dissipating away from the center of the target plate and this indicates the parametric effect of x/D_c on the transfer coefficient in this region.

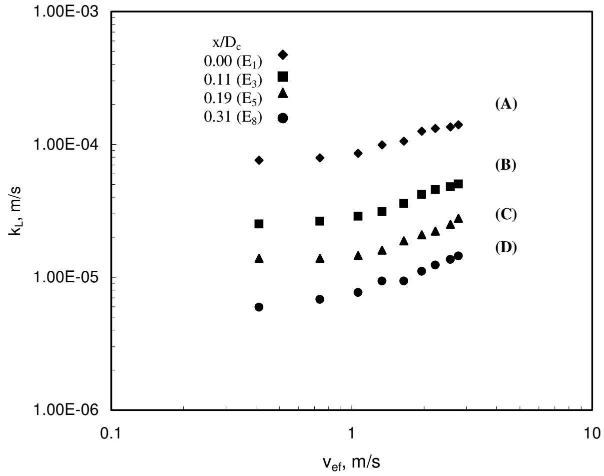

Figure 7. Comparison plots of coefficients at stagnation point and in the region of radial direction from stagnation point.

Correlations developed

Similar to the stagnation point/impingement region as reported in part 1 of this work (Feroz and Prasad, 2006), in the region of the radial direction from the stagnation point also there exists a critical value for $d_{jef}/D_c \approx 0.037$, beyond which the coefficient data showed a different trend. The issuing jet essentially influences the flow over the transfer surface and this depends on the effective nozzle-hole diameter, d_{jef} through which the jet is issuing. The size of the confining cell determines mass flow rates within the cell. The entire data showed distinctly 2 different regions, one for d_{jef}/D_c less than or equal to 0.037 and the other for d_{jef}/D_c greater than 0.037. Based on this, the entire data in the region of the radial direction from the stagnation point are divided into 2 regions: one for $d_{jef}/D_c > 0.037$ and the other for $d_{jef}/D_c \leq 0.037$. Further analysis of the data separately in these 2 regions (Figures 8 and 9) indicates 2 distinct flow regimes, characterized by critical Reynolds number as $Re_{ef} = 18{,}000$ for $d_{jef}/D_c > 0.037$ and $Re_{ef} = 30{,}000$ for $d_{jef}/D_c \leq 0.037$, just as in the case of the stagnation point/impingement region.

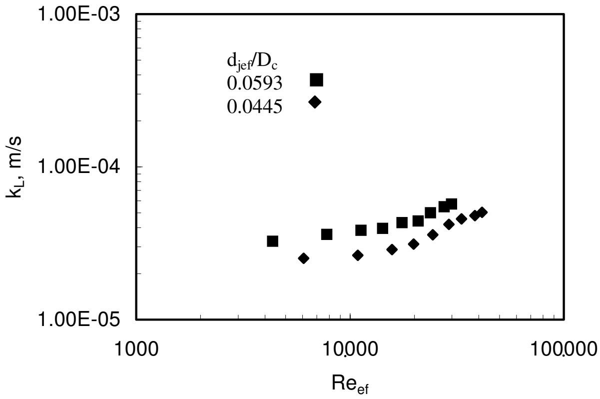

Figure 8. Variation in mass transfer coefficients with Reynolds numbers for $d_{jef}/D_c > 0.037$ in the region of radial direction from stagnation point.

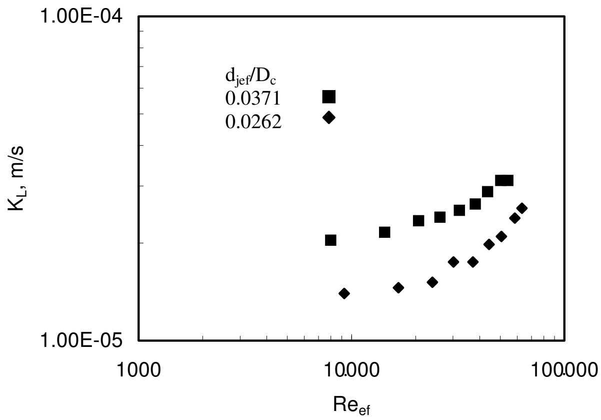

Figure 9. Variation in mass transfer coefficients with Reynolds numbers for $d_{jef}/D_c \leq 0.037$ in the region of radial direction from stagnation point.

Considering the compound effect of all geometric parameters, including the effect of 'x/D_c', in addition to the combined effect of the gravitational and centrifugal components of the forces due to secondary flows (Froude number), the data on the reduction of ferri-cyanide ion in the region of the radial direction from the stagnation point were correlated using the following format of equation:

$$J_D = C(Re_{ef})^{n_1}(Fr)^{n_2}(h/D_d)^{n_3}(dr_{jef}/D_c)^{n_4}(x/Dr_c)^{n_5} \quad (1)$$

The data yielded the following correlation equations:

1. For d_{jef} / D_c > 0.037 (Re_{ef} ≤ 18,000)

$$J_D = 4.47x10^8(Re_{ef})^{-1.56}(h/D_d)^{-0.13}(d_{jef}/D_c)^{3.26}(x/D_c)^{-1.20}(Fr)^{0.35} \quad (2)$$

2. For d_{jef} / D_c > 0.037 (Re_{ef} > 18,000)

$$J_D = 2651.9(Re_{ef})^{-0.91}(h/D_d)^{-0.15}(d_{jef}/D_c)^{2.72}(x/D_c)^{-1.21}(Fr)^{0.14} \quad (3)$$

3. For d_{jef} / D_c ≤ 0.037 (Re_{ef} ≤ 30,000)

$$J_D = 3544.8(Re_{ef})^{-1.04}(h/D_d)^{-0.083}(d_{jef}/D_c)^{2.34}(x/D_c)^{-1.17}(Fr)^{0.09} \quad (4)$$

4. For d_{jef} / D_c ≤ 0.037 (Re_{ef} > 30,000)

$$J_D = 2949(Rer_{ef})^{-1.04}(h/D_d)^{-0.085}(d_{jef}/D_c)^{2.4}(x/D_c)^{-1.18}(Fr)^{0.19} \quad (5)$$

The above equations are valid for the ranges of variables in the present study (Feroz and Prasad, 2006). The average and standard deviations for the above equations are 5% to 10%.

The plots of the data correlated in accordance with Eqs. (2)-(5) (correlation factor versus flow Reynolds number) are shown in Figures 10-13.

Correlation factor

$$(cf) = J_D/(Fr)^{n_2}(h/D_d)^{n_3}(d_{jef}/D_c)^{n_4}(x/D_c)^{n_5} \quad (6)$$

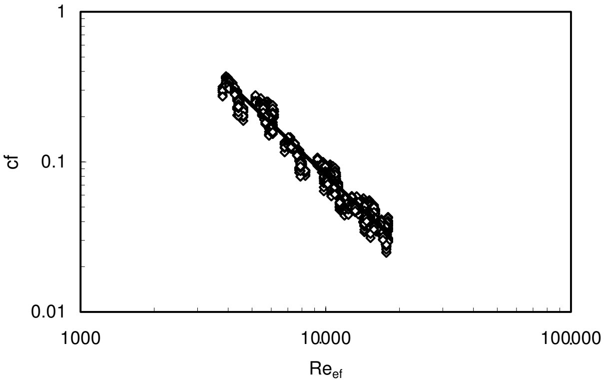

Figure 10. Correlation plot of Eq. (2) for d_{jef}/D_c > *0.037* and Re_{ef} ≤ *18,000* in the region of radial direction from stagnation point.

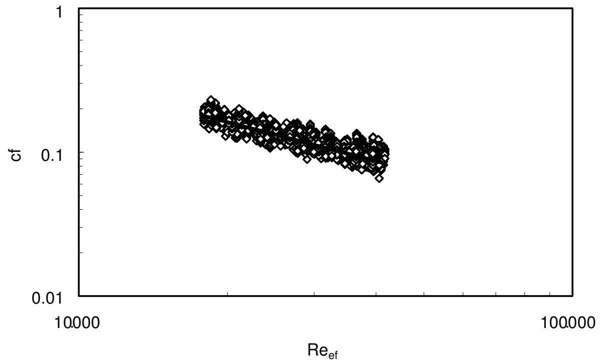

Figure 11. Correlation plot of Eq. (3) for d_{jef}/D_c > *0.037* and Re_{ef} > *18,000* in the region of radial direction from stagnation point.

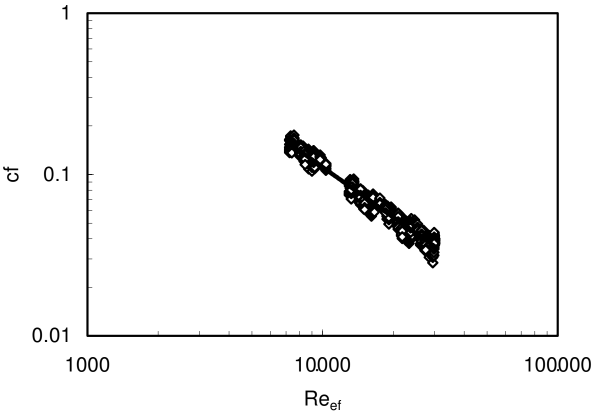

Figure 12. Correlation plot of Eq. (4) for d_{jef}/D_c ≤ *0.037* and Re_{ef} ≤ *30,000* in the region of radial direction from stagnation point.

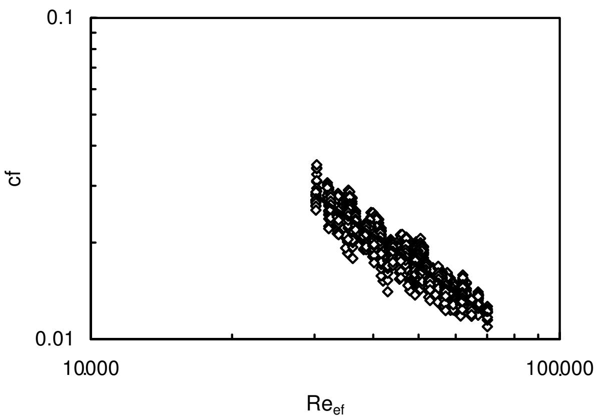

Figure 13. Correlation plot of Eq. (5) for $d_{jef}/D_c \leq$ *0.037* and $Re_{ef} >$ *30,000* in the region of radial direction from stagnation point.

Conclusions

The effect of the pertinent dynamic and geometric variables on the transfer process in the region of the radial direction from the stagnation point showed similar trends as in the stagnation point/impingement region as reported earlier in part 1 of this work (Feroz and Prasad, 2006). The coefficients decreased with an increase in the height of the disc distributor from the target surface 'h' and with an increase in cell diameter D_c. The coefficients increased with an increase in nozzle 'd_j' and disc distributor 'D_d' sizes.

The proximity of the electrode in the region of radial direction from the center stagnation point (x = *0 or* x/D_c = 0) was found to be affecting the transfer process significantly in this region. Therefore 'x/D_c' was also considered a pertinent geometric variable while correlating the data in this region. Correlations were proposed for the region of the radial direction from the stagnation point, valid for the ranges of the variables covered in the present study (Feroz and Prasad, 2006).

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Nomenclature

cf	correlation factor
C	constant
D_c	diameter of the cell, m
D_d	diameter of the disc distributor, m
D_L	diffusivity, m^2/s
d_j	diameter of the nozzle, m
d_{jef}	equivalent diameter = $\sqrt{N} \times d_j$, m
E_1	central electrode at x = *0 or* $x/D_c = 0$
$E_2, E_3 \ldots$	concentric ring electrodes
Fr	Froude number ($v_{ef}^2/g\ d_{jef}$).
g	acceleration due to gravity, m^2/s
h	height of the nozzle-hole assembly from the target surface, m
J_D	mass transfer factor
k_L	mass transfer coefficient, m/s
N	number of nozzle-holes on the disc distributor
Q	flow rate, m^3/s
Re_{ef}	Reynolds number based on d_{jef}, ($v_{ef} d_{jef} \rho/\mu$)
Sc	Schmidt number ($\mu/\rho\ D_L$)
v_{ef}	velocity based on d_{jef}, m/s
x	average radial distance of the ring electrode on the target surface from the center of the cell, m
μ	viscosity of the electrolyte solution, kg/m - s
ρ	density of electrolyte solution, kg/m^3

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