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A novel two-impinging-jets reactor for copper extraction and stripping processes

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Abstract

A novel two-impinging-jets reactor (TIJR) for metals extraction was proposed and tested through solvent extraction of copper by means of a weak extractant with moderately slow chemical kinetics such as LIX 84, as a typical example of hydrometallurgical solvent extraction processes. The results obtained for the extraction and stripping rates of copper per unit volume of the TIJR were much higher than those expected in a conventional reactor such as a continuous-stirred tank reactor (CSTR). These experimental results clearly indicate the greater performance capability of TIJR relative to that of CSTR. In addition, the effects of the upper disk speed, aqueous and organic flow rates, the reactor's dimension including the disk diameter and the distance between the disks have been investigated. Furthermore, the effect of impinging jets has been investigated using a non-impinging-jets reactor (NIJR).

Keywords: Opposed jets; Impinging streams; Impingement zone; Impinging jets; Liquid–liquid extraction; Copper/LIX system; Copper

1. Introduction

Solvent extraction of copper has become an important process and is used in several hydrometallurgical plants to recover copper from oxide ores and post-flotation tailings producing the least expensive copper in the world. In industry, solvent extraction of copper is usually carried out in continuous-stirred tank reactor (CSTR) and is a well-known process. In addition, the efficiency of the LIX group of reagents in copper extraction is rather well-documented [1–5]. Hydroxy oximes are well-established extractants for copper extraction, and they are used in several industrial installations. It is now estimated that about 15% of all the copper production in the world is produced by hydrometallurgical processes, i.e., extraction by hydroxy oximes or ACORGA reagents.

The extraction of copper using LIX reagents as the extractant can be expressed as

$$Cu^{2+}_{aq} + 2HL_{or} \Leftrightarrow CuL_{2or} + 2H^{+}_{aq} \quad (1)$$

where HL represents extractant, and subscripts aq and or are aqueous and organic phases, respectively. The extraction is then followed by stripping process, i.e., the copper is recovered from the loaded organic phase by means of sulfuric acid solution of an appropriate concentration.

During the past decades several new extractants of LIX type have been proposed. They are blends of two or three various hydroxy oximes exhibiting different strengths of copper extraction. The addition of a weaker extractant to the stronger one, i.e., 2-hydroxy-5-nonylbenzophenone oxime to 2-hydroxy-5-dodecylbenzaldhyde (LIX 865 or LIX 864 as it contains LIX 65N or LIX 64N) and 2-hydroxy-5-nonylacetophenone oxime (LIX 84) to 2-hydroxy-5-dodecylbenzaldehyde oxime (LIX 984), acts in the same way as alkylphenol or alcohol additives present in ACORGA reagents. However, in this case both hydroxy oximes are chemically active and they extract copper. As a result, higher extraction and stripping of copper are obtained in the extraction and stripping processes.

Impinging streams (IS) is a unique and multipurpose technique, which was first employed by Elperin [6] and further developed by Tamir [7]. It provides a powerful technique for intensifying transfer processes. The method has been successfully applied to the absorption and desorption of gases [8–14]; dissolution of solids [15]; drying of solids [16]; dust collection [17]; absorption with chemical reactions [18,19]; two phase chemical reaction [20]; mixing [21]; bioreaction [22]; solid–liquid enzyme reactions [23], and evaporative cooling of air [24]. It should be added that the application

Abbreviations: CSTR, continuous-stirred tank reactor; IS, impinging streams; NIJR, non-impinging-jets reactor; TIJR, two-impinging-jets reactor

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Nomenclature

C	concentration ($kg\,m^{-3}$)
d	disk diameter (m)
D_s	diffusion coefficient of solvent in the aqueous phases ($m^2\,s^{-1}$)
E	extraction and stripping efficiencies
Eh	enhancing effect of opposing jets
h	distance between disks (m)
J	constant, in Eq. (12)
K	constant, in Eq. (13)
m	distribution ratio
N	upper disk speed (rpm)
NE	extraction rate ($g\,min^{-1}$)
NS	stripping rate ($g\,min^{-1}$)
Q	volumetric flow rate of the liquid phases ($dm^3\,min^{-1}$)
RE	extraction rate of copper per unit volume of reactor ($g\,min^{-1}\,dm^{-3}$)
RS	stripping rate of copper per unit volume of reactor ($g\,min^{-1}\,dm^{-3}$)
V_r	reactor volume (dm^3)

Greek symbols

α	adjustable parameters, in Eq. (10)
β	adjustable parameters, in Eq. (11)
γ	interfacial tension ($N\,m^{-1}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)

Subscripts

aq	aqueous phases
A	aqueous phases
ex	extraction
i	inlet of reactor
lix	LIX reagent
o	outlet of reactor
or	organic phases
st	stripping
su	sulfuric acid

Superscript

eq	at equilibrium

of the IS technique in liquid–liquid extraction has been reported elsewhere [25–27].

On the basis of these extensive investigations, it can be concluded that almost all processes in chemical engineering can be carried out by applying IS technique, presumably with a higher efficiency in comparison with conventional methods.

The great potential of the IS technique in chemical processes, on the one hand, and importance of copper extraction in industry, on the other hand, was the major motivation for the present investigation. The main objective of the present investigation was to apply and test a novel two-impinging-jets reactor (TIJR) for copper extraction and stripping processes. To achieve this goal, a number of experiments have been conducted on the extraction of copper from its sulfate solution by means of LIX 84 (15% v/v) as a weak reagent with moderately slow chemical kinetics diluted with kerosene and the stripping of the loaded solvent by means of sulfuric acid solution as a stripping solution, applying a TIJR. In addition, a non-impinging-jets reactor (NIJR) was employed to test the effectiveness of the TIJR.

2. Experimental

2.1. Chemicals

Sulfuric acid solution used as stripping solution was of analytical grade only.

2.2. Experimental apparatus

TIJR. The experimental setup shown in Fig. 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 0.0015–0.003 m distances between disks; (2) a variable-speed electric motor in order to study the effect of the upper disk speed on the extraction and stripping efficiencies. Note that in the present investigation, only the upper disk was rotated and the lower disk was fixed. A schematic diagram of the disks is given in Fig. 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 TIJR 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 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 0.001 m diameter in order to introduce high-velocity jets to one another.

CSTR. To compare the performance capability of the TIJR with a conventional reactor that usually used in the copper extraction and stripping processes, a conventional mixer has been used in the present investigation. The CSTR was a laboratory-scale baffled tank with an active volume of 1 dm^3 equipped with a turbine-type impeller and variable-speed electric motor.

2.3. Experimental procedure and analytical technique

In each experimental run, the upper disk speed was adjusted at the desired value, and then the organic and aqueous

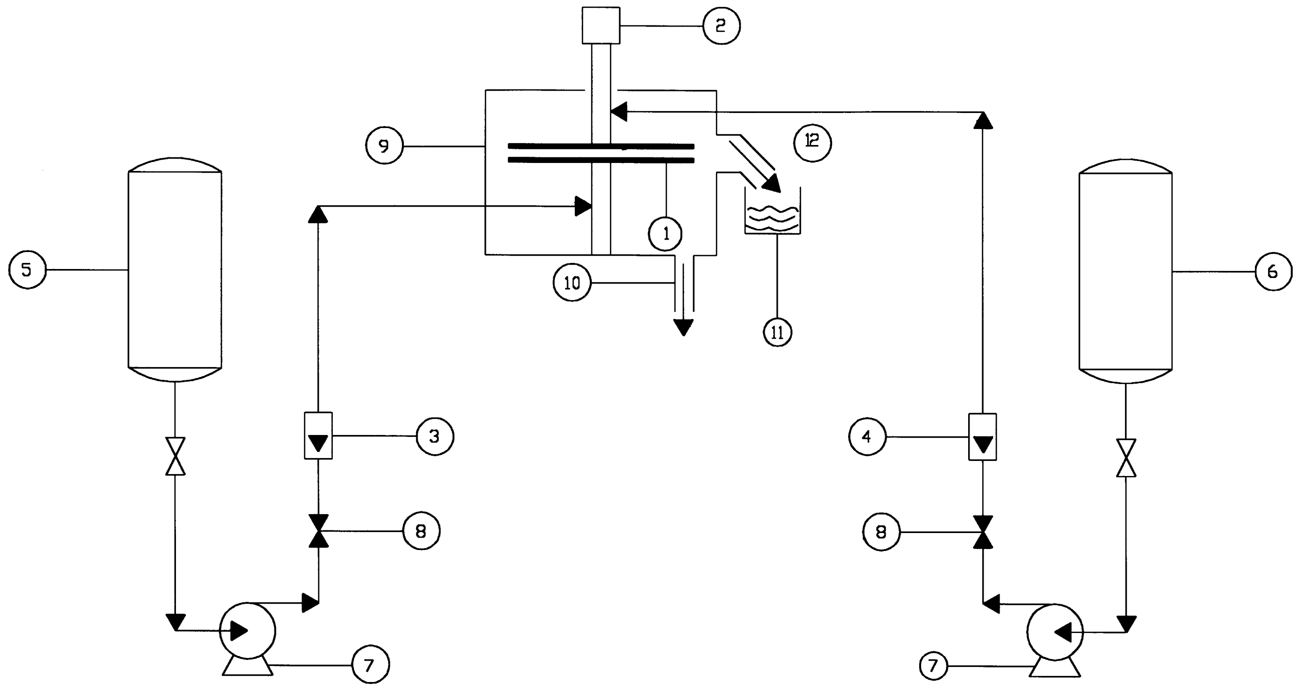

Fig. 1. Experimental setup: (1) circular disks; (2) variable-speed electric motor; (3 and 4) solution rotameters; (5 and 6) feed vessels; (7) feed pumps; (8) needle valves; (9) cylindrical vessel; (10) bulk dispersion outlet; (11) sampling cup; (12) sampling connection.

phases were fed to the TIJR at given volumetric flow rates. 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 measurement of the copper concentration in both the streams. 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 the effect of additional mass transfer in the sampling cups as much as possible. The analysis of the aqueous samples was performed by an iodometric method, i.e., titration with sodium thiosulfate, and using atomic absorption spectrometer (Shimadzu 680). The concentration of copper in the organic phases was determined by stripping a sample with concentrated sulfuric acid solution three times. The three aqueous solutions were added together and treated exactly as described above for the aqueous phase analysis. The accuracy of the analytical methods was tested using known samples of aqueous solution. The maximum error did not exceed ±2.5 and ±4% for the titration and atomic absorption spectrometry. Note that for each data point, 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 aqueous and organic solutions with a standard deviation of 4–6%.

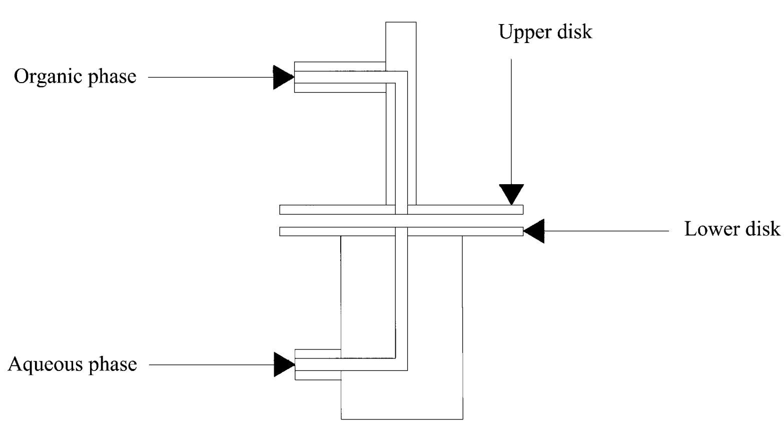

Fig. 2. Cross-section of the circular disks.

To explore which phase was a continuous phase and which one was a disperse phase, a number of experiments have been conducted on the measurement of the conductivity of the outlet dispersion by using Konductometer CG 857 from Schott Gerate with measuring cell constant $k = 1.01\,\text{cm}^{-1}$ at the upper disk speeds of 600–1400 rpm. It was found that the aqueous solutions were continuous phases at the bulk dispersion outlet of the TIJR for both the extraction and the stripping processes.

3. Experimental results and discussion

To examine the effect of various operating parameters such as the upper disk speed, throughput, reactor's dimensions including the disk's diameter and distance between the disks, and the effect of impinging jets, a number of experimental runs have been conducted on the extraction and stripping processes of copper by means of LIX 84 diluted with kerosene and sulfuric acid solution, respectively. The operating conditions of the experiments were as follows:

1. Upper disk speed, N (rpm): 600–1400
2. Pressure of the aqueous and organic streams at the inlet of the rotameters: 0.65 atm
3. Temperature within the reactor (°C): ∼18
4. Aqueous to organic flow ratio (A/O) in the extraction and stripping processes: 1/1
5. Flow rate of aqueous and organic solutions, $Q_{\text{or}} = Q_{\text{A}}$ ($\text{dm}^3\,\text{min}^{-1}$): 0.110–0.300
6. Concentration of copper in copper sulfate solution at the inlet of the reactor $C_{\text{A,i}}$ ($\text{kg}\,\text{m}^{-3}$): 4.44
7. Concentration of copper in the loaded organic phase at the inlet of the reactor $C_{\text{or,i}}$ ($\text{kg}\,\text{m}^{-3}$): 3.5
8. Concentration of sulfuric acid in the stripping solution ($\text{kg}\,\text{m}^{-3}$): 200
9. pH of copper sulfate solution: 2.9
10. Concentration of LIX 84 in the solvent (% v/v): 15
11. Specific gravity of kerosene at 15 °C: 0.81
12. Aromatic content of kerosene (% v/v): 20
13. Kinematic viscosity of kerosene at 40 °C: $1.7 \times 10^{-6}\,\text{m}^2\,\text{s}^{-1}$
14. Disks diameter (d): 0.15–0.25 m
15. Distance between disks (h): 0.0015–0.003 m

3.1. *Definition of the extraction and stripping efficiencies, extraction and stripping rates*

The extraction and stripping efficiencies may be expressed as follows:

$$E = \frac{C_{\text{A,i}} - C_{\text{A,o}}}{C_{\text{A,i}} - C_{\text{A,o}}^{\text{eq}}} \tag{2}$$

where $C_{\text{A,i}}$ and $C_{\text{A,o}}$ are the concentrations of copper in the inlet and outlet aqueous solutions, respectively, and $C_{\text{A,o}}^{\text{eq}}$ is the equilibrium concentration of copper in the outlet aqueous phases. Since the interfacial area between the phases in the extraction and stripping processes were not known, the overall rates of extraction and stripping of copper and the overall extraction and stripping rates of copper per unit volume of the TIJR were determined from the experimental results by the following relations given under steady state conditions

$$\text{NE} = Q_{\text{A}}(C_{\text{A,i}} - C_{\text{A,o}}) \tag{3}$$

$$\text{NS} = Q_{\text{A}}(C_{\text{A,o}} - C_{\text{A,i}}) \tag{4}$$

$$\text{RE} = \frac{Q_{\text{A}}(C_{A,\text{i}} - C_{A,\text{o}})}{V_{\text{r}}} \tag{5}$$

$$\text{RS} = \frac{Q_{\text{A}}(C_{\text{A,o}} - C_{\text{A,i}})}{V_{\text{r}}} \tag{6}$$

where NE, NS, Q_{A}, RE, RS and V_{r} are the extraction rate, stripping rate, volumetric flow rate of aqueous solutions, extraction and stripping rates of copper per unit volume of reactor, and reactor volume, respectively.

To obtain the equilibrium data for the test systems, a number of experiments have been performed before carrying out the final experiments. These results were completely agreed with those reported by Ali et al. [3] for the test systems. According to these results, it was found that the distribution ratios, m, for the extraction and the stripping processes at the operating conditions could be well correlated as

$$\log(m_{\text{ex}}) = 2\log(C_{\text{lix}}) - 1.55 \quad \text{for the extraction} \tag{7}$$

$$\log(m_{\text{st}}) = \log(C_{\text{su}}) - 1.27 \quad \text{for the stripping} \tag{8}$$

where ex, st and lix denote the extraction, stripping and the reagent, respectively, and m defined as $C_{\text{or}}/C_{\text{A}}$ for the extraction process and as $C_{\text{A}}/C_{\text{or}}$ for the stripping process. It should be also added that the further details of equilibrium data concerning the test systems have been reported by Ali et al. [3].

3.2. *Effect of the upper disk speed (N)*

The influence of the upper disk speed, N, on the extraction and stripping efficiencies, E, are demonstrated in Figs. 3 and 4. As can be observed, an increase in the latter quantities is visible by increasing the upper disk speed within the range 600–1400 rpm. This can be attributed to an increase in the mixing and turbulence. In addition, 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 resistance.

3.3. *Effect of the liquid flow rates*

Figs. 5–8 demonstrate the dependency of the extraction and stripping efficiencies, E, the extraction and stripping rates, RE and RS, on the aqueous flow rates. Note that in

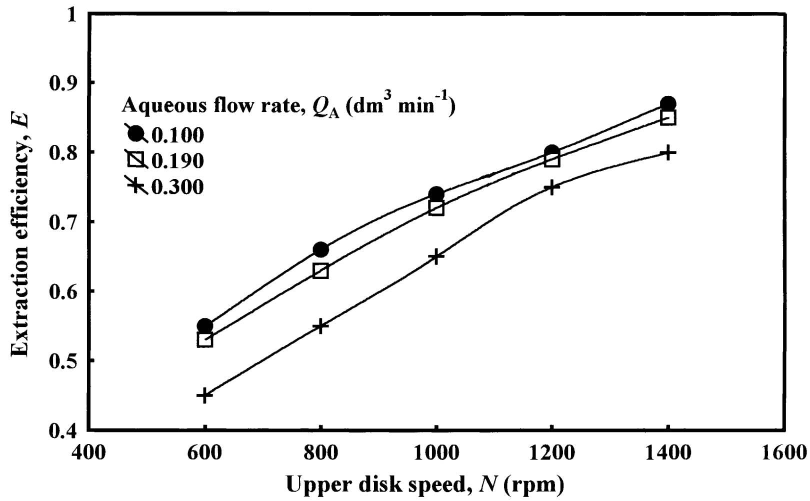

Fig. 3. Effect of upper disk speed on the extraction efficiency, E. Disk diameter, d, 0.20 m; distance between disks, h, 0.0015 m.

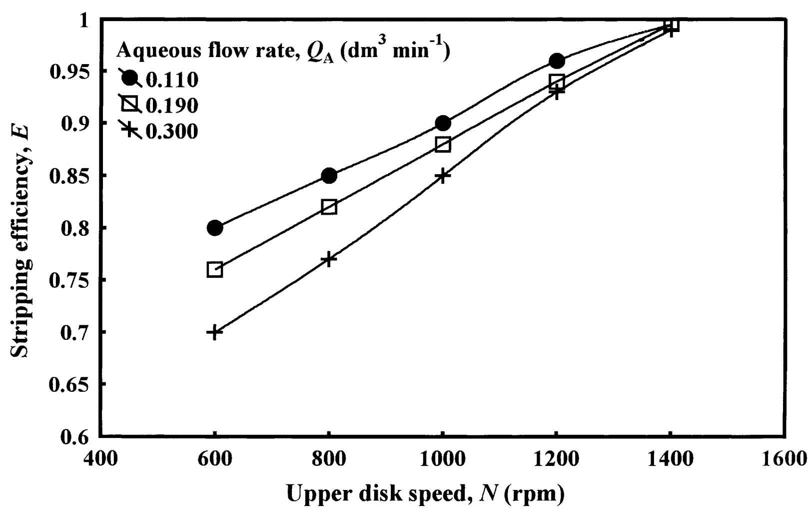

Fig. 4. Effect of upper disk speed on the stripping efficiency, E. Disk diameter, d, 0.20 m; distance between disks, h, 0.0015 m.

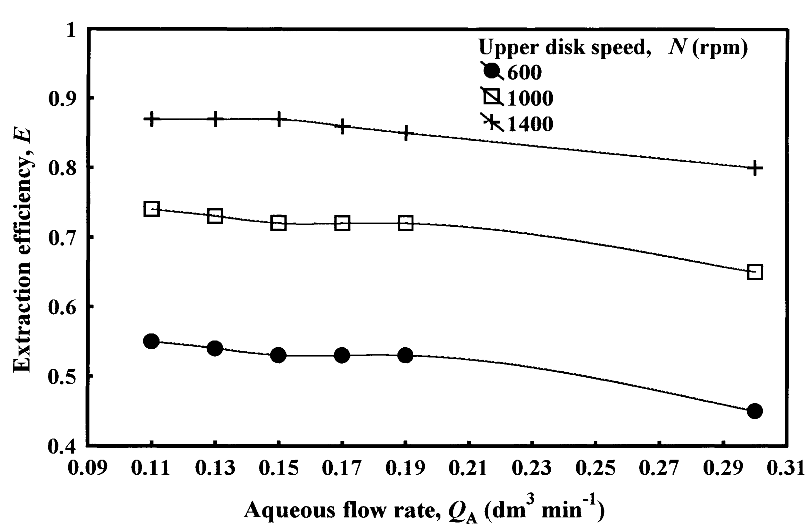

Fig. 5. Effect of the aqueous flow rate on the extraction efficiency, E. Disk diameter, d, 0.20 m; distance between disks, h, 0.0015 m.

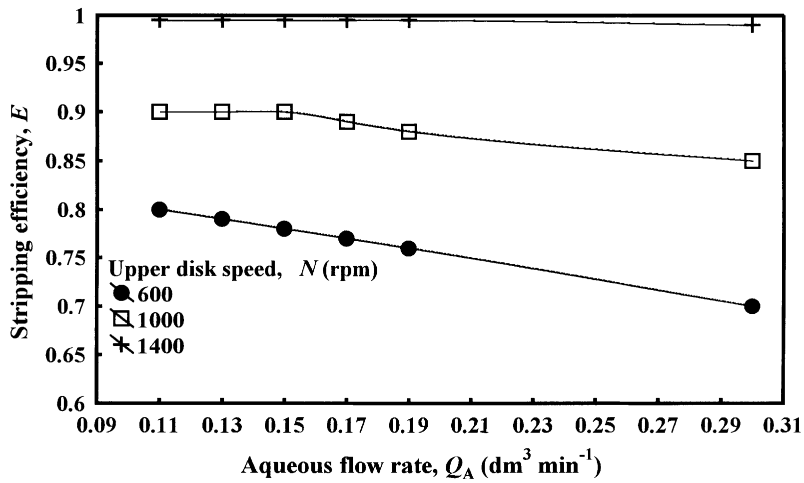

Fig. 6. Effect of the aqueous flow rate on the stripping efficiency, *E*. Disk diameter, *d*, 0.20 m; distance between disks, *h*, 0.0015 m.

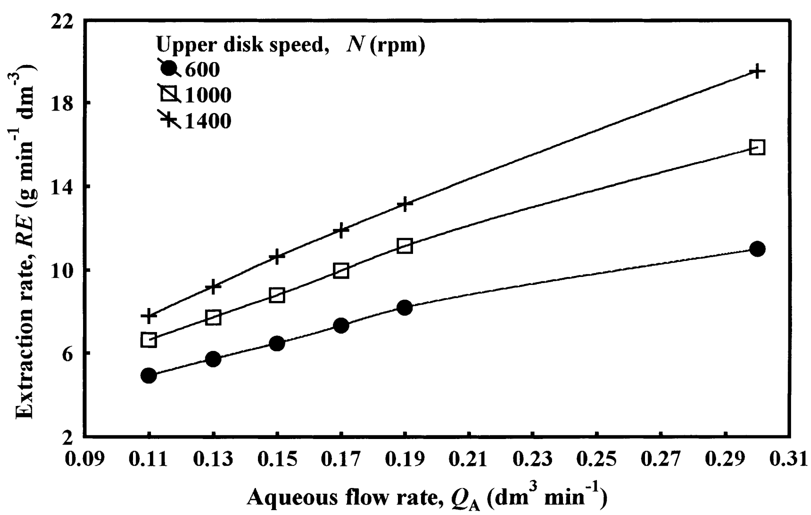

Fig. 7. Effect of the aqueous flow rate on the extraction rate per unit volume, RE. Disk diameter, *d*, 0.20 m; distance between disks, *h*, 0.0015 m.

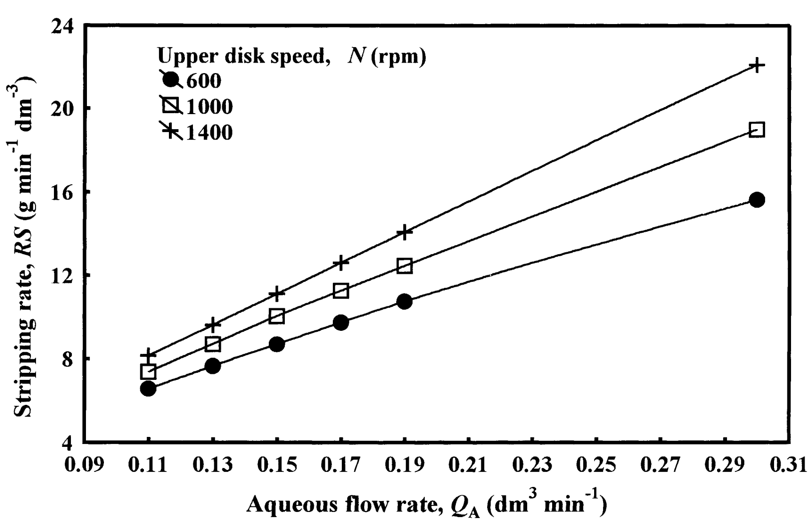

Fig. 8. Effect of the aqueous flow rate on the stripping rate per unit volume, RS. Disk diameter, *d*, 0.20 m; distance between disks, *h*, 0.0015 m.

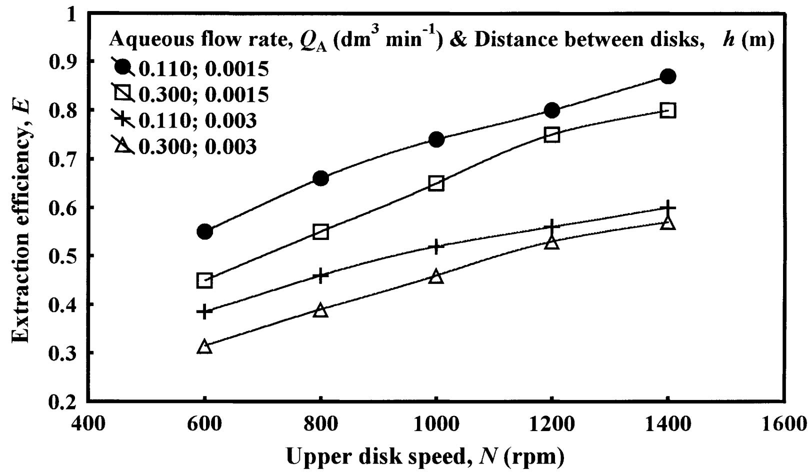

Fig. 9. Effect of the distance between disks, *h*, on the extraction efficiency, *E*. Disk diameter, *d*, 0.20 m.

the present investigation the organic flow rates were identical to those of the aqueous flow rates in both the extraction and stripping processes. As can be observed from Figs. 5 and 6, an increase in the aqueous flow rates within the range of 0.110–0.300 $dm^3\,min^{-1}$ decreases the extraction and stripping efficiencies. This behavior can be explained as follows: in the high throughput (both the aqueous and organic flow rates), the mean residence time of the streams within the reaction compartment is low; hence the extraction and stripping efficiencies were decreased. Furthermore, as can be observed from Figs. 7 and 8, an increase in the flow rates within the aforementioned range of the aqueous and organic flow rates, leads to increases in the extraction and stripping rates of copper. 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.

3.4. Effect of the disk diameter (d) and the distance between disks (h)

To explore the influence of the distance between the disks, *h*, on the extraction and stripping efficiencies, a number of experimental runs were conducted with various distances between the disks. These experimental results are shown in Figs. 9 and 10. Note that in the present investigation, the distances between disks smaller than 0.0015 m were not taken into account because of the longer time needed for complete separation of the dispersions than those related to larger distances. As can be observed from Figs. 9 and 10, a decrease in the distance between disks, *h*, from 0.003 to 0.0015 m increases the extraction and stripping efficiencies.

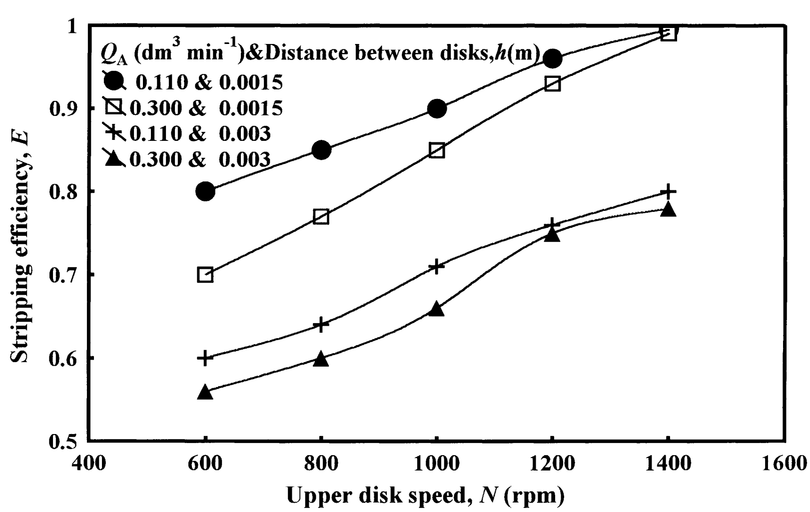

Fig. 10. Effect of the distance between disks, *h*, on the stripping efficiency, *E*. Disk diameter, *d*, 0.20 m.

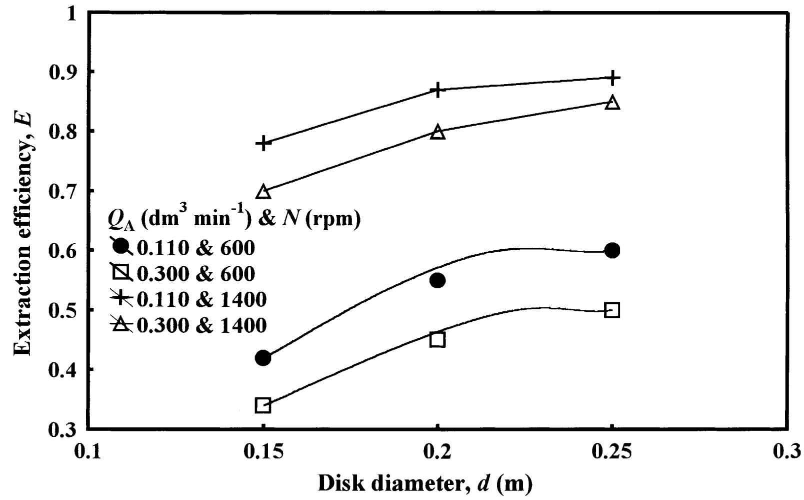

Fig. 11. Effect of the disk diameter on the extraction efficiency, E. Distance between disks, h, 0.0015 m.

The latter is due to much higher shear forces acting on the phases as well as an increase in the bulk turbulence.

The influence of the disk diameters, d, on the extraction and stripping efficiencies are demonstrated in Figs. 11 and 12. As can be noticed from these figures, an increase in the disk diameters from 0.15 m to 0.25 m increases the extraction and stripping efficiencies, but the latter was not appreciable at the high upper disk speeds for disk diameters larger than 0.20 m. This may be attributed to the dominant effects of impinging process and high rate shear forces acting on the phases.

3.5. Effect of opposing 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 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 distance between the two inlet pipes in the NIJR was 0.005 m. A schematic diagram of the NIJR is given in Fig. 13. Therefore, the aqueous and organic phases did not impinge upon 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 the enhancing effect of opposing jets under identical operating conditions

$$\mathrm{Eh} = \frac{\text{extraction (stripping) rate in TIJR}}{\text{extraction (stripping) rate in NIJR}} \quad (9)$$

The enhancing effect of the opposing jets is shown in Figs. 14 and 15. From these figures it can be seen that: (1) the opposing jets generally promote extraction and stripping rates of copper; (2) the enhancing effect of the opposing jets on the extraction and stripping rates were diminished at the high-upper disk speeds for various aqueous and organic

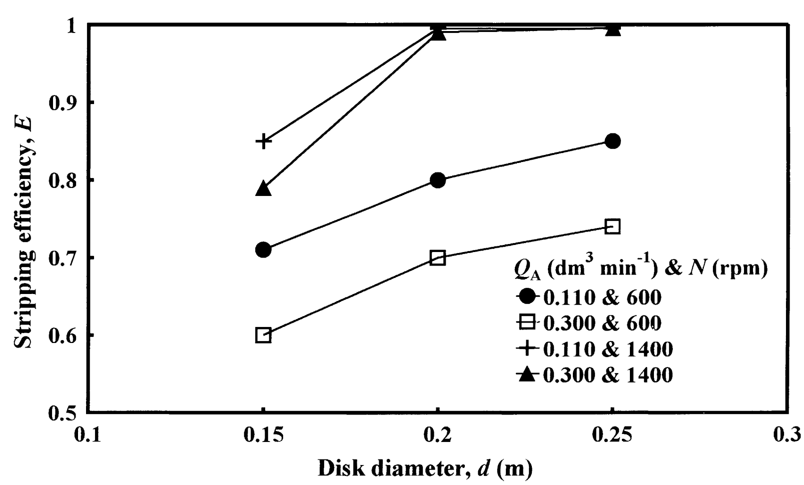

Fig. 12. Effect of the disk diameter on the stripping efficiency, E. Distance between disks, h, 0.0015 m.

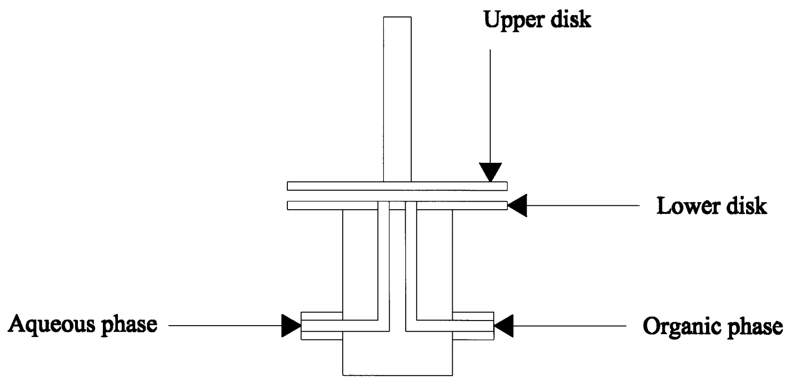

Fig. 13. Cross-section of the disks in the NIJR. Distance between the two-inlet pipes, 0.005 m.

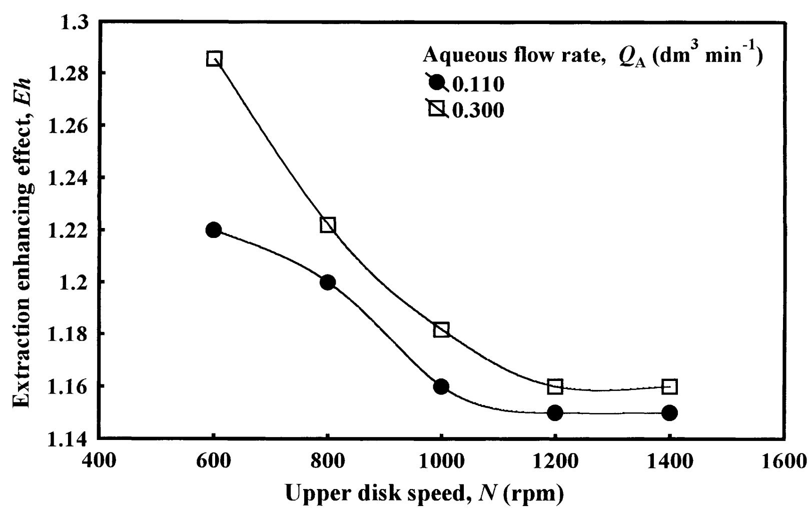

Fig. 14. Effect of IS on the extraction rate, NE. Disk diameter, d, 0.20 m; distance between disks, h, 0.0015 m.

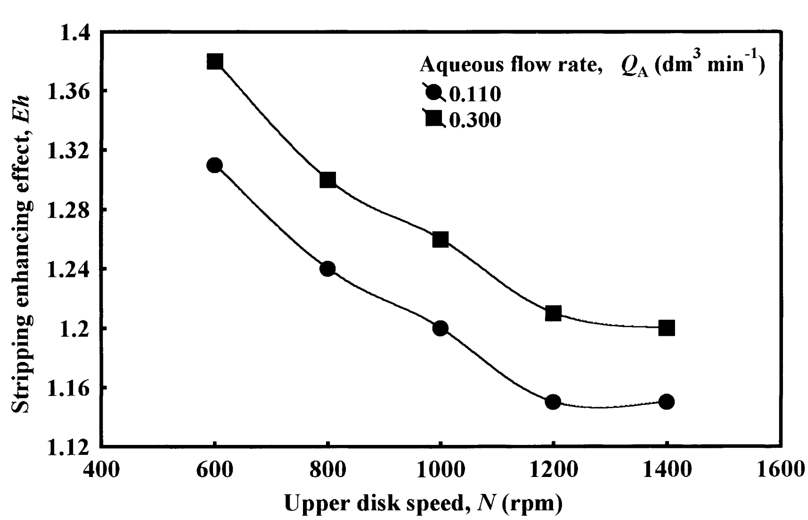

Fig. 15. Effect of IS on the stripping rate, NS. Disk diameter, d, 0.20 m; distance between disks, h, 0.0015 m.

flow rates. The latter can be explained by noting that at the much higher upper disk speed, the effect of high rate shear forces acting on the phases is more effective than that of opposing jets. However, the TIJR is superior relative to NIJR at the high upper disk speeds yet.

3.6. Correlation of the extraction and stripping rates

Since the extraction and stripping processes of copper in the TIJR are complicated, the measured quantities were correlated through dimensional analysis. It is assumed that the following independent variables should play roles in the extraction and stripping rates of copper per unit volume of the reactor:

$$\mathrm{RE} = f(\rho_{\mathrm{aq}}, \rho_{\mathrm{or}}, \nu_{\mathrm{aq}}, \nu_{\mathrm{or}}, \gamma, D_{\mathrm{s}}, C_{\mathrm{A,i}}, \times d, V_{\mathrm{r}}, N, Q_{\mathrm{A}}, Q_{\mathrm{or}}, \mathrm{pH}) \quad (10)$$

$$\mathrm{RS} = f(\rho_{\mathrm{aq}}, \rho_{\mathrm{or}}, \nu_{\mathrm{aq}}, \nu_{\mathrm{or}}, \gamma, D_{\mathrm{s}}, C_{\mathrm{or,i}}, \times d, V_{\mathrm{r}}, N, Q_{\mathrm{A}}, Q_{\mathrm{or}}, C_{\mathrm{su}}) \quad (11)$$

where ρ, ν, γ, D_{s}, d, V_{r}, N, pH and C_{su} are density, kinematic viscosity, interfacial tension, diffusion coefficient of the solvent in aqueous solutions, disk diameter, reactor volume, upper disk speed, pH of copper sulfate solution, and concentration of sulfuric acid in stripping solution, respectively. Subscripts aq and or denote aqueous and organic phases, respectively.

Eqs. (10) and (11) were transformed into the following groups through the Buckingham Pi method:

$$\frac{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^3}{\gamma^2}\mathrm{RE} = J\left(\frac{\rho_{\mathrm{or}}}{\rho_{\mathrm{aq}}}\right)^{\alpha 1}(\mathrm{pH})^{\alpha 2}\left(\frac{D_{\mathrm{s}}}{\nu_{\mathrm{aq}}}\right)^{\alpha 3}\left(\frac{\nu_{\mathrm{or}}}{\nu_{\mathrm{aq}}}\right)^{\alpha 4} \times\left(\frac{Q_{\mathrm{A}}\gamma}{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^3}\right)^{\alpha 5}\left(\frac{C_{\mathrm{A,i}}}{\rho_{\mathrm{aq}}}\right)^{\alpha 6}\left(\frac{Q_{\mathrm{or}}\gamma}{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^3}\right)^{\alpha 7} \times\left(\frac{N\rho_{\mathrm{aq}}^2\nu_{\mathrm{aq}}^3}{\gamma^2}\right)^{\alpha 8}\left(\frac{d\gamma}{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^2}\right)^{\alpha 9}\left(\frac{V_{\mathrm{r}}\gamma^3}{\nu_{\mathrm{aq}}^6\rho_{\mathrm{aq}}^3}\right)^{\alpha 10} \quad (12)$$

$$\frac{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^3}{\gamma^2}\mathrm{RS} = K\left(\frac{\rho_{\mathrm{or}}}{\rho_{\mathrm{aq}}}\right)^{\beta 1}\left(\frac{D_{\mathrm{s}}}{\nu_{\mathrm{aq}}}\right)^{\beta 2}\left(\frac{C_{\mathrm{su}}}{\rho_{\mathrm{aq}}}\right)^{\beta 3}\left(\frac{\nu_{\mathrm{or}}}{\nu_{\mathrm{aq}}}\right)^{\beta 4} \times\left(\frac{Q_{\mathrm{A}}\gamma}{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^3}\right)^{\beta 5}\left(\frac{C_{\mathrm{or,i}}}{\rho_{\mathrm{aq}}}\right)^{\beta 6}\left(\frac{Q_{\mathrm{or}}\gamma}{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^3}\right)^{\beta 7} \times\left(\frac{N\rho_{\mathrm{aq}}^2\nu_{\mathrm{aq}}^3}{\gamma^2}\right)^{\beta 8}\left(\frac{d\gamma}{\rho_{\mathrm{aq}}\nu_{\mathrm{aq}}^2}\right)^{\beta 9}\left(\frac{V_{\mathrm{r}}\gamma^3}{\nu_{\mathrm{aq}}^6\rho_{\mathrm{aq}}^3}\right)^{\beta 10} \quad (13)$$

The constants J and K, and the exponents $\alpha 1$–$\alpha 10$ and $\beta 1$–$\beta 10$ are adjustable parameters. The latter parameters could be determined by substituting the known quantities into the above correlations, and then fitting the experimental data to the correlations through non-linear optimization based on the well-known quadratic objective function. The extraction and stripping rates of copper per unit volume of the TIJR were correlated by the above equations and were applied in dimensional forms. It was found that

$$\mathrm{RE}\ (\mathrm{g\,min^{-1}\,dm^{-3}}) = 0.09 d^{-0.2} V_{\mathrm{r}}^{-1} Q_{\mathrm{A}}^{0.8} N^{0.4} \quad (14)$$

$$\mathrm{RS}\ (\mathrm{g\,min^{-1}\,dm^{-3}}) = 0.047 C_{\mathrm{su}}^{0.15} d^{-0.2} V_{\mathrm{r}}^{-1} Q_{\mathrm{A}}^{0.8} N^{0.4} \quad (15)$$

3.7. Comparative evaluation of the settling characteristic of the phases

Since in mixer–settlers, the settler is a larger piece of equipment than the mixer, the question always exists how easy it would be to separate the dispersion after leaving the TIJR. Therefore, this important question should be answered before any attempt to design a new kind of two-phase reactor. Otherwise, the latter would be questionable. To examine the settling characteristic of the phases leaving the TIJR and to compare the latter with a conventional CSTR, an attempt was made to compare the dispersion band thickness of the TIJR in a continuous gravity settler. To achieve this, a number of experiments were conducted before performing the final experimental runs. The conventional CSTR used in the present investigation was a laboratory tank as described earlier. The continuous gravity settler was a horizontal Pyrex cylindrical vessel of 0.20 m length and 0.064 m diameter. This settler was employed in both the systems. The interface was controlled near the midpoint of the settler by a simple gravity leg positioned on the aqueous discharge. The experimental runs were carried out in the continuous mode of operation with identical flow rates for both systems within the range 0.110–0.300 $\mathrm{dm^3\,min^{-1}}$ and the upper disk speeds of 600–1400 rpm. From these experimental runs, it was found that there were no significant differences in the dispersion band thicknesses of the TIJR and conventional CSTR, especially at the upper disk speeds below 1400 rpm. However, since the characterization of the continuous gravity settler with respect to various operating parameters was not the objective of these experiments and was beyond the scope of the present investigation, the main emphasis has been placed on the comparative evaluation of the dispersion band thicknesses in the continuous gravity settler for both the TIJR and the CSTR to answer the basic question.

3.8. Evaluation of the performance capability of the TIJR

To compare the performance capability of the TIJR with a conventional CSTR, a number of experiments were carried out by using the baffled tank with active volume of 1 $\mathrm{dm^3}$, equipped with a turbine-type impeller that was used in the evaluation of the dispersion-band thickness. The experiments were carried out at the same conditions of the TIJR and the impeller speed of 500–1400 rpm and the aqueous phase flow rate of 0.500–2.5 $\mathrm{dm^3\,min^{-1}}$. The maximum

Table 1
Extraction and stripping rates of copper per unit volume of reactors

Reactor types	RE ($g\,min^{-1}\,dm^{-3}$)	RS ($g\,min^{-1}\,dm^{-3}$)
CSTR	2	3
TIJR	19	22

Table 2
Power input requirements for various reactors

Reactor types	Power input ($kJ\,m^{-3}$ of liquid)
CSTR (mixer) [7]	150–250
TIJR	175–250

rates of extraction and stripping of copper per unit volume of the CSTR obtained were 2 and $3\,g\,min^{-1}\,dm^{-3}$, respectively, which have been reported in Table 1.

A comprehensive analysis of the TIJR should take into account both mass-transfer properties and power input requirement. The performance capability of the TIJR in comparison with a conventional CSTR is evaluated on the basis of Tables 1 and 2, which contain data for extraction and stripping rates of copper per unit volume of the reactor, RE and RS, and power input requirements, respectively. From these data, it can be concluded that TIJR is superior relative to conventional mixers with respect to extraction and stripping rates of copper per unit volume of reactor for nearly identical power input requirements.

4. Conclusions

A novel TIJR was investigated with respect to its capability in copper extraction by means of LIX 84 as a weak extractant with slow chemical kinetics in kerosene. It was found that the novel TIJR is much more effective than conventional CSTRs with respect to extraction and stripping rates of copper per unit volume of the reactor. In addition, the following observations concerning copper extraction by means of LIX 84 as a weak extractant with a moderately slow chemical kinetics in kerosene within the TIJR were made:

1. Increase in the upper disk speed increases the extraction and stripping efficiencies due to the increase in shear forces acting on the phases, and hence promoting the rate of drop breakage and coalescence.
2. Increase in the total throughput decreases the extraction and stripping efficiencies, presumably due to the decrease in the mean residence time of the streams.
3. Decrease in the distance between the disks increases the extraction and stripping efficiencies due to much higher shear forces acting on the phases, and hence promoting the rate of drop breakage and coalescence and promoting the surface renewal mechanism.
4. Opposing jets have a profound effect on the extraction and stripping rates of copper.

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