Liquid–Liquid Extraction with Chemical Reaction in a Novel Impinging-Jets Reactor

Asghar Molaei Dehkordi

Dept. of Chemical Engineering, Amirkabir University of Technology, Tehran, Iran

The theory of mass transfer accompanied by chemical reaction for the pseudo-first-order heterogeneous liquid–liquid reactions was used to measure the effective interfacial area in a novel two-impinging-jets reactor (TIJR), which is characterized by a small reactor volume equipped with two simple nozzles directed toward each other. Aqueous and organic streams were jetted through the nozzles into rotating and stationary disks, resulting in a highly turbulent mixture of aqueous and organic phases. Experiments were also conducted on the physical extraction of n-Butyl formate into distilled water to measure the overall volumetric mass-transfer coefficients. Due to both the impinging process and high rate shear forces acting on the phases, the overall volumetric mass-transfer coefficients and volumetric extraction rates obtained by the physical and chemical method, respectively, increased dramatically compared to those obtained by conventional reaction systems and an air-driven two-impinging-streams reactor developed by the present author. The enhancing effect of impinging jets on the conversion of aqueous NaOH solution was tested by another nonimpinging-jets reactor.

Introduction

Liquid–liquid extraction with interphase chemical reaction is commonly used in the chemical industry. Typical applications of liquid-liquid extraction with chemical reaction are in the recovery of metals from leach liquors, nitration, and hydrolysis.

In liquid-liquid extraction with interphase chemical reaction, the two reactive species are present in two different, distinct phases, aqueous and organic. One phase is continuous and the other is dispersed. Therefore, the reactive species must diffuse to a reaction zone or interface, and the reaction product must diffuse away to the selective phase to allow fresh reactive elements to proceed the process. The reaction zone may be in either phase, or extend to both phases. In the limit it may reduce to a reaction plane, and depend upon the reaction type and the mode of contacting.

The overall rate of process is controlled by both the kinetics of the reaction and by the diffusion characteristics of the systems. However, under certain conditions, a chemical process may be either entirely diffusion-controlled or entirely kinetically controlled. For a very slow reaction accompanied by high mass-transfer rates, the overall extraction rate is determined by the kinetics of reaction, whereas for a very fast reaction, the rate of diffusion controls the overall rate of process.

The knowledge of the specific interfacial area and the mass-transfer coefficient is essential for the rational design of a variety of liquid-liquid contactors. The most important practical method of determination of the specific interfacial area is to make use of a chemical reaction occurring in such a contactor. Alkaline hydrolysis of esters is an appropriate chemical system for the measurement of interfacial area of a variety of liquid-liquid contactors. Ghosh et al. (2001), Verma and Sharma (1975), Nanda and Sharma (1966), Fernandez and Sharma (1967), Puranik and Sharma (1970), Chaudhuri et al. (1996), and Woezik and Westerterp (2000) have used this technique for the measurement of interfacial areas a in a variety of liquid-liquid contactors such as packed columns, mechanically agitated contactors, spray columns, and so on. Under some restrictions, it is also possible to use alkaline hydrolysis of esters to determine both mass-transfer coefficient and interfacial area of liquid-liquid contactors. Puranik and Sharma (1970) were the first to report about the use of such a method for the measurements of the overall mass-transfer coefficient K_L, and specific interfacial area a in a liquid-liquid contactor. Later, Verma and Sharma (1975) and

---

Correspondence concerning this article should be addressed to A. M. Dehkordi.

Sarkar et al. (1980) used the same technique for determining the mass-transfer coefficients of packed columns and mechanically agitated columns.

The impinging jets (IJ) technique is a unique flow configuration. The first patent for this technique was probably published by Carver et al. (1956). The IJ method was employed by Elperin (1961) for gas-solid suspensions and further developed by Tamir in various chemical engineering processes (Tamir, 1994). In addition, Mujumdar and coworkers (Hosseinalipour and Mujumdar, 1997a,b, 1995a; Seyedein et al., 1994) have conducted extensive investigations on the modeling and application of IJ technique in heat-transfer processes. The method provides a powerful technique for intensifying transfer processes. The principle of impinging jets is to bring the two jets flowing along the same axis in the opposite direction into collision. As the result of such a collision, a relatively narrow zone, called the impingement zone of high turbulence intensity, is created which offers excellent conditions for intensifying heat- and mass-transfer rates. The IJ technique has been successfully applied to the absorption and desorption of gases (Herskowits et al., 1987; Tamir et al., 1990a,b; Herskowits et al., 1988; Kleingeld et al., 1999), dissolution of solids (Tamir and Grinholtz, 1987), drying of solids (Kitron and Tamir, 1988; Kudra and Mujumdar, 1989, 1995; Kudra et al., 1991; Hosseinalipour and Mujumdar, 1995b), dust collection (Berman and Tamir, 1996), absorption with chemical reaction (Herskowits et al., 1990; Sohrabi and Jamshidi, 1997), two-liquid phase reaction (Sohrabi et al., 1993), mixing (Unger et al., 1998; Devahastin and Mujumdar, 2002, 2001a,b), evaporative cooling of air (Yao et al., 1995), bioreactions (Sievers et al., 1995; Sohrabi and Marvast, 2000), liquid-liquid extraction (Berman and Tamir, 2000; Dehkordi et al., 2001; Dehkordi, 2001, 2002a), and copper extraction and stripping processes (Dehkordi, 2002b,c).

The major objectives of the present investigation were as follows:

(1) To determine the interfacial area between two immiscible phases in a novel two-impinging-jets reactor (TIJR) by the chemical method

(2) To determine overall volumetric mass-transfer coefficient $K_L a$ by physical method

(3) To determine overall volumetric mass-transfer coefficient $K_L a$ from Danckwerts' plots and comparing the latter with those obtained by physical method.

To achieve these objectives, the liquid-liquid extraction with interphase chemical reaction using the n-Butyl formate-aqueous NaOH solution system and physical extraction of the ester into distilled water applying a TIJR has been investigated. Furthermore, a nonimpinging-jets reactor was employed to verify the effectiveness of the TIJR.

Theory

Overall volumetric mass-transfer coefficient by physical method

If the solubility of a solute A, which is being transferred from a phase A to another phase B, is sufficiently low to assume the properties of the phase B constant, and, if the resistance to mass transfer lies entirely in the phase B (by saturating the phase A with the phase B), the logarithmic-mean driving force can be applied to determine the overall

volumetric mass-transfer coefficient $K_L a$. Thus, the following expression can be used to obtain the values of overall volumetric mass-transfer coefficient

$$Q_A([A_o] - [A_i]) = K_L a V_c [\Delta A]_{\ln} \tag{1}$$

where $[A_o]$, $[A_i]$, V_c, and $[\Delta A]_{\ln}$ are the outlet concentration of solute A (in this case phase A) in the phase B, the inlet concentration of solute A in the phase B, the contactor volume, and the logarithmic-mean concentration driving force of solute A, respectively. The logarithmic-mean driving force $[\Delta A]_{\ln}$ is normally defined by

$$[\Delta A]_{\ln} = \frac{([A_i^*] - [A_i]) - ([A_o^*] - [A_o])}{\ln\left[\dfrac{([A_i^*] - [A_i])}{([A_o^*] - [A_o])}\right]} \tag{2}$$

where $[A_i^*]$ and $[A_o^*]$ are the equilibrium concentrations of the solute A in the phase B corresponding to inlet and outlet conditions of contactor, respectively.

Note that in the experiments for the determination of the overall volumetric mass-transfer coefficient $K_L a$ by the physical method $[A_i^*] = [A_o^*]$, which is equal to the solubility of phase A in the phase B at the operating conditions. On substituting Eq. 2 in Eq. 1 and taking $[A_i^*] = [A_o^*] = [A^*]$, Eq. 1 reduces to

$$K_L a = \frac{Q_A}{V_c} \ln\left(\frac{[A^*] - [A_i]}{[A^*] - [A_o]}\right) \tag{3}$$

Interfacial area (a) by chemical method

In a fast heterogeneous liquid-liquid reaction with the following relation

$$A_{\text{or}} + B_{\text{aq}} \rightarrow C_{\text{or}} + D_{\text{aq}} \tag{4}$$
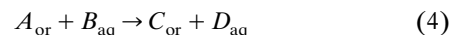
in which the component A from a first phase diffuses into a second phase containing B with which it reacts in the same phase, the volumetric rate of extraction of component A, which undergoes a pseudo-first-order reaction with a component in the other phase. This may be expressed by Danckwerts' model (Danckwerts, 1970) as follows

$$R_A a = a[A^*]\left(D_A K_2 [B] + K_L^2\right)^{0.5} \tag{5}$$

where $R_A a$, a, D_A, K_2, and K_L are the extraction rate of A per unit volume of reactor, the interfacial area between the two immiscible phases per unit volume of reactor, the diffusion coefficient of A in the phase B, the second-order reaction rate constant, and the overall mass-transfer coefficient, respectively.

The criterion for a pseudo-first-order reaction is given by

$$\left[1 + \frac{D_A K_2 [B]}{K_L^2}\right]^{0.5} \ll 1 + \frac{[B] D_B}{[A^*] D_A} \tag{6}$$

where D_B is the diffusion coefficient of the reactant B.

If the reaction is very fast relative to mass-transfer phenomena, then the volumetric extraction rate of A may be ex-

pressed as

$$R_A a = a[A^*](D_A K_2 [B])^{0.5} \qquad (7)$$

which may be applied with an error of 5% or less if

$$\frac{(D_A K_2 [B])^{0.5}}{K_L} > 3 \qquad (8)$$

For a fast pseudo-first-order reaction regime of heterogeneous liquid-liquid reaction, if $R_A a$ and the solubility $[A^*]$ are known, Eq. 5 can be used to analyze the experimental data. Equation 5 can be rearranged to the following relation

$$(R_A a/[A^*])^2 = D_A K_2 a^2 [B] + (K_L a)^2 \qquad (9)$$

It follows from Eq. 9 that a plot of $(R_A a/[A^*])^2$ vs. $[B]$ known as the Danckwerts' plot should yield a straight line with a slope of $D_A K_2 a^2$ and an intercept of $(K_L a)^2$. It should be mentioned that the solubility of NBF in aqueous NaOH solution, $[A^*]$, cannot be measured experimentally because of the hydrolysis; therefore, it was estimated by the following relation (Ghosh et al., 2001)

$$\log\left(\frac{[A^*]}{[A_w]}\right) = -K_s I \qquad (10)$$

where $[A_w]$, and I are the solubility of NBF in distilled water and ionic strength of the solution in kmol/m^3, respectively. In addition, $K_s = i_+ + i_- + i_{ester}$ and the value of i_{ester} was obtained from the solubility data of NBF in aqueous solution of sodium chloride (Ghosh et al., 2001). Nanda and Sharma (1966), Fernandez and Sharma (1967), Alwan et al. (1983), Chaudhuri et al. (1996), Ghosh et al. (2001), Sarkar et al. (1980), and Laddha and Degaleesan (1976) have shown that this procedure can be successfully used for a variety of esters.

Experimental Studies
Chemical systems

The values of overall volumetric mass-transfer coefficient $K_L a$ were determined by physical extraction of the low soluble ester, that is, n-Butyl formate (NBF) into distilled water. As the organic phase was saturated with distilled water, the resistance to mass transfer was entirely to the aqueous phase side only.

The previous works (Ghosh et al., 2001; Chaudhuri et al., 1996; Sarkar et al., 1980; Woezik and Westerterp, 2000) indicate that the alkaline hydrolysis of NBF is a suitable chemical system for the measurement of the interfacial area in various liquid-liquid contactors. Thus, at the low concentration of hydroxyl ion, the system NBF-aqueous NaOH solution can be used for making Danckwerts' plots, so that the values of K_L and the interfacial area a can be obtained from a set of experimental runs separately. It should be mentioned that the range of concentration of sodium hydroxide solution was 0.40 to 0.75 kmol/m^3. Higher concentrations of aqueous NaOH solution were not considered since they would have created significant changes in the physicochemical properties, particularly in the diffusivity and rate kinetic constant.

Chemicals

Caustic soda was of analytical grade, but NBF was of technical grade and distilled water was used in all the experiments. The purity of the ester was around 99% in all the experiments. The organic phase (NBF) was always saturated with distilled water in the case of a nonreacting system, that is, for the measurement of overall volumetric mass-transfer coefficient $K_L a$ by the physical method.

Method of analysis

In the alkaline hydrolysis of NBF, the aqueous solution was analyzed by noting a decrease in the alkali content of the outlet aqueous NaOH solution, that is, by acid-base titration. Furthermore, the concentration of NBF in the aqueous solution for the determination of $K_L a$ was analyzed by a simple saponification method, as discussed by Nanda and Sharma (1966) and Puranik and Sharma (1970). In all the above methods, the accuracy of the analytical methods was first tested with the known samples of the solutions.

Experimental apparatus

The experimental setup shown in Figure 1 consisted of the following parts: (1) two circular disks (upper and lower) made of stainless steel (SS) of 0.15, 0.20, 0.25 m diameters and 0.0015 to 0.003 m distances between disks; (2) a variable-speed electric motor in order to study the effect of the upper disk speed on the overall volumetric mass-transfer coefficient and the conversion of aqueous NaOH solution. Note that in the present investigation only the upper disk was rotated and the lower disk was fixed. The disks are shown in Figure 2. The aqueous and organic solutions were introduced into the lower and upper disks, respectively. Thus, the contact between the aqueous and organic phases took place between the rotating (upper) and stationary (lower) disks only. Other parts of the experimental setup (Figure 1) were as follows: (3 and 4) aqueous and organic solutions rotameters; (5 and 6) feed vessels both made of SS; (7) centrifugal feed pumps made of SS; (8) needle valves made of SS; (9) cylindrical vessel of 0.30 m diameter and 0.30 m height used for collection of the dispersion leaving the disks; (10) bulk dispersion outlet; (11) sampling cup; (12) sampling connection. Furthermore, the upper and lower disks have been equipped with simple nozzles of 0.001m diameter in order to introduce high-velocity jets to one another.

Experimental procedure

In each experimental run, the upper disk speed was adjusted at the desired value and then the organic and aqueous solutions were fed to the upper and lower disks at given volumetric flow rates, respectively. The aqueous and organic flow rates were regulated using the needle valves. When the steady-state condition was established, the samples were taken by sampling cups through the sampling connection for the measurements. An aqueous solution sample was withdrawn immediately with a syringe from the bottom of the sampling cups without waiting for complete phase separation in order to avoid as much as possible the effect of additional mass transfer and the extent of the reaction in the sampling cups. The analysis of the aqueous samples was performed by the titration and saponification methods. For each data point,
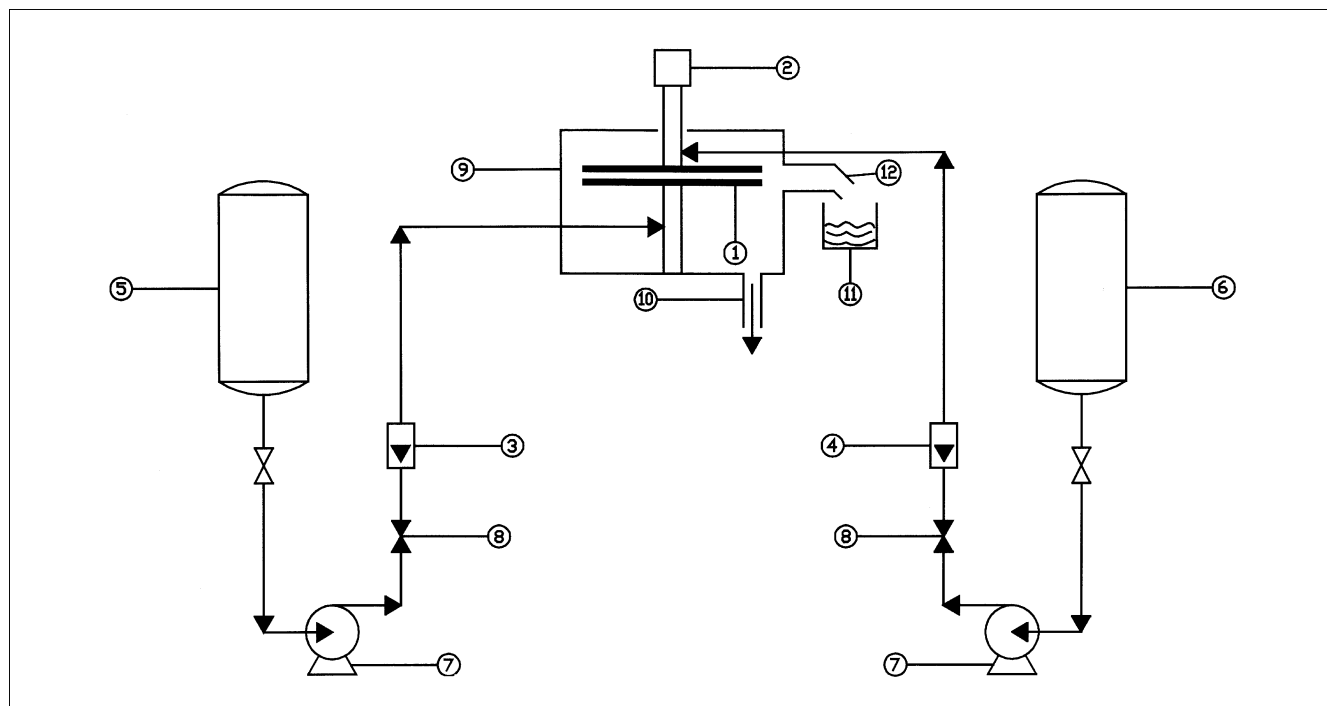
Figure 1. Experimental setup.

(1) Circular disks; (2) variable-speed electric motor; (3 and 4) solution rotameters; (5 and 6) feed vessels; (7) feed pumps; (8) needle valves; (9) cylindrical vessel; (10) bulk dispersion outlet; (11) sampling cup; (12) sampling connection.

the experimental run was repeated at least three times, and, hence, each data point was determined based on the mean value of at least three measurements of outlet concentrations of the phases with a standard deviation of 3–5%.

Results and Discussions

The operating conditions for the determination of $K_L a$ by the physical method and the construction of Danckwerts' plots to determine the effective interfacial area were as follows:

(a) Upper disk speed N: 600 to 1,400 rev/min

(b) Aqueous flow rate Q_A: 0.110 to 0.300 dm^3/min

(c) Aqueous to organic flow ratio (A/O): 1/1

(d) Temperature within the reactor: ~ 20°C

(e) Concentration of NaOH solution, $[B_i]$: 0.4 to 0.75 kmol/m^3

(f) Disks diameters d: 0.15 to 0.25 m

(g) Distance between the disks h: 0.0015 to 0.003 m

Overall volumetric mass-transfer coefficient ($K_L a$) and the conversion of aqueous NaOH solution (X_c)

Influence of the Upper Disk Speed (N). The systems NBF-distilled water and NBF-aqueous NaOH solution were chosen to determine the overall volumetric mass-transfer coefficient and interfacial area. The effects of the upper disk speed on the overall volumetric mass-transfer coefficient and the conversion of aqueous NaOH solution are shown in Figures 3 and 4. It appears that $K_L a$ and the conversion of aqueous NaOH solution X_c increase with an increase in the upper disk speed over the range of 600 to 1,400 rev/min. This can be attributed to an increase in the mixing and turbulence.

Also, an increase in the upper disk speed increases the shear forces exerted on the phases and turbulence that leads to an increase in the surface renewal mechanism, and, hence, an increase in the interfacial mass-transfer area and the elimination of mass-transfer resistances.

Influence of the Liquid Flow Rate (Q). Figures 5 and 6 show the plots of the overall volumetric mass-transfer coefficient and the conversion of aqueous NaOH solution as a function of the aqueous flow rates with the upper disk speed as a parameter. Note that in all of the experiments the organic flow rates were equal to those of the aqueous phases either in the determination of the overall volumetric mass-transfer coefficients by the physical method and in the determination of the effective interfacial areas by the chemical method. As can be observed from Figure 5, an increase in the liquid flow rates within the range of 0.110 to 0.300 dm^3/min decreases the conversion of the aqueous NaOH solution (the extent of the reaction). Such a behavior can be explained as follows: in the high total throughput (both the aqueous and the organic flow rates), the mean residence time of the streams within the reaction compartment is low; hence, the conversion of aqueous NaOH solution was decreased. In addition, as can be seen in Figure 6, an increase in the flow rates within the aforementioned range of the aqueous and organic flow rates leads to increases in the overall volumetric mass-transfer coefficients. This behavior may be explained by: (1) an increase in the mixing and turbulence due to both the impinging process and the high-rate shear forces acting on the phases; (2) increase in the rate of breakage and coalescence phenomena and a consequent increase in the interfacial mass-transfer area, as well as enhancement of the surface renewal mechanism produced by eddies.
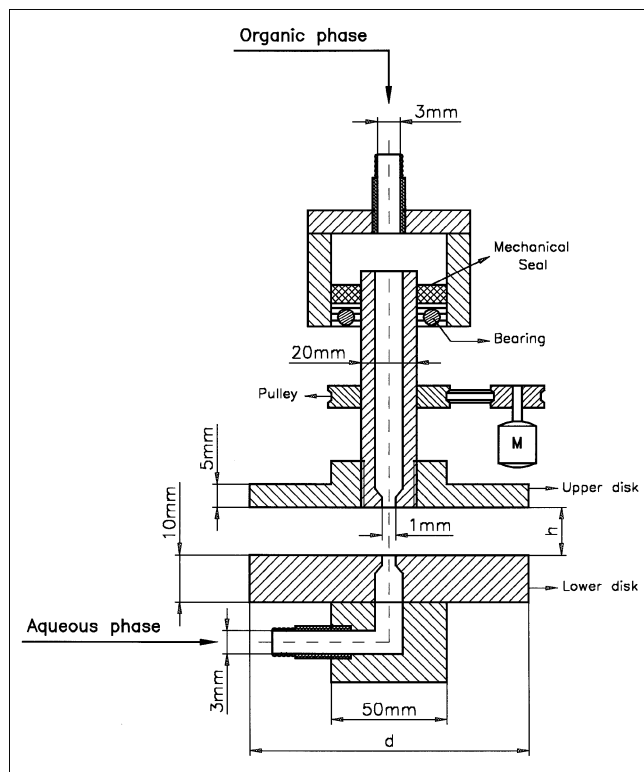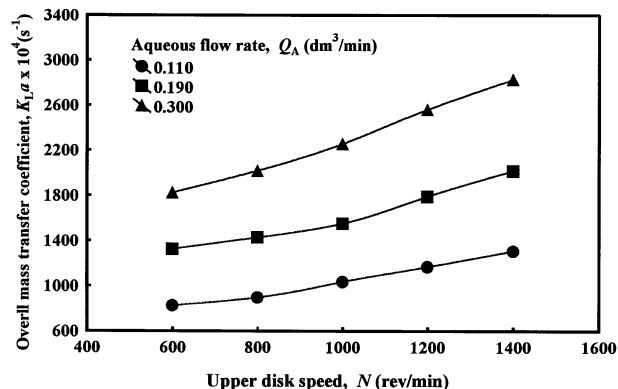
Figure 2. Cross section of the disks.

Figure 4. Overall volumetric mass-transfer coefficient vs. upper disk speed.

Disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

various aqueous-flow rates and the upper disk speeds. It was found that an increase in the disk diameter from 0.15 to 0.25 m increases the conversion of aqueous NaOH solution, but the latter was not appreciable at the high upper disk speeds for disk diameters larger than 0.20 m.

Influence of the Distance between Disks (h). To explore the effect of the distance between the disks h on the conversion of aqueous NaOH solution, a number of experiments were carried out with the various distances between the disks from 0.0015 m to 0.003 m. These experimental results are shown in Figure 9. As may be observed from Figure 9, a decrease in the distance between disks h from 0.003 to 0.0015 m increases the conversion of aqueous NaOH solution. The latter is due to much higher shear forces acting on the phases, as well as an increase in the bulk turbulence produced by eddies.

It should be mentioned that, for the distances smaller than 0.0015 m, some difficulties were encountered in the separation of the exit dispersions and need to longer times for complete phase separation. Thus, the distances smaller than 0.0015 m were not considered in the present investigation.
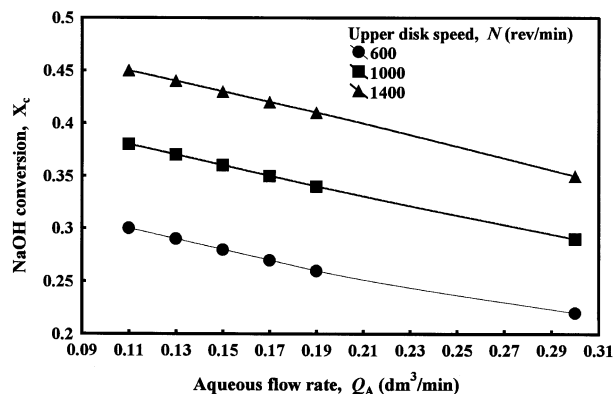
Figure 7 shows the variations of the volumetric extraction rates against $K_L a$ at a particular inlet concentration of the aqueous NaOH solution. This figure illustrates that an increase in the $K_L a$ leads to an increase in the $R_A a$; hence, the overall rate of the process controls by mass-transfer phenomena.

Influence of the Disk Diameter (d). The effect of the disk diameter d on the conversion of aqueous NaOH solution was investigated while other operating conditions were kept unchanged. Figure 8 shows the plot of the conversion of aqueous NaOH solution as a function of the disk diameter at the

Figure 3. Conversion of aqueous NaOH solution vs. upper disk speed.

$[B_i] = 0.75$ kmol/m^3; disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

Figure 5. Conversion of aqueous NaOH solution vs. the aqueous flow rate.

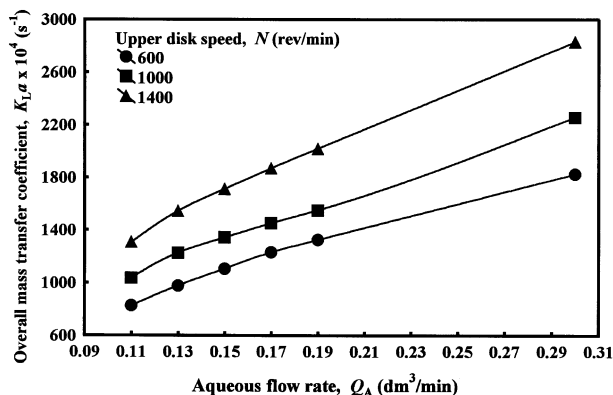$[B_i] = 0.75$ kmol/m^3; disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

Figure 6. Overall volumetric mass-transfer coefficient vs. aqueous flow rate.

Disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

Figure 8. Effect of the disk diameter on the conversion of aqueous NaOH solution.

$[B_i] = 0.75$ kmol/m^3; distance between the disks h, 0.0015 m.

Influence of Impinging Jets. As can be noticed from the experimental setup, the reactor could be assembled in the two following modes: either as a TIJR or as a nonimpinging-jets reactor (NIJR). In the latter mode of operation, both aqueous and organic phases were introduced separately through the lower disk without premixing of the aqueous and organic phases. The NIJR is shown in Figure 10. The distance between the inlet pipes on the lower disk in the NIJR was 0.005 m. The aqueous and organic phases, therefore, did not impinge to one another within the reaction compartment. Thus, the following ratio could be defined in order to compare the performance capability of the TIJR and NIJR and to verify the enhancing effect of impinging jets under identical operating conditions

$$Eh = \frac{\text{The conversion of aqueous NaOH solution in TIJR}}{\text{The conversion of aqueous NaOH solution in NIJR}}$$

(11)

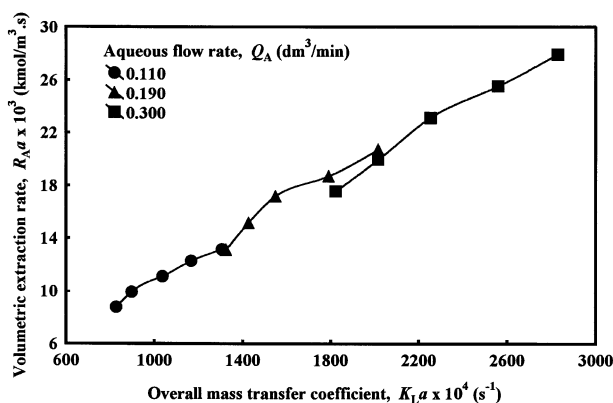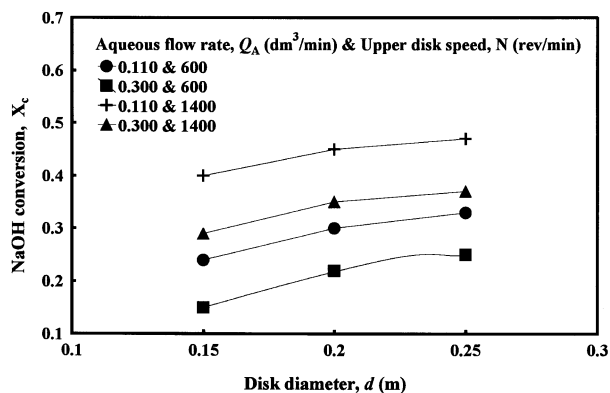Figure 11 shows the enhancing effect of the IJ on the conversion of aqueous NaOH solution. From this figure, it can be noticed that: (1) the IJ generally promote the conversion of aqueous NaOH solution; (2) the enhancing effect of the IJ on the conversion was diminished at the high upper disk speeds for various aqueous and organic flow rates.

Danckwerts' Plots. NBF was contacted with various inlet concentrations of aqueous NaOH solution within the range of 0.40 to 0.75 kmol/m^3 to determine the values of overall volumetric mass-transfer coefficients and the interfacial areas from construction of Danckwerts' plots. In order to satisfy the conditions for the pseudo-first-order mechanism, lower concentrations of NaOH solution were used. Figure 12 shows the plots of $(R_A a/[A^*])^2$ vs. the average concentration of the reactive species $[B]$ with the upper disk speed and aqueous NaOH solution flow rate as parameters. The individual values of overall volumetric mass-transfer coefficients and the interfacial areas obtained from these Danckwerts' plots are given in Figures 13 and 14. As can be noticed from Figure 13 there is a relatively good agreement between the experimental and calculated overall volumetric mass-transfer coefficients obtained from the intercepts of Danckwerts' plots. However, the corresponding experimental values of overall volumetric mass-transfer coefficients were generally around 10% lower as shown in Figure 13.
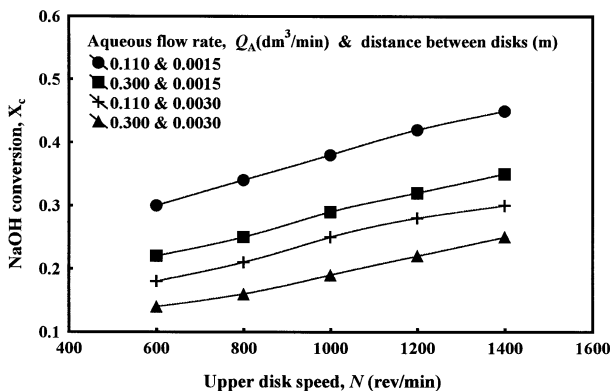

Figure 7. Volumetric extraction rate vs. the overall volumetric mass-transfer coefficient.

$[B_i] = 0.75$ kmol/m^3; disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

Figure 9. Effect of the distance between the disks on the conversion of aqueous NaOH solution.

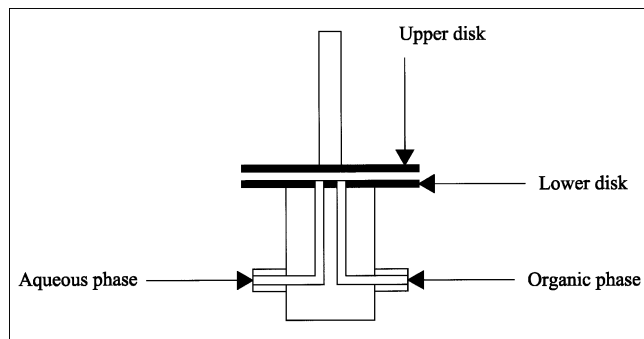$[B_i] = 0.75$ kmol/m^3; disk diameter d, 0.20 m.

Figure 10. Cross section of the disks in NIJR.

The distance between the inlet pipes on the lower disk 0.005 m.

Figure 14 demonstrates the values of interfacial areas calculated from the slopes of Danckwerts' plots vs. the upper disk speeds and the aqueous flow rate as a parameter. As can be observed from Figure 14, an increase in the upper disk speed and the aqueous flow rate causes a corresponding increase in the interfacial areas, which can be expected. Notice that the quantities $[A^*]$, D_A, D_B, and K_2 are functions of the concentration of NaOH solution as well. The values of D_A and K_2 at the various concentrations of aqueous NaOH solution and 20°C have been tabulated by Sarkar et al. (1980). However, a number of correlations reported for K_2, $[A^*]$, D_A, and the ratio of D_A to D_B concerning n-Butyl formate-NaOH system can be found elsewhere (Onda et al., 1975; Woezik and Westerterp, 2000). In addition, Verma and Sharma (1975) and Nanda and Sharma (1966) reported much data concerning the system investigated. The results obtained from the experiments are summarized in Table 1. It is clear that, within the range studied, the assumption of pseudo-first-order reaction has been held for all of the experiments.

Evaluation of the Performance Capability of the Reactor. The evaluation of the performance capability of the TIJR in comparison with other reactor types is based on the mass-transfer performance and power input requirements. The latter quantities are summarized in Tables 2 and 3 that contain the data
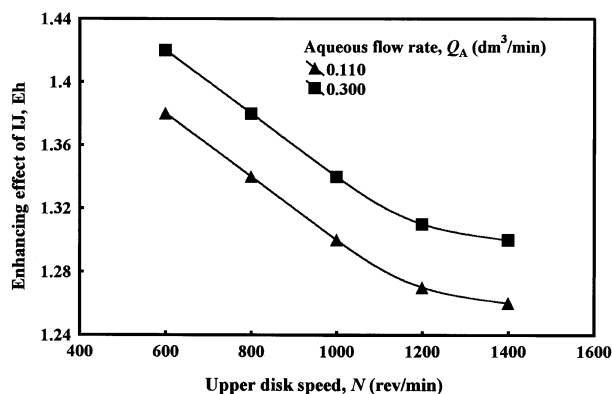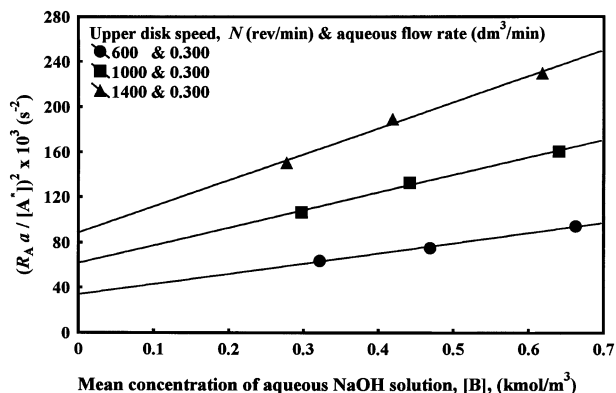

Figure 12. Danckwerts' plot of $(R_A a/[A^*])^2$ vs. mean concentration of aqueous NaOH solution $[B]$.

Disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

for the overall volumetric mass-transfer coefficients and volumetric extraction rates, as well as power input requirements per extraction rates, respectively. It is clear that the TIJR has a much better performance capability with respect to the overall volumetric mass-transfer coefficient and volumetric extraction rate. However, the TIJR needs higher power input requirements relative to mechanically agitated columns.

The power input requirement for the TIJR is the sum of the power requirement for the upper disk and feed pumps. To determine the power required for the pumps during the experimental work, the pressure drops across the nozzles for both the aqueous and organic streams were measured. According to the experimental results, the maximum pressure drop across the nozzles was ~ 68 kPa. Therefore, the powers required for the feed pumps could be determined by applying the well-known Bernoulli's equation (White, 1986). The contribution of the upper disk to the total power input could be determined based on the Newton's law that is applied to a ring of radius r and width dr on the upper disk. The latter can be written as

$$dF(r) = \tau(r)dS(r) \text{ with } dS(r) = 2\pi r \times dr \qquad (12)$$

Figure 11. Enhancing effect of IJ on the conversion of aqueous NaOH solution.

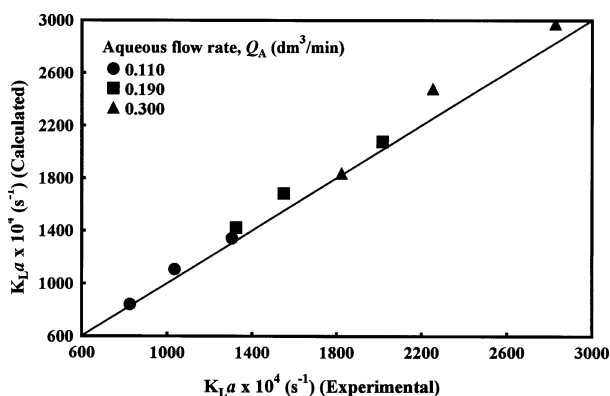$[B_i] = 0.75$ kmol/m³; disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

Figure 13. Calculated vs. experimental overall volumetric mass-transfer coefficient $K_L a$.

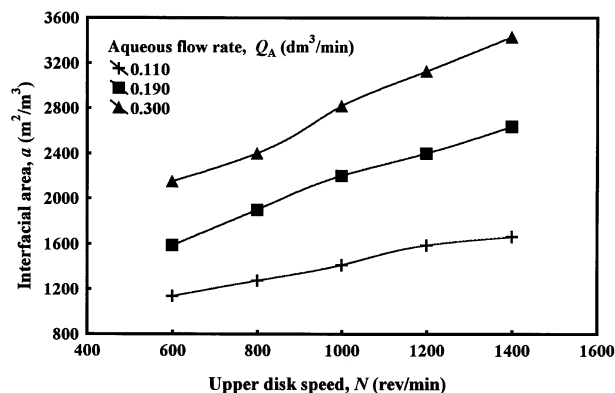Disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

Figure 14. Interfacial area vs. upper disk speed.

Disk diameter d, 0.20 m; distance between the disks h, 0.0015 m.

where $\tau(r)$ is the shearing stress at a distance r from the center of the disk, and dS(r) is the surface of the annular element with width dr. The tangential velocity at a distance r from the axis is equal to

$$v(r) = 2\pi Nr. \qquad (13)$$

Thus, the elementary power can be written as

$$dP = v(r)dF(r). \qquad (14)$$

Also, the expressions of the shearing stress were derived elsewhere (Schlichting, 1979; White, 1974).

Conclusions

Overall volumetric mass-transfer coefficient and the conversion of aqueous NaOH solution

(1) The values of the overall volumetric mass-transfer coefficient and the conversion of aqueous NaOH solution increase with an increase in the upper disk speed.

(2) An increase in the aqueous NaOH solution flow rate over the range of 0.110 to 0.300 dm³/min results in decreasing the conversion of aqueous NaOH solution. Conversely, such an increase in the distilled water flow rates increases the overall volumetric mass-transfer coefficients.

(3) The volumetric extraction rate increases with increasing overall volumetric mass-transfer coefficients; that is, within the range studied the overall rate of the process is controlled by mass-transfer phenomena.

(4) The values of the overall volumetric mass-transfer coefficients calculated from the intercepts of Danckwerts' plots are in good agreement with those obtained by the physical method.

Effective interfacial area (a)

(1) An increase in the upper disk speed increases the effective interfacial area.

(2) The values of the effective interfacial areas increase with an increase in both the aqueous and the organic solutions flow rates.

(3) The TIJR offers higher values of interfacial areas as compared with mechanically agitated columns (typically, the columns have interfacial area of 500 m²/m³).

Table 3. Power Input Requirements for Various Reactors

Reactor Type	Power Input Requirement (kJ/kmol Extracted)
Oldshue Ruston Columns (Tamir, 1994; Sarkar et al., 1980)	~ 1,500
Air-Operated-Two-Impinging-Streams Reactor (Dehkordi, 2002a)	~ 23,000
TIJR	~ 2,500

**Table 1. Results from Alkaline Hydrolysis of NBF in the TIJR*

Q_A (dm³/min)	N (rev/min)	$[B_i]$ (kmol/m³)	d (m)	$[1+(D_A K_2[B]a^2)/(K_L a)^2]^{0.5}$	$1+[B]/[A^*]$
0.110	600	0.75	0.20	1.81	12.02
0.110	1,000	0.75	0.20	1.71	11.39
0.110	1,400	0.75	0.20	1.65	10.81
0.190	600	0.75	0.20	1.61	12.35
0.190	1,000	0.75	0.20	1.75	11.70
0.190	1,400	0.75	0.20	1.69	11.13
0.300	600	0.75	0.20	1.66	12.61
0.300	1,000	0.75	0.20	1.62	12.11
0.300	1,400	0.75	0.20	1.61	11.62

*The ratio of D_B to D_A has been taken equal to one.

Table 2. Evaluation of Performance Capability of Various Reactors

Chemical System	A/O	Reactor Type	$K_L a \times 10^4$ (s⁻¹)	$R_A a \times 10^4$ (kmol/m³·s)
n-Butyl formate-aqueous NaOH solution	1.66/1	Oldshue Rushton Column (Sarkar et al., 1980)	250	11
n-Butyl formate-aqueous NaOH solution	1/1	Air-Operated-Two-Impinging-Streams Reactor (Dehkordi, 2002a)	750	45
n-Butyl formate-aqueous NaOH solution	1/1	TIJR	2,800	270

Acknowledgment

Notation

a = interfacial area, m^2/m^3
$[A]$ = concentration of NBF in distilled water, $kmol/m^3$
$[A^*]$ = solubility of NBF in aqueous alkali solution, $kmol/m^3$
$[A_w]$ = solubility of NBF in distilled water, $kmol/m^3$
$[B]$ = concentration of aqueous NaOH solution, $kmol/m^3$
d = disk diameter, m
D_A = diffusion coefficient of solute A in phase B, m^2/s
D_B = diffusion coefficient of the reactant, m^2/s
Eh = enhancing effect of impinging jets
F = force, N
h = distance between disks, m
I = ionic strength, $kmol/m^3$
K_2 = second-order kinetic rate constant, $m^3/kmol \cdot s$
K_L = overall mass-transfer coefficient, m/s
$K_L a$ = overall volumetric mass-transfer coefficient, s^{-1}
$K_s = i_+ + i_- + i_{ester}$, $m^3/kmol$
N = upper disk speed, rev/min
Q = volumetric flow rate of liquid phase, dm^3/min
r = distance from center of disk, m
$R_A a$ = extraction rate per unit volume of reactor, $kmol/s \cdot m^3$
S = surface, m^2
v = velocity, m/s
V_c = contactor (reactor) volume, dm^3
X_c = conversion of aqueous NaOH solution
τ = shear stress, N/m^2

Subscripts

A = aqueous phase
aq = aqueous phase
i = inlet of reactor
ln = logarithmic mean
o = outlet of reactor
or = organic phases

Superscript

$*$ = at equilibrium

Abbreviations

IJ = impinging jets
NBF = n-Butyl formate
NIJR = nonimpinging-jets reactor
SS = stainless steel
TIJR = two-impinging-jets reactor

Literature Cited

Alwan, S., S. Hiraoka, and I. Yamada, "Extraction Rate of n-Amyl Acetate with Alkaline Hydrolysis in Aqueous Phase," *Chem. Eng. Commun.*, **22**, 317 (1983).

Berman, Y., and A. Tamir, "Experimental Investigation of Phosphate Dust Collection in Impinging Streams (IS)," *Can. J. Chem. Eng.*, **74**, 817 (1996).

Berman, Y., and A. Tamir, "Extraction in Thin Liquid Films Generated by Impinging Streams," *AIChE J.*, **46**, 769 (2000).

Carver, J. A., S. Plains, and W. F. Rollman, "Method and Apparatus for Mixing and Contacting Fluids," U.S. Patent No. 2,751,335 (Jun. 19, 1956).

Chaudhuri, B., S. Bhattacharjee, and B. K. Dutta, "Kinetics of Alkaline Hydrolysis of 2-Ethylbutylformate," *Can. J. Chem. Eng.*, **74**, 806 (1996).

Danckwerts, P. V., *Gas-Liquid Reactions*, McGraw-Hill, New York (1970).

Dehkordi, A. M., T. Kaghazchi, and M. Sohrabi, "Application of an Air-Operated Two Impinging Streams Extractor in Liquid-Liquid Extraction and Comparison with Other Contactor Types," *Can. J. Chem. Eng.*, **79**, 227 (2001).

Dehkordi, A. M., "Novel Type of Impinging Streams Contactor for Liquid-Liquid Extraction," *Ind. Eng. Chem. Res.*, **40**(2), 681 (2001).

Dehkordi, A. M., "Liquid-Liquid Extraction with an Interphase Chemical Reaction in an Air-Driven-Two-Impinging-Streams Reactor: Effective Interfacial Area and Overall Mass-Transfer Coefficient," *Ind. Eng. Chem. Res.*, **41**(16), 4085 (2002a).

Dehkordi, A. M., "A Novel Two-Impinging-Jets Reactor for Copper Extraction and Stripping Processes," *Chem. Eng. J.*, **87**(2), 227 (2002b).

Dehkordi, A. M., "Experimental Investigation of an Air-Operated-Two-Impinging-Streams Reactor for Copper Extraction Processes," *Ind. Eng. Chem. Res.*, **41**(10), 2512 (2002c).

Devahastin, S., and A. S. Mujumdar, "A Numerical Study of Flow and Mixing Characteristics of Laminar Confined Impinging Streams," *Chem. Eng. J.*, **85**, 215 (2002).

Devahastin, S., and A. S. Mujumdar, "A Numerical Study of Mixing in a Novel Impinging Stream Inline Mixer," *Chem. Eng. Process.*, **40**, 459 (2001a).

Devahastin, S., and A. S. Mujumdar, "A Study of Turbulent Mixing of Confined Impinging Streams using a New Composite Turbulence Model," *Ind. Eng. Chem. Res.*, **40**, 4998 (2001b).

Elperin, I. T., "Heat and Mass Transfer in Opposing Currents (in Russian)," *J. Eng. Physics*, **6**, 62 (1961).

Fernandez, J. B., and M. M. Sharma, "Effective Interfacial Area in Agitated Liquid-Liquid Contactor," *Chem. Eng. Sci.*, **22**, 1267 (1967).

Ghosh, B., D. C. Mukherjee, S. Bhattacharjee, and B. Chaudhuri, "Alkaline Hydrolysis of Isoamylformate: Effect of Dissolved Electrolytes on Kinetics," *Can. J. Chem. Eng.*, **79**, 148 (2001).

Herskowits, D., V. Herskowits, and A. Tamir, "Desorption of Acetone in a Two-Impinging-Stream Spray Desorber," *Chem. Eng. Sci.*, **42**(10), 2331 (1987).

Herskowits, D., V. Herskowits, K. Stephan, and A. Tamir, "Characterization of a Two-Phase Impinging Jet Absorber: I. Physical Absorption of CO_2 in Water," *Chem. Eng. Sci.*, **43**(10), 2773 (1988).

Herskowits, D., V. Herskowits, K. Stephan, and A. Tamir, "Characterization of a Two-Phase Impinging Jet Absorber: II. Absorption with Chemical Reaction of CO_2 in NaOH Solutions," *Chem. Eng. Sci.*, **45**(5), 1281 (1990).

Hosseinalipour, S. M., and A. S. Mujumdar, "Flow and Thermal Characteristics of Steady Two-Dimensional Confined Laminar Opposing Jets: I. Equal Jets," *Int. Comm. Heat Mass Transfer*, **24**, 27 (1997a).

Hosseinalipour, S. M., and A. S. Mujumdar, "Flow and Thermal Characteristics of Steady Two-Dimensional Confined Laminar Opposing Jets: II. Unequal Jets," *Int. Comm. Heat Mass Transfer*, **24**, 39 (1997b).

Hosseinalipour, S. M., and A. S. Mujumdar, "Comparative Evaluation of Different Turbulence Models for Confined Impinging and Opposing Jet Flows," *Num. Heat Transfer*, Part A, **28**, 647 (1995a).

Hosseinalipour, S. M., and A. S. Mujumdar, "Superheated Steam Drying of a Single Particle in an Impinging Streams Dryer," *Drying Technol.*, **13**, 1279 (1995b).

Kitron, Y., and A. Tamir, "Performance of a Coaxial Gas-Solid Two-Impinging-Streams (TIS) Reactor: Hydrodynamics, Residence Time Distribution, and Drying Heat Transfer," *Ind. Eng. Chem. Res.*, **27**, 1760 (1988).

Kleingeld, A. W., L. Lorenzen, and F. G. Botes, "The Development and Modeling of High-Intensity Impinging Streams Jet Reactors for Effective Mass Transfer in Heterogeneous Systems," *Chem. Eng. Sci.*, **54**, 4991 (1999).

Kudra, T., and A. S. Mujumdar, "Impinging Stream Dryers for Particles and Pastes," *Drying Technol.*, **7**, 219 (1989).

Kudra, T., and A. S. Mujumdar, *Impinging Stream Dryers. In Handbook of Industrial Drying*, 2nd ed., A. S. Mujumdar, ed., Marcel Dekker, New York (1995).

Kudra, T., A. S. Mujumdar and V. L. Meltser, *Impinging Stream Dryers; Principles, Practice and Potential: Drying of Solids*, Sarita Prakashan, Meerut, India (1991).

Laddha, G. S., and T. E. Degaleesan, *Transport Phenomena in Liquid Extraction*, Tata McGraw-Hill Publishing Company, New Delhi, India (1976).

Nanda, A. K., and M. M. Sharma, "Effective Interfacial Area in Liquid-Liquid Extraction," *Chem. Eng. Sci.*, **21**, 707 (1966).

Onda, K., H. Takeuchi, M. Fujine, and Y. Takahashi, "Study of Mass Transfer between Phases by a Diaphragm Cell," *J. Chem. Eng. Jpn.*, **8**, 30 (1975).

Puranik, S. A., and M. M. Sharma, "Effective Interfacial Area in a Packed Liquid Extraction Column," *Chem. Eng. Sci.*, **25**, 257 (1970).

Sarkar, S., C. J. Mumford, and C. Phillips, "Liquid-Liquid Extraction with Interphase Chemical Reaction in Agitated Columns. 2. Hydrodynamics and Mass Transfer in Rotating Disk and Oldshue Rushton Contactors," *Ind. Eng. Chem. Process Des. Dev.*, **19**, 672 (1980).

Schlichting, H., *Boundary Layer Theory*, 7th ed., McGraw-Hill, New York (1979).

Seyedein, S. H., M. Hasan, and A. S. Mujumdar, "Modeling of a Single Confined Turbulent Slot Jet Impingement Using Various k-ϵ Turbulence Models," *Appl. Math. Modeling*, **18**, 526 (1994).

Sievers, M., E. S. Gaddis, and A. Vogelpohl, "Fluid Dynamics in an Impinging-Streams Reactor," *Chem. Eng. Process.*, **34**, 115 (1995).

Sohrabi, M., and A. M. Jamshidi, "Studies on the Behavior and Application of the Continuous Two-Impinging Streams Reactors in Gas-Liquid Reactions," *Chem. Technol. Biotechnol.*, **69**, 415 (1997).

Sohrabi, M., T. Kaghazchi, and F. Yazdani, "Modeling and the Application of the Continuous Impinging Streams Reactors in Liquid-Liquid Heterogeneous Reactions," *Chem. Technol. Biotechnol.*, **58**, 363 (1993).

Sohrabi, M., and M. A. Marvast, "Application of a Continuous Two Impinging Streams Reactor in Solid-Liquid Enzyme Reactions," *Ind. Eng. Chem. Res.*, **39**, 1903 (2000).

Tamir, A., and M. Grinholtz, "Performance of a Continuous Solid-Liquid Two-Impinging Streams (TIS) Reactor: Dissolution of Solids, Hydrodynamics, Mean Residence Time and Holdup of the Particles," *Ind. Eng. Chem. Res.*, **26**, 726 (1987).

Tamir, A., D. Herskowits, and V. Herskowits, "Impinging-Jets Absorber," *Chem. Eng. Process.*, **28**, 165 (1990a).

Tamir, A., D. Herskowits, V. Herskowits, and K. Stephan, "Two-Impinging Jets Absorber," *Ind. Eng. Chem. Res.*, **29**, 272 (1990b).

Tamir, A., *Impinging Streams Reactors: Fundamentals and Applications*, Elsevier, Amsterdam (1994).

Unger, D. R., F. J. Muzzio, and R. S. Brodkey, "Experimental and Numerical Characterization of Viscous Flow and Mixing in an Impinging Jet Contactor," *Can. J. Chem. Eng.*, **76**, 546 (1998).

van Woezik, B. A. A. and K. R. Westerterp, "Measurement of Interfacial Areas with the Chemical Method for a System with Alternating Dispersed Phases," *Chem. Eng. Process.*, **39**, 299 (2000).

Verma, R. P., and M. M. Sharma, "Mass Transfer in Packed Liquid-Liquid Extraction Columns," *Chem. Eng. Sci.*, **30**, 279 (1975).

White, F. M., *Fluid Mechanics*, 2nd ed., McGraw-Hill (1986).

White, F. M., *Viscous Fluid Flow*, McGraw-Hill, New York (1974).

Yao, B., Y. Berman, and A. Tamir, "Evaporative Cooling of Air in Impinging Streams," *AIChE J.*, **41**, 1667 (1995).