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Emulsion liquid membrane based on a new flow pattern in a counter rotating Taylor-Couette column for cadmium extraction

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ABSTRACT

Study of emulsion liquid membrane for cadmium extraction using a counter rotating Taylor-Couette column (TCC) has been done. Characterization was also carried out for determining flow regime, shear stress, and energy loss distribution. It was found that featureless turbulent regimes were obtained with the increase of angular frequency ratio at certain values, produces high mixing activity leading to the enhancement of cadmium extraction rate during the process. Much lower shear stress in TCC system compared to that of stirred vessel led to better emulsion stability thus able to perform better extraction efficiency. High cadmium extraction efficiency of almost 100% with membrane breakage in order of 10^{-7} makes this method very promising for application in a large scale.

1. Introduction

Emulsion liquid membrane (ELM) as an alternative of liquid-liquid extraction has been employed to separate many contaminants such as metals, weak acid/bases, and hydrocarbon from industrial liquid waste. Combination of extraction and stripping in a container is able to purify as well as to concentrate the solute simultaneously. Instead of using separate equipment for extraction and stripping processes as occurs in solvent extraction system, the use of single contactors makes this system becomes economically feasible. About 40% of cost could be reduced by applying ELM system [1]. The ability of ELM system to recover very low concentration of solute is another advantage of this process.

In water in oil (W/O) emulsion, organic membrane acts as barrier that separate external feed phase, in which solute is located, with internal stripping phase. Organic membrane phase contains surfactant, carrier, and diluent. With the aid of surfactant, the interfacial tension of membrane and internal phase can be lowered that both phases can mix well by the aid of mechanical energy. The use of surfactant is also important in maintaining the emulsion stability. Due to the insolubility of solute in membrane phase, the application of carrier is indispensable that can form complex with solute and diffuse through membrane phase towards internal stripping phase. Once complex of carrier and solute reached internal phase, the solute will be stripped, and the free carrier will diffuse back to the interface of external and membrane phase.

ELM system involves three main steps. Emulsion is prepared by mixing water and organic membrane phase. The prepared emulsion is then used in extraction process to recover solute. Afterward, the solution is led to settle, clean solution in the bottom layer is sampled. The concentration of raffinate is tested to evaluate the efficiency of extraction process. The used emulsion is then broken to recover the membrane solution.

ELM processes have been studied by many of researchers by occupying conventional stirred tanks as a mixing contactor. Nevertheless, several problems appeared in extraction process. On stirred tanks, ELM systems face problem of emulsion stability. To find better extraction rate, high stirring speed is indispensable, however, it is detrimental for emulsion stability [2,3]. Many researchers concerned in both membrane breakage and emulsion swelling occurred in stirred tanks [4,5].

To overcome emulsion stability as well as produce the best extraction efficiency, the use of Taylor-Couette column (TCC) extractor is promising rather than stirred tank extractor. This equipment provides relatively low and uniform fluid shear and help maintaining the stability of emulsion without compromising the extraction efficiency. So far, study on ELM using TCC for heavy metals removal has been examined by Park [6]. The targeted compound is extracted within a Taylor column in which the inner cylinder is rotated while the outer cylinder is fixed. The system provided high overall removal efficiencies in relatively short

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contact time. However, in general TCC with single inner cylinder rotation only works well in a small gap of the two cylinders for better fluid mixing that impedes its working capacity.

In this work, a counter rotating Taylor-Couette column (TCC) was proposed. In principle, the TCC system developed is greatly difference with that reported in previous study for extraction using ELM [6]. In this system, the inner and outer concentric cylinders can be rotated independently that allows high fluid mixing and working capacity. Various flow regimes were characterized. The TCC performances in term of extraction efficiency, emulsion swelling and membrane breakage on cadmium extraction were studied and compared to that of stirred vessel extraction.

2. Theory

TCC was designed to minimize the possibility of emulsion instability while maintaining the high extraction performance. This system consists of two independent cylinders; solution is flowed in the gap of those two cylinders. In this system, the inner and outer concentric cylinders can be rotated independently. With this configuration, various flow conditions of concentric independently rotating cylinders are allowed including co- or counter- rotation, inner cylinder rotation and fixed outer cylinder as well as outer cylinder rotation and fixed inner cylinder conditions.

To characterize the flow regimes, Andereck et al. [7] mapped out flow patterns for different rotation rates of the inner and outer cylinders. The patterns are mapped based on Reynolds number of the outer and inner cylinders. They found 19 principles regimes in flow between independently rotating cylinders, ranging from stable to unstable flows corresponding to the Couette flow to featureless turbulent flow regimes. The map also covers the unexplored regime as its flow pattern was not specifically identified yet.

Characterization in TCC with two counter rotating cylinders can be done by taking into account some control parameters as described below [7]. Radius ratio, η is determined by:

$$\eta = \frac{R_i}{R_o} \tag{1}$$

R_i and R_o are radii of the inner and outer cylinders, respectively. Aspect ratio, Γ can be defined by:

$$\Gamma = \frac{L}{d} \tag{2}$$

L is the length of fluid column, while d is the gap width, can be calculated as R_o–R_i. Reynolds numbers of the inner and outer cylinders are as follow:

$$Re_i = \frac{R_i \omega_i d}{v} \tag{3}$$

$$Re_o = \frac{R_o \omega_o d}{v} \tag{4}$$

where Re_i and Re_o are Reynolds number of the inner and outer cylinders, respectively, ω_i and ω_o are angular velocity of the inner and outer cylinders, respectively, and υ is fluid kinematic viscosity. The angular velocity of the inner cylinder, ω_i is always defined as positive, whereas the angular velocity of the outer cylinder, ω_o can be either positive (for co-rotating system) or negative (for counter-rotating system). Other dimensionless control parameters of the system are the ratio of angular velocities, i.e.:

$$\psi = -\frac{\omega_o}{\omega_i} \tag{5}$$

Taylor number is also dimensionless quantity used to characterize this system. Later it can be used to describe the TCC flow stability. Taylor number can be defined as [8]:

$$Ta = \frac{1}{4}\sigma(R_o - R_i)^2(R_o + R_i)^2(\omega_i - \omega_o)^2 v^{-2} \tag{6}$$

where σ is:

$$\sigma = \left(((1+\eta)/2)/\sqrt{\eta}\right)^4 \tag{7}$$

To represent profile of velocity along the cylinder gap, u is defined by:

$$u = Ar + \frac{B}{r} \tag{8}$$

In expression above, r varies from R_i to R_o, while A and B can be calculated by:

$$A = \omega_i \frac{(\eta^2 - \psi)}{\eta^2 - 1} \tag{9}$$

$$B = \omega_i R_i^2 \frac{(1 - \psi)}{1 - \eta^2} \tag{10}$$

Estimation of wall shear stress, τ (Pa) can be done by using the following equation:

$$\tau = -2\mu \frac{B}{R_i^2} \tag{11}$$

where μ denotes viscosity of the solution (Pa s).

The energy loss along the gap width under counter-rotating of the inner and outer cylinders can be determined as [9]:

$$\frac{dH}{ds} = 4\mu \frac{\omega_i R_i}{h^2} \frac{R_i^4}{r^4} \frac{(1-\eta)^2}{\eta^2} \frac{(1-\psi)^2}{(1-\eta^2)^2} \left[\frac{\eta^2 - \psi}{\eta^2 - 1} \frac{r}{R_i} + \frac{R_i}{r} \frac{1-\psi}{1-\eta^2}\right]^{-1} \tag{12}$$

3. Experimental

3.1. Reagents and solutions

Deionized water was used for all of the solutions preparation. The membrane phase consisted of kerosene (commercial grade), non-ionic surfactant (Span 80, Merck), and carrier (Trioctylamine, Merck). Cadmium solution was prepared from cadmium chloride, supplied by Sigma Aldrich. Stripping solution was prepared from a 25% solution of ammonia, supplied by Merck.

3.2. Emulsion preparation

An ultrasonicator was used to prepare the emulsion. The emulsification setup consisted of a jacketed cylindrical glass reactor, allowing the emulsification cell to be cooled with water. Ultrasonic irradiation was performed at 22.5 kHz using a USG-150 commercial ultrasonicator equipped with a titanium horn mounted at the top of the cylindrical glass cell. A predetermined volume of Span 80 and TOA were dissolved in kerosene and stirred at 500 rpm for 5 min using magnetic stirrer to prepare the membrane phase. An adequate amount of 0.1 M ammonia as the internal aqueous phase was then added into the prepared membrane phase solution. The mixture was then homogenized using the ultrasonicator by immersing the probe at the interface of the membrane-internal phase. Coolant was circulated around the jacket to maintain the process temperature at 20 °C.

3.3. Cadmium extraction

Extraction studies were carried out by dispersing the emulsion into the feed phase, of cadmium chloride in deionized water. The experiments were performed in a counter-rotating TCC as schematically depicted in Fig. 1. In this step, the rotation speed and acid

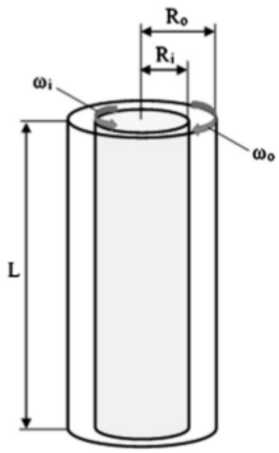

Fig. 1. Schematic of the counter-rotating TTC cell employed for cadmium extraction.

concentration in the feed phase were varied to determine the optimal extraction efficiency of Cd(II). The speed of inner cylinder was maintained at 10 Hz corresponding to 62.8 rad/s, whereas the speed of outer cylinders was varied from 0 to 10 Hz with interval of 2.5 Hz corresponding to 0, −15.7, −31.4, −47.1, and −62.8 rad/s. A set of data contains 10 intervals of extraction: ½, 1, 3, 5, 7, 10, 15, 20, 25, and 35 min were performed. After the shearing, the solution was left for settling for 5 min. For comparison purposes, cadmium extractions were also done using stirred vessel by mixing the solution using blade stirrer at 300, 500, 600, and 700 rpm. Each experiment was performed in triplicate, and the mean values are presented.

At the end of extraction, the emulsion phase was separated from the feed phase using a separatory funnel, and the aliquots were collected to analyze the Cd(II) concentration.

3.4. Data analysis

Viscosity of the emulsion was determined using Viscometer DV-III Rheometer (Bookfield DV-III), used for evaluation of the wall shear stress. Cadmium concentration in the external feed phase was measured using an atomic absorption spectrophotometer (AAS-6650 Shimadzu) at wavelength of 228.85 nm to evaluate the extraction efficiency, Eff (%) as given by the following equation:

$$\mathrm{Eff} = \frac{C_e^0 - C_e}{C_e^0} \times 100 \tag{13}$$

where C_e^0 is initial concentration of cadmium in feed phase (mg/L), C_e is final concentration of cadmium in the raffinate (mg/L).

Emulsion swelling, E_{sw} (%) was calculated by measuring the water content before and after extraction process as given in Eq. (14) [10]. Water content of the solution was determined using Karl Fischer titrator (870 KF titrino Plus). Following the volumetric titration method, iodine required to be reacted with water is previously dissolved in water determination, and water content is determined by measuring the amount of iodine consumed as a result of reaction with water in a sample. The water content can be calculated based on the amount of added reagent.

$$E_{sw} = \frac{V_{em} - V_{em}^0}{V_{em}^0} \times 100\% \tag{14}$$

where V_{em} is volume of emulsion at any time (*L*), and V_{em}^0 is initial volume of emulsion (*L*).

Membrane breakage as a parameter of emulsion instability was also considered as shown in Eqs. (15) and (16) [11]. A simple method was chosen to determine membrane breakage, by measuring pH of raffinate. In this work, solution pH was measured using Fisher Scientific accumet AB15+. The pH meter is standardized or calibrated to ensure the accuracy of the results. Three types of buffer solutions with pH of 4, 7, and 10 were used to perform internal calibration. The pH measurements were carried out at room temperature.

$$\varepsilon = \frac{V_s}{V_{int}^0} \times 100 \tag{15}$$

$$V_s = V_{ext}^0 \frac{10^{pH_0-14} - 10^{pH-14}}{10^{pH-14} - C_{OH^-}^{int}} \tag{16}$$

where V_s is the volume of internal phase split to external phase, V_{int}^0 is the initial volume of internal phase, V_{ext}^0 is the initial volume of external phase, $C_{OH^-}^{int}$ is the initial concentration of OH^- in the internal phase, pH_0 is the initial pH of the external phase and pH is the external phase pH being in contact with the emulsion after a certain time of stirring.

4. Results and discussion

4.1. Characterization

The TCC system has R_i, R_o and L of 2 cm, 3.5 cm and 15 cm, respectively, giving η and Γ to be 0.571 and 10, respectively. From these sizes, total gap volume that can be used for ELM processes is about 300 mL. The kinematic viscosity of emulsion needs to be determined for evaluating Reynolds number of both Re_i and Re_o. For this case, kinematic viscosity was 0.1 cm/s.

In all experiments investigated, the inner cylinder was rotated at a constant ω_i of 62.8 rad/s while the outer cylinder rotation, ω_o was varied at 0, −15.7, −31.4, −47.1, and −62.8 rad/s. The negative sign indicated that the outer cylinder rotated at opposite direction of inner cylinder rotation (counter rotation).

4.1.1. Flow regime

The flow regime as a function of Reynolds number of the inner and outer cylinders is presented in Fig. 2. Reynolds number phase space of the explored regimes is depicted by the solid line. The dashed lines are flow region boundaries of unstable (upper left) and stable (lower right), shown here for radius ratio of $\eta = 0.571$ as experimentally studied in this work. The dashed line in the right

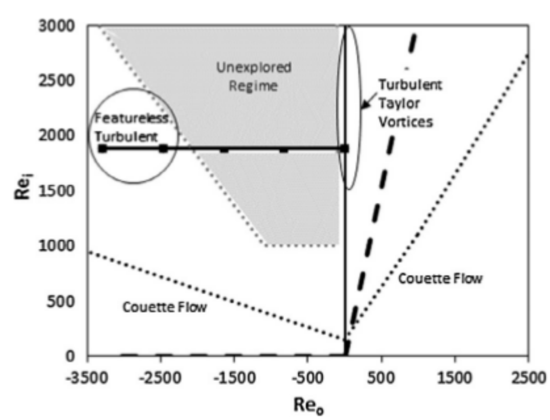

Fig. 2. Flow regimes in TCC system.

quadrant interferes stability boundary, as also obtained by Esser and Grossman [12], follow the Rayleigh stability criterion $Re_o/Re_i = \eta$ for Re_o and $Re_i \gg 1$. Other dashed line in the left quadrant also follows the stability boundary of Esser and Grossmann [12], taken at $Re_i = 0$. From the figure, it can be revealed that the whole examined regimes were in the unstable region and resulted in several specifications of a flow state.

Based on Re_o and Re_i, the flow patterns under investigated conditions are then observed in more detail based on the flow regimes reported by Andereck et al. [7]. At a fixed inner cylinder rotation of 62.8 rad/s and the outer cylinder was set at stationary condition, turbulent Taylor vortices (TTV) regime was achieved. Tsukahara, et al [13] also found this regimes in their system. The vortices were elongated in circumferential direction. Once the outer cylinder was rotated at certain rotation values, different flow patterns were clearly observed in which at ω_o of −15.7 rad/s and −31.4 rad/s corresponding to Re_o of −822 and −1644, respectively, unexplored regimes refers to Andereck et al. [7] were achieved. Although these regions exhibited turbulent-based flows, shown as gray area in the figure, but their specific flow patterns have not been reported in the literatures. Further increase in ω_o to be −47.1 and −62.8 representing Re_o of −2466 and −3287, respectively resulted in featureless turbulent flow (TUR) regimes.

4.1.2. Taylor number and shear stress

Effect of angular frequency ratio (ψ) on Taylor number (Ta) is shown in Fig. 3. Taylor number is a dimensionless number that characterizes the importance of centrifugal or inertial forces due to rotation of a fluid about an axis, relative to viscous forces. As both of the cylinders moved in opposite direction, angular frequency of the outer cylinder (ω_o) is always denoted as negative. It can be observed that at a constant rotation of inner cylinder of 62.8 rad/s, accelerating the rotation of outer cylinder from 0 up to −62.8 rad/s enhanced the Taylor number and thus flow instability. The result showed that at angular frequency ratio of 0, in which the outer cylinder was fixed, the lowest Ta of 2.5×10^5 was obtained. While at the highest angular frequency ratio tested of −1, the highest Ta of about 1×10^6 was achieved. This indicated that Ta number is increased almost linearly by 75% under the investigated conditions.

Other important parameter that should be examined in TCC system is the wall shear stress (τ). Basically, the shear stress acting on the wall must be equal and opposite of the shear stress acting on the fluid. Fig. 4 presents the effect of angular frequency ratio on the wall shear stress of the inner cylinder. As previously mentioned, the negative values shown in the figure indicated that the wall shear stress direction is against to the fluid flow direction with respect to the inner cylinder rotation. It was demonstrated that the

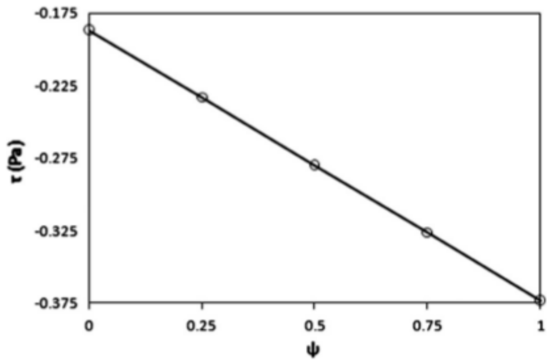

Fig. 4. Effect of angular frequency ratio on wall shear stress.

wall shear stress linearly increased with the increase of ψ. At angular frequency ratio of 0, in which the outer cylinder was fixed, the lowest shear stress of 0.186 Pa was obtained. While at the highest angular frequency ratio of −1, the highest wall shear stress of 0.373 Pa was achieved. This result exhibits the improvement of τ by 50% under the investigated conditions.

The results above reflected that under counter-rotating cylinders condition, although the improvement of Ta number is higher than that of τ with the increase of angular frequencies ratio in the range of investigated conditions, their improvement tends to have similar value at a very high outer cylinder rotation. It means that at a certain high value of angular frequency ratio where the inner cylinder rotation is kept constant, say above −500, the flow instability decreases considerably and the flow pattern might be switched from turbulent to Couette flow regimes. In this condition, the inner cylinder rotation is not important and can be considered to be an object at stationary condition. If the expected flow pattern is turbulent, this condition should be avoided. Thus, it is important to adjust the outer cylinder rotation for obtaining turbulent flow that has better fluid mixing compared to other flow pattern.

4.1.3. Energy loss distribution

The distribution of energy loss along the gap width for all examined conditions under counter rotating of inner and outer cylinders is presented in Fig. 5. In this study the aspect and radius ratios were 0.571 and 10, respectively. For the case of inner cylinder rotating while the outer cylinder was at rest, denoted as ψ_1 in the figure, it can be seen that the energy loss remains relatively constant along the gap width up to a certain value of about 0.8 and then increases with increasing radius. At the surface of the

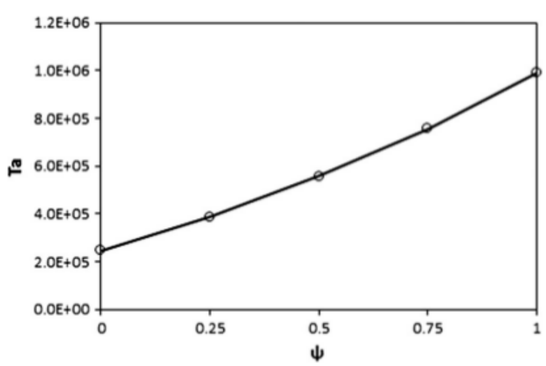

Fig. 3. Relationship of angular frequency ratio to Taylor number.

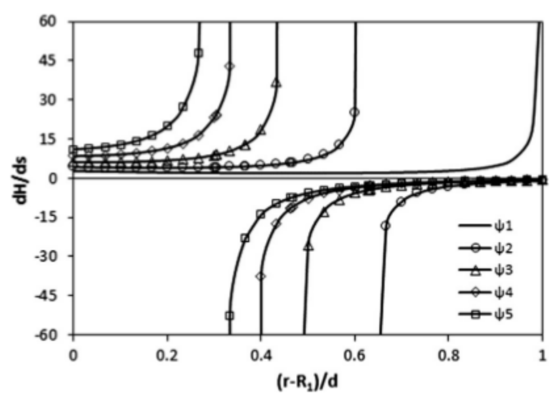

Fig. 5. Energy losses distribution along the gap width of TCC.

outer cylinder, the energy loss tends to be infinite showing the flow at the outer cylinder is strongly stable. Therefore, any small disturbances in the region are likely to be damped out. On the contrary, the fluid particles close to the inner cylinder have the smallest loss of energy. This becomes a possible locality where instability can first occur, as generally observed in experiments [7,8,14].

Fig. 5 also indicates different distribution of energy losses when the outer cylinder rotated at various angular frequencies. It can be seen that in general, the energy loss increases up to a certain distance between the two counter rotating cylinders. At one particular radial position between the two cylinders, the energy loss tends to be infinite. The location of this position highly depends on the ratio of the angular frequencies of two counter rotating cylinders. Therefore, in this work, by changing the angular frequency of the outer cylinder while keeping the angular frequency of the inner cylinder remains constant, the infinite energy loss position changed along the gap between the two counter rotating cylinders. In general, the infinite energy loss position has come closer to the inner cylinder with the increase of angular frequency ratio. For instance, at angular frequency ratio of 0.25 and 1 the infinite energy loss positions were found at around 0.63 and 0.3, respectively. At these positions, the flow is strongly stable. Therefore, any small disturbances in the area are likely to be damped out. Conversely, the fluid particles close to the counter rotating cylinder surfaces have the smallest energy loss. Therefore, the instability generally occurs on the cylinder surfaces. The occurrence of instability may take place first on the inner cylinder or the outer cylinder, depending on other factors such as influences from radius of cylinders and the magnitudes of the rotating speeds. If the flow at the inner cylinder exceeds the critical condition, Taylor vortex flow pattern may first occur along the inner cylinder. If the flow at the outer cylinder exceeds the critical condition, the flow near the outer cylinder may directly transit to turbulent. If both of the flow at the inner cylinder and the flow at the outer cylinder exceed their critical conditions, complex flow pattern may be formed. In this study, the complex flow pattern behavior increased with the increase of angular frequency ratio in which featureless turbulent flows were formed under angular frequency ratio of 0.75 and 1 as elucidated previously in Fig. 2.

4.2. Extraction study

The use of TCC in cadmium extraction is believed to be able to increase extraction capacity. This is due to in TCC; extraction can occur along the cylinder, enhance contact area. Faster extraction process could also be expected using this system. Hence, to see the performance of a counter-rotating TCC for cadmium extraction, effect of angular frequency ratio, thus flow regimes on the cadmium extraction efficiency was investigated. Rotational speed of the inner cylinder was maintained constant, while rotational speed of outer cylinder was varied. Ratio of angular frequency of outer and inner cylinders were varied at 0, 0.25, 0.5, 0.75, and 1, denoted ψ_1, ψ_2, ψ_3, ψ_4, and ψ_5, respectively. It is presented in Fig. 6 that extraction efficiency at the end of the process for all angular frequency ratios was almost similar. The difference was only come from extraction time. Lower angular frequency ratio needed longer extraction time. At angular frequency ratio of 0.25, system could extract more than 50% of cadmium within 1 min and kept increasing until the end of the process, with final extraction efficiency of 96%. At angular frequency ratio of 0.5, faster process was occurred. Within 10 min, about 96% of cadmium could be extracted. Increasing angular frequency ratioto 0.75 and 1 resulted in the same degree of extraction, only shortened extraction time. Both were able to reach equilibrium at 7 min of extraction time. Similar results were also obtained by Park [6] that higher Reynolds number as well as Taylor number enhanced ELM performance.

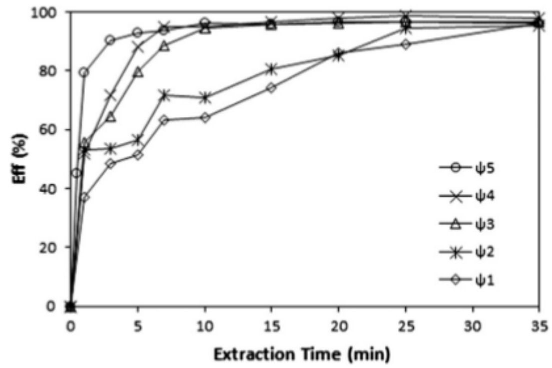

Fig. 6. Effect of angular frequency ratio on cadmium extraction efficiency using TCC.

In order to improve cadmium extraction efficiency in a counter-rotating TCC system, effect of HCl concentration in the feed solution was studied. Fig. 7 reveals the obtained result of cadmium extraction conducted at a fixed angular frequency ratio of 1. At 0.05 M of HCl, the system was able to extract more than 50% of cadmium in 1 min and increased significantly until the end of extraction process. At this condition, the maximum extraction efficiency of 72% was achieved. The addition of HCl concentration provides better extraction rate and efficiency. The result shows that at HCl concentration of 0.1 M, about 80% cadmium was successfully extracted in 1 min. Cadmium extraction efficiency improved significantly at further extraction time in which more than 96% cadmium was removed at 35 min of extraction process. Further increase of HCl concentration to be 0.5 M managed to accelerate and improve the performance of cadmium extraction in which almost 100% of cadmium could be extracted within 3 min. It was revealed that the presence of HCl facilitated cadmium transport through membrane phase into internal stripping phase by forming solute-carrier complex [15,16].

Table 1 shows comparison of the developed TCC performance on heavy metals extraction. As shown, in general TCC provides high extraction efficiency in relatively short contact time. Regardless of the feed solution containing metal to be extracted, however, extraction efficiency is not only highly affected by the emulsion composition but also by the TCC configuration. Instead of use single inner cylinder rotation, the use of two independently counter-rotating cylinders of TCC minimizes energy loss along the gap, forms complex flow pattern and thus facilitates mass transport in

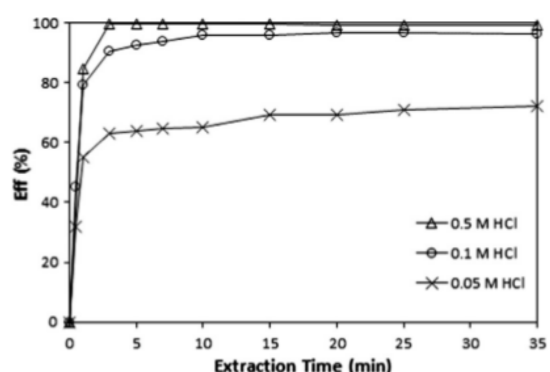

Fig. 7. Effect of HCl concentrations in the feed solution on cadmium extraction efficiency using TCC.

Table 1
TCC for heavy metals extraction in ELM system.

Ref.	Park [6]	Present study
Feed solution	Cd_2SO_4	$CdCl_2$ in 0.5 M HCl
Concentration	220 ppm	150 ppm
Volume	200 ml	250 ml
Emulsion composition		
Volume	20 ml	50 ml
Surfactant	Span 80 (3% w/v)	Span 80 (4 wt.%)
Carrier	Cyanex 301 (2% v/v)	TOA (4 wt.%)
Diluent	Soltrol 220 (70% v/v)	Kerosene
Stripper	HCl (2 M)	NH_3 (0.1 M)
TCC specification		
Gap	15.6 mm	15 mm
Length	94 mm	150 mm
Capacity	300 ml	390 ml
Inner cylinder rotation	500 rpm	600 rpm
Outer cylinder rotation	–	–600 rpm
Extraction efficiency	96% for 3 min	~100% for 3 min
Remarks	Extraction was initiated after reached the expected rotation	Extraction was initiated from 0 rpm

ELM process. As elucidated in section before that in general all parameters investigated in term of rotation speed of the two counter-rotating cylinders provide turbulent-based flow pattern. Turbulent flows normally produce high fluid mixing along the cell so it will give better extraction process. In more specific, the increase of angular frequency of the outer cylinder while the inner cylinder kept at a particular rotation, the flow regimes changed from turbulent Taylor vortices to featureless turbulent regimes. It means that the increase of angular frequency of the outer cylinder produces high mixing activity leading to the enhancement of cadmium extraction rate during the process.

4.3. Comparison with stirred vessel

The results of cadmium extraction by means of TCC were compared to that of stirred vessel. For this purpose, similar emulsion composition and formation were used and then employed to extract the cadmium in 0.1 M HCl. The extraction processes using stirred vessel were studied at various stirring speed of 300, 500, 600, and 700 rpm that are relative similar with that of rotation speed under TCC process. However, it is difficult for direct comparison based on extraction speed as the system is principally different. So that, to simplify the comparison purposes, extraction speed parameters were transformed into shear stress parameters. For TCC, the shear stress was evaluated using Eq. (11) whilst for stirred vessel, it was calculated by the following equation [17,18]:

$$\tau = \mu \times \gamma \tag{17}$$

and

$$\gamma = 3.3 N^{1.5} d_i \left(\frac{\rho}{\mu}\right)^{0.5} \tag{18}$$

where γ is shear rate (s^{-1}), N is stirring speed (s^{-1}), d_i is diameter of the impeller (m), and ρ is fluid density (kg m^{-3}).

From those equations, the shear stress of 6.94, 14.94, 19.64, and 24.75 Pa were obtained for stirring speed of 300, 500, 600, and 700 rpm, respectively. While in TCC, the shear stress of 0.19, 0.23, 0.28, 0.33, and 0.37 Pa were given by rotational speed ratio of the outer and inner cylinders of 0, 0.25, 0.5, 0.75, and 1, respectively. These results provide an impression that the shear stress in TCC system was 45 times on average much lower than that of stirred vessel system. Fig. 8 shows cadmium extraction efficiency as a

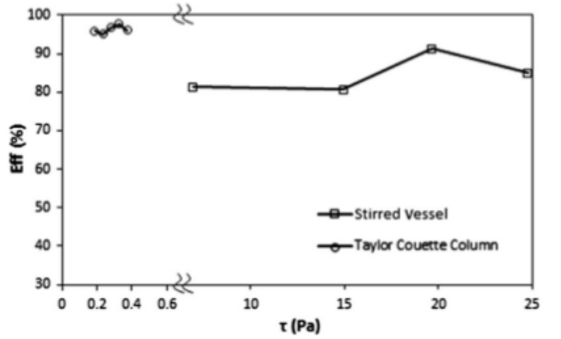

Fig. 8. Effect of shear stress on extraction efficiency in TCC and stirred vessel.

function of shear stress. It can be observed that as expected, low shear stress of TCC provides high extraction efficiency under all investigated conditions compared to stirred vessel. The cadmium extraction efficiency of about 96% on average was achieved by TCC system whilst only about 83% on average under stirred vessel system.

The lower shear stress, the lower emulsion instability and thus able to provide better extraction process [6]. Instead of reaching higher extraction efficiency, the system with higher shear stress could only raise up the emulsion swelling and membrane breakage as shown in Figs. 9 and 10, respectively. On the one side, emulsion swelling occurs due to the penetration of external aqueous phase solution into emulsion globule, thus increasing emulsion volume during the process. This case ruin the extraction rate for diluting the internal phase as well as the concentrated solute in the internal phase [19]. On the other side, membrane breakage involves the spill out of internal phase to external phase, causes the loss of

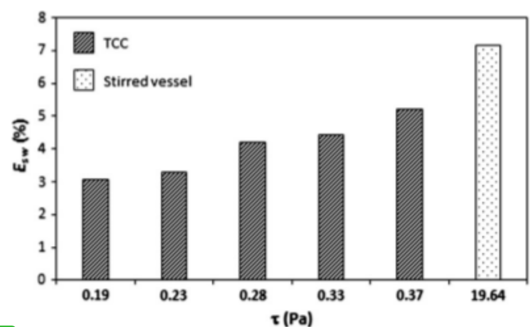

Fig. 9. Effect of shear stress on emulsion swelling in TCC and stirred vessel.

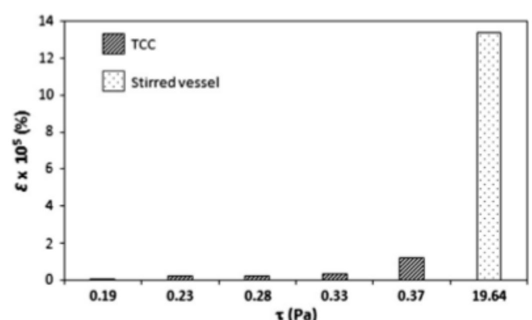

Fig. 10. Effect of shear stress on membrane breakage in TCC and stirred vessel.

stripping phase agent and entrapped solute. The concentration gradient is therefore decrease, results in the reduction of mass transfer ability. The back diffusion of entrapped solute increases the raffinate concentration thus lowers the extraction efficiency [20,21]. Under the same emulsion formula and cadmium solution, it was found that stirred vessel suffered about 44% higher emulsion swelling and about 97% higher membrane breakage than that of TCC.This finding is beneficial for the application of TCC in a large scale for recovering cadmium under ELM system. It is also important as fundamental study for further process scale up.

5. Conclusion

Rotational speed affects flow regimes, shear stress, tangential velocity as well as energy loss distribution along the gap of TCC. Under the investigated conditions in term of rotation speed of the two counter-rotating cylinders, high fluid instability regimes were obtained thus provided turbulent-based flow patterns: turbulent Taylor vortices, turbulent based (unexplored) and featureless turbulent flow regimes. Higher angular frequency ratio resulted in high mixing activity with low shear stress hence enhanced cadmium extraction. Shorter equilibrium time was also achieved with higher extraction efficiency than that of stirred vessel extraction. Under the similar condition, TCC system was able to extract more than 96% of cadmium that is 15% higher than the stirred vessel system.

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