

Removal of molybdenum (VI) from effluent waste water streams by cross flow micellar enhanced ultrafiltration (MEUF) using anionic, non-ionic and mixed surfactants

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Micellar Enhanced Ultrafiltration (MEUF) has been used to remove dissolved molybdenum efficiently from the waste streams by using two surfactants: sodium dodecyl sulfate (SDS) and Tween 20 in a lab-scale membrane system. Effect of feed flow rate, time, molar ratio of surfactant to metal (S/M ratio), feed pH and feed molybdenum concentration on %rejection of molybdenum has been studied. Effect of non-ionic (Tween 20) and mixed surfactant (SDS + Tween 20) on %rejection of molybdenum is also studied. Molybdenum is removed by 90.3% at optimized parameters (feed flow rate, time, S/M ratio, pH, feed molybdenum concentration, concentration of SDS) and non-ionic and mixed surfactants removed molybdenum by 92 and 90.4% respectively. Distribution coefficient, loading of micelles and micellar binding constants have been calculated for both the anionic surfactant and mixed surfactant from experimental results. Gel layer formation is found to be negligible since all experiments have been carried out at low range of pollutants.

Keywords: MEUF, Molybdenum, Ultrafiltration, SDS, Tween 20

Heavy metal pollution of industrial wastewater represents a major problem for the environment as metal ions are non-biodegradable; have a very high toxicity and some of them have proved to be carcinogenic. If these metals directly discharged in sewers, metal ions seriously damage the subsequent biological treatments in depuration plants and render the treated sludge un-usable for the agricultural purposes. Consequently, the removal of metal ion from aqueous solutions is a problem frequently encountered in the treatment of industrial wastewaters. Thus, it is indispensable to treat metal-contaminated wastewaters prior to their discharge to the environment. Studies aimed at the control of the discharge of toxic substances from industrial effluent sources to surface waters has become increasingly important over the last three decades with the realization that these waters have been affected by human activities¹.

Industries like metal finishing; metal plating, petroleum refining, tanning, wood preserving, mineral smelting, chemical manufacturing, textile mills, and fertilizer plants contribute high concentrations of molybdenum to the environment. The disposal of molybdenum containing industrial wastewater elicits several environmental concerns. Disposal of

molybdenum ion poses a threat to the environment by greatly affecting terrestrial and aquatic life. The US Department of Health published the limit of maximum emission of the molybdate ion as 40 ppm².

Different methods were developed to remove heavy metal ions from waste water³⁻⁷. These techniques have their own disadvantages which include secondary pollution of deposition, inconvenient operation, high cost, low selectivity and difficulty of recycling. To overcome above disadvantages surfactant based MEUF was developed to remove metal ions from aqueous streams efficiently. The micellar enhanced ultrafiltration (MEUF) has been shown to be a promising method for the removal of low-levels of toxic heavy metal ions and organic compounds from industrial effluents⁸⁻¹³. The advantages of this method are the low-energy requirements^{14,15} and its high removal efficiency owing to the effective trapping of pollutants by the micelles¹⁶.

Many methods were developed in the past to remove molybdenum ion from aqueous solutions but removal of molybdenum ion using MEUF found to be an efficient technology. Methods like Adsorption¹⁷⁻²³, Extraction and stripping^{24,25}, Ion exchange²⁶, Nano-filtration²⁷, Precipitation^{28,29} were developed

with high efficiency of separation of molybdenum from waste water stream but these can be implemented at only higher concentrations of molybdenum (>10 mM). In this work, MEUF was used competitively to remove molybdenum where low concentrations of Mo^{6+} presents in aqueous solutions.

The present work was carried out with the objective to understand and compare the rejection characteristics of molybdenum ion in the presence of different surfactants like Sodium dodecyl Sulfate (anionic), Tween 20 (non-ionic) and SDS + Tween 20 (mixed). The effects of feed flow rate, operating time, Surfactant/Metal (S/M) ratio, feed pH, and feed molybdenum concentration on percent rejection of molybdenum were studied.

Experimental Section

Materials

The surfactants sodium dodecyl sulfate (SDS) and Tween 20 were procured from Merck Ltd., Mumbai, India and was used without any further purification. Sodium molybdate ($\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$) used as molybdenum VI source and was received as a gift sample from Rajesh Enterprises, Thane, India. pH adjustments were done using 0.5 N NaOH and 34.5% of HCl. NaOH, HCl, cetylpyridinium chloride (CPC), chloroform and methylene blue were procured from SD Fine chemicals Ltd., (Mumbai, India). Deionized water was used in all the experimental runs. The reagent used for analysis of molybdenum -4-(2-Pyridylazo) resorcinol monosodium salt indicator (PAR) was procured from SD Fine chemicals Ltd., (Mumbai, India). All the chemicals were of analytical grade and had a purity $\geq 98.5\%$.

The membrane for ultrafiltration cell was procured from Sartorius (Germany). It was a polysulfone (PS) membrane with 30 kDa molecular weight cut off (MWCO) and has an effective membrane area of 200 cm^2 .

Experimental setup

Ultrafiltration experiments were carried out in a cross-flow continuous mode system, procured from Sartorius, Germany. The feed solution was mixed continuously throughout the run time by connecting the feed tank to magnetic stirrer. The membrane was fixed in between the movable and stationary stainless steel flanges. These flanges have three connections for feed inlet, permeate and retentate outlets which are in turn connected to three individual pressure gauges.

Feed solution was pumped through the peristaltic pump to membrane castle. Because of pressure difference (Trans Membrane Pressure) across the membrane enable the feed to permeate through the membrane. The permeate and retentate were recycled back to feed tank to maintain the system in continuous process mode. At a particular run time, 10 mL of sample was collected through the respective valves. All the tubing's were made up of contamination-free and sorption-free material. This set up is represented schematically in Fig. 1. After each run, membrane was cleaned by back flushing with DI water.

Experimental procedure

Laboratory wastewater was prepared by dissolving sodium molybdate in DI water. Feed solution was prepared by dissolving sodium molybdate and surfactant in the desired ratio. CMC of SDS (sodium dodecyl sulfate) was measured using conductivity meter in the presence of molybdenum and Tween 20. For every run, 400 mL of waste water was taken as feed volume and the process was carried out at room temperature ($29 \pm 2^\circ\text{C}$). Individual pressures were measured using pressure gauges and TMP (Trans Membrane Pressure) was calculated. Before and after each run, permeate flux was calculated using DI water to check permeability of membrane. After each run, the membrane was cleaned with DI water for 30 min by back flushing. Feed pH was adjusted using NaOH and HCl. For all experiments TMP and permeate flow rate was measured and 10 mL of permeate sample collected for further analysis.

Analytical methods

SDS analysis: SDS was analysed by using "Two phase titration" using chloroform, methylene blue and cetylpyridinium chloride (CPC).

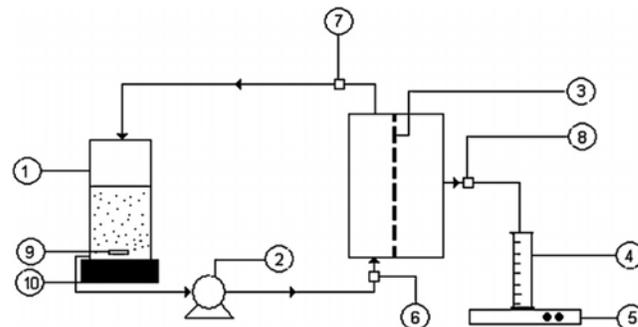


Fig. 1—Schematic representation of cross flow Ultrafiltration apparatus. 1) Feed tank; 2) peristaltic pump; 3) polysulfone membrane; 4) measuring cylinder; 5) weight balance; 6) feed inlet pressure sensor; 7) retentate pressure sensor; 8) permeate pressure sensor; 9) magnetic stirrer; 10) magnetic motor

Tween 20 analysis: Tween 20 was analysed by measuring total organic content using “Total Organic Content (TOC)” analyser.

Molybdenum analysis: Molybdenum analysis was developed by using UV/VIS- spectrophotometer. After the addition of PAR (4- (2- Pyridylazo) Resorcinol Monosodium salt) indicator, absorbance was measured at λ_{260} nm.

The retentate concentrations were calculated using material balance as follows;

$$C_F V_F = C_P V_P + C_R V_R \quad \dots (1)$$

$$C_R = (C_F V_F - C_P V_P) / V_R \quad \dots(2)$$

where, C_F , C_P , C_R are molybdenum concentrations in feed, permeate and retentate and V_F , V_P , V_R are volumes of feed, permeate and retentate. The C_R can be calculated by using the above material balance equation when the retentate is continuously recycled to feed tank.

% Rejection of molybdenum and SDS were calculated by using following formulas;

$$\% \text{ Rejection} = (1 - [Mo]_P / [Mo]_F) \times 100 \quad \dots(3)$$

$$\% \text{ Rejection of SDS} = (1 - [SDS]_P / [SDS]_F) \times 100 \quad \dots(4)$$

where subscripts P and R, indicates the permeate and retentate streams.

Results and Discussions

Ultrafiltration of molybdenum without surfactant

Feed solution of 1mM concentration was prepared by dissolving sodium molybdate salt in DI water. Feed solution of 400 mL was kept in feed tank and was subjected to ultra-filtration using polysulfone membrane. TMP and permeate flow rates were measured while collecting the sample for further analysis. By this study, molybdenum was removed up to 41% using 1 mM feed Mo concentration, 150 mL/min as feed flow rate and sample was collected at 30th min of run time. Low rejection in absence of surfactant was observed since low molecular weight compounds (molybdenum) that are normally permeable to ultrafiltration membranes³⁰. Nearly half of the feed molybdenum concentration was observed in permeate stream in absence of surfactant. Thus, there is no adsorption of metal ions on membrane surface and membrane resistance is almost zero³¹. In this study 41% rejection of molybdenum was obtained without surfactant attributing to hydrophobic membrane and hydrophilic solute interaction offering some membrane resistance^{32,33}.

Effect of Feed flow rate

Feed solution was prepared by dissolving sodium molybdate and SDS in DI water so that S/M ratio was 10 and pH was 8. Maximum %R of Mo was about 80% obtained at 150mL/min. which was empirically optimized and used for further runs. %R of Mo increased with feed flow rate since increase in feed flow rate resulted in increase of feed pressure which directly affects the micelles, letting it to pass through membrane pores. It was observed at the lower feed flow rates (<150 mL/min) and at the higher feed flow rates (>150 mL/min), micelles easily pass through the membrane due to less pressure at lower flow rates and more pressure at higher flow rates. At feed flow rate (150 mL/min), micelle remain into retentate and do not pass through the membrane pores³¹.

Effect of filtration time

The feed solution was prepared as mentioned in feed flow rate study and samples were collected from 10 to 70 min with varying interval of 10 min. During each sample collection, TMP and permeate flow rates were noted.

Sample collected at 30th min gave maximum %R of molybdenum of about 80% and was taken as the optimum time. Permeate flow rate decreased with increase in run time marginally as there was negligible concentration polarization. At 30th min, equilibrium was attained and resulted in maximum rejection of molybdenum. After the equilibrium point concentration polarization increased causing reduction in permeate flow rate and therefore, TMP increased as in the following equation. Increase in TMP results in increase in pressure near membrane which causes forcible transfer of micelle through the membrane pores. It was observed that permeate flux is higher at less filtration time. After 30 min the flux declined indicating the fouling of membrane due to concentration polarization³⁴⁻³⁶.

$$\text{After equilibrium; } TMP (\uparrow) = \frac{P_F + P_R}{2} - P_P (\downarrow) \quad \dots(5)$$

Surfactant / Metal (S/M) ratio study using SDS

Molybdenum concentration was kept constant at 1mM and the SDS concentration was varied to change S/M ratio from 5 to 12. Feed solutions were prepared individually for each S/M ratio and were subjected to ultra-filtration. At constant feed flow rate and time, %rejection of molybdenum was found to be the highest at S/M ratio of 6.

It was expected at CMC of SDS (8 mM), the %rejection of pollutant was maximum but in this study, at S/M ratio of 6 the %rejection was high since CMC of SDS decreased to 6 mM from 8 mM in the presence of 1mM of molybdenum³⁴. Effect of 1 mM molybdenum on CMC of SDS was observed from conductance measurement as shown in Fig. 2.

It is evident from S/M ratio study that %rejection of SDS increased with S/M ratio since there is an increase in surfactant concentration above the CMC of the surfactant which in turn reduced the monomers and formed more number of micelles which results in more % rejection. Figure 2 indicates marginal decrease in permeate flow rate with increase in S/M ratio. This may be attributed to the fact that the number of micelles increased with increase in surfactant concentration.

Effect of feed pH

Feed solutions of different pH (3 to 12 pH) were prepared using NaOH and HCl. The feed was subjected to ultra-filtration and samples were collected after 30 min for further analysis. The experimental results indicating, increase in pH increased the % rejection of molybdenum. The percent rejection of molybdenum was found to be the highest at pH 10 and is taken as optimum pH in the present investigation.

From this experiment, it is observed that higher rejections of molybdenum occurred at higher pH since increase in pH causes de-protonation of SDS^{37,38} for the removal of metals by MEUF process due to the low binding ability of surfactant for metal at low pH.

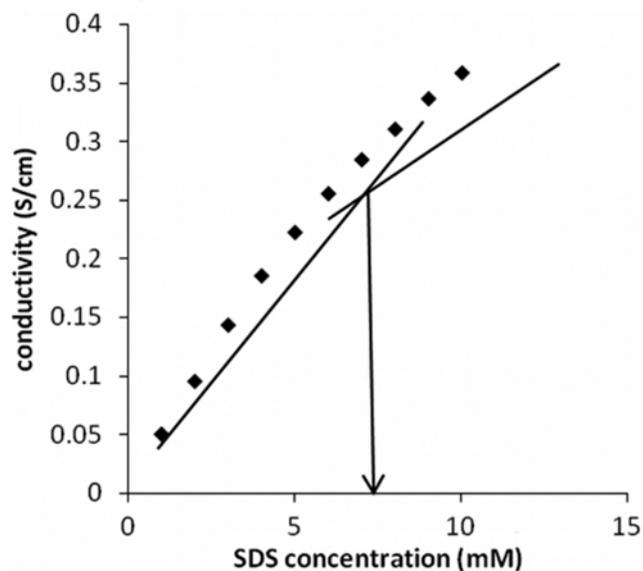


Fig. 2—Effect of 1 mM molybdenum on CMC of SDS

At very high pH (>10), % rejection of molybdenum decreased because Na^+ ions dominated more than molybdenum ions. This process can be explained structurally in Scheme I.

Effect of feed molybdenum concentration

Maintaining the constant S/M ratio of 6, feed molybdenum concentration was varied from 0.5 to 5mM. The results are presented in Fig. 3.

It was found that the increase in feed molybdenum concentration resulted in decrease of %rejection of molybdenum which indicates that MEUF benefits preferably at low concentrations ranges (1-2 mM) [Ref. 31]. At much lower concentration of 0.5 mM molybdenum and at constant S/M ratio of 6, the percent rejection was observed to be very less as the concentration of surfactant used was below CMC (3 mM) of SDS, thus the micellisation is not effective.

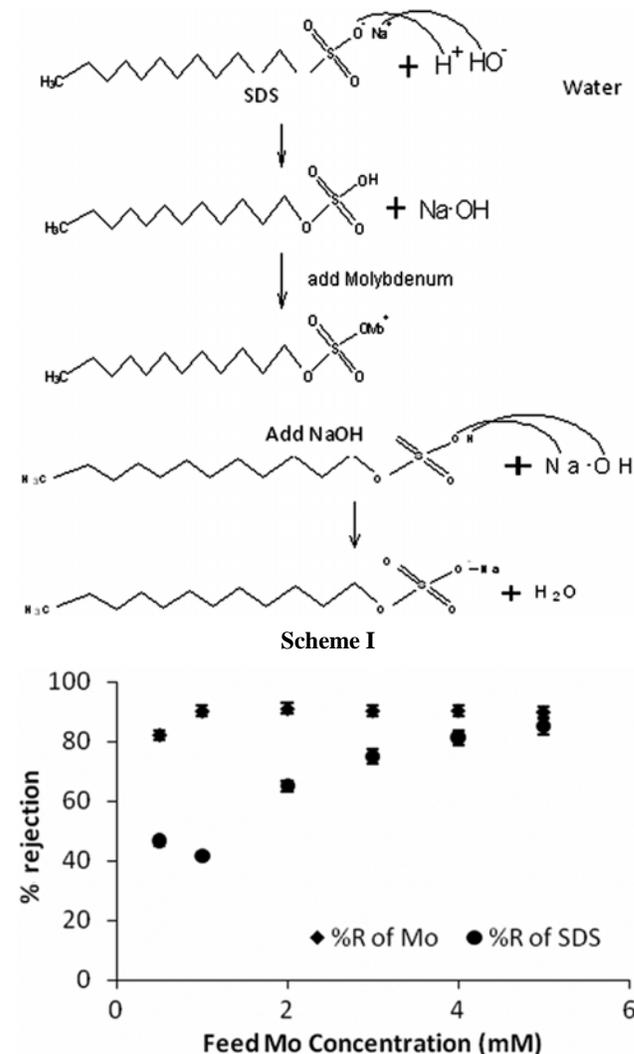


Fig. 3—Effect of feed molybdenum concentration on %rejection of Mo

Effect of Non-ionic surfactant (Tween 20)

Tween- 20 surfactant having CMC of 0.06 mM was taken in the feed solution with 1 mM molybdenum. Using the experimentally optimized conditions of feed flow, time, S/M ratio, pH and feed Mo concentration, feed solution was ultrafiltered and samples were analysed. The results obtained are shown in Table 1.

It is evident from the Table 1, that %rejection of molybdenum (92%) was higher than that obtained using only SDS surfactant. The high rejections obtained using Tween 20 may be due to long hydrocarbon chain of the surfactants affecting the binding and removal capacity of micelles. Hydrocarbon chain of Tween 20 was much longer than SDS chain and, thus, it had high rejection. These results obtained using non-ionic surfactant gave a clue for the selection of surfactant based on hydrocarbon chain length so that wastage of surfactant can be greatly minimized.

Non-ionic surfactants form large micelles, can give high solubilization capacities (per mole of surfactant), and have low monomer concentrations in micellar solutions. These surfactants would appear to be good for use in MEUF. However, it has been found that stable macroemulsions are formed when non-ionic surfactants are stirred with some of the pollutants of interest. Since the ultrafiltration process occurs under turbulent conditions, this is unacceptable. Also, the solubilization capacities of non-ionic species are not very high compared to anionic species and cationic species per kg of surfactant because of high molecular weights. Since surfactants are sold on weight basis rather than on a molar basis, nonionics are not economically attractive for use in MEUF³⁹. Because of these drawbacks of using only non-ionic surfactants, mixed surfactants became effective and attractive for MEUF though the non-ionic surfactant gave good rejection of molybdenum.

Table 1 —Effect of Tween 20 on %rejection of molybdenum

Operating conditions	
Feed molybdenum concentration	= 1 mM
Feed flow rate	= 150 mL/min
Sample collection time	= 30 min
TMP	= 5.3 psi
S/M ratio	= 6
Results	
PF (permeate flow rate)	= 20 mL/min
RF (retentate flow rate)	= 124 mL/min
Mo in permeate	= 0.08 mM
Tween 20 in permeate	= 0.03 mM
%rejection of Mo	= 92%
%rejection of Tween 20	= 50%

Effect of mixed surfactant (SDS + Tween 20)

Three experimental runs were conducted to study the effect of mixed surfactants on the rejection of molybdenum. The results obtained are presented graphically in the Fig. 4. With constant S/M ratio of 6, concentrations of Tween 20 + SDS combination was taken as 0.04 + 5.96, 0.06 + 5.94 and 0.08 + 5.92 mM respectively. Molybdenum was removed efficiently in presence of 0.04 mM of Tween 20 as SDS reached its CMC (6 mM) in presence of 0.04 mM of Tween 20.

The CMC of SDS is greatly reduced by mixing with Tween 20 and the degree of counterion binding of micelles in mixed surfactant systems is reduced with an increase in the molar ratio of Tween 20/SDS. In MEUF with mixed surfactants, the efficiency of Mo ions rejection increased at first and then decreased gradually and the secondary resistance with an increase in non-ionic surfactant:SDS molar ratio. The residual quantity of SDS and the total amount of surfactant in the permeate also decreased markedly. An increase in the nonionic surfactant:SDS molar ratio caused a decrease in the CMC and a decrease in the degree of counterion binding. The separation of molybdenum ions in MEUF with mixed surfactants was affected by a combination of these two factors mainly⁴⁰.

Fundamentals of D, L_m, K_p

For all surfactants, an increase in surfactant concentration increased molybdenum and SDS rejections. In order to explain this behaviour, the distribution coefficient (D), Micellar loading (L_m) and Micellar binding constant (K_p) were calculated using the following equations. Distribution coefficient is the ratio of molybdenum concentration in retentate and in the permeate. An increase in the value of D indicates that more and more surfactant molecules join the micellar phase, binding with more and more metal ions³¹.

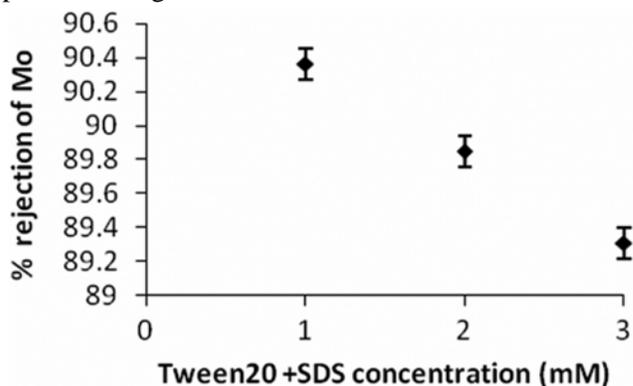


Fig. 4 —Effect of concentration of mixed surfactants (Tween 20 + SDS) on % rejection of molybdenum. where, 1) 0.04 + 5.96 mM; 2) 0.06 + 5.94 mM; 3) 0.08 + 5.92 mM of Tween 20+SDS, respectively

$$\text{Distribution coefficient (D)} = \frac{[P]_R}{[P]_P} \quad \dots(6)$$

$$\text{Micellar loading (L}_m) = \frac{[P]_R - [P]_P}{[S]_R - \text{CMC}} \quad \dots(7)$$

$$\text{Micellar binding constant (K}_p) = \frac{[P]_M}{[P]_W \times [S]} \text{ (mole}^{-1}\text{)} \quad \dots(8)$$

where, subscripts P, R indicating permeate and retentate streams and [P], [S] indicating concentrations of pollutant and surfactant. $[P]_M = [P]_R - [P]_P$, $[P]_W = [P]_P$ and $[S] = [S]_R - \text{CMC}$.

The D, L_m and K_p were calculated and they represent indirectly the maximum % rejection. At any particular condition, micellar properties can be estimated by using these three parameters. Variations of D, L_m and K_p with feed molybdenum and mixed surfactant molar ratio were shown in Figs. 5 and 6.

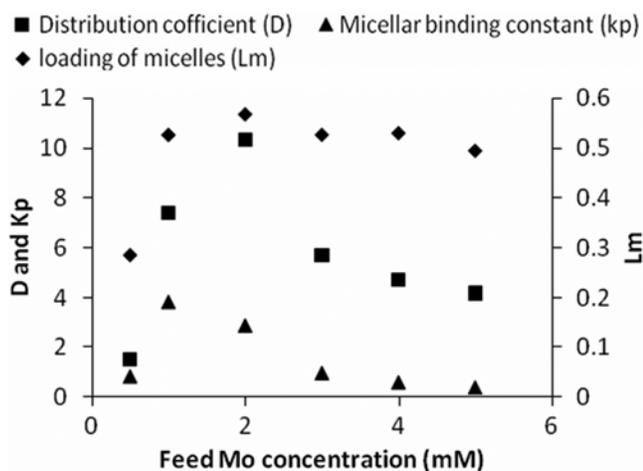


Fig. 5 —Effect of feed molybdenum concentration on D, K_p , L_m

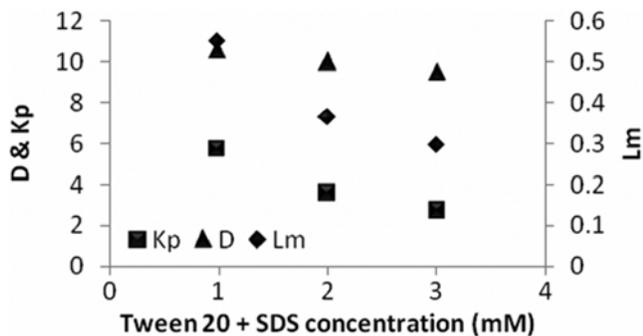


Fig. 6 —Effect of mixed surfactant (Tween 20 + SDS) concentration on D, K_p , L_m , where, 1) 0.04+5.96 mM; 2) 0.06 + 5.94 mM; 3) 0.08 + 5.92mM of Tween 20 + SDS, respectively

Conclusions

MEUF has been applied successfully to remove molybdenum ions from aqueous solutions. In the present investigation, the system attained equilibrium at 30 min of run time.

In MEUF process, the surfactant micelles require an optimum feed pressure or feed flow rate to get rejected at the membrane pores. From the feed flow rate study, it is found to be optimum at 150 mL/min. An optimum time is required for equilibrium attainment at the membrane surface so the maximum rejection could be obtained. From the time study it is found to be 30 min. In the presence of 1 mM of molybdenum CMC of SDS decreases to 6 from 8 mM so the %rejection of Mo is found maximum at S/M of 6. Permeate flow rate decreases with increase in S/M ratio as addition of surfactant above its CMC results in formation of more number of micelles.

%Rejection of molybdenum is found to increase with pH due to deprotonation of SDS. Addition of NaOH helps to remove hydrogen atoms from the SDS and thereby accommodating more molybdate ions. Increasing Mo concentration results in decrease of %rejection of Mo indicating that MEUF is feasible only at lower concentration ranges (1-2 mM). Thus it can be adopted as secondary or tertiary waste water treatment.

Using experimentally optimized conditions and with SDS, molybdenum can be removed up to 90.3% where as Tween 20 and mixed (Tween 20 + SDS) can removed up to 92 and 90.36%. Overall, using cross flow MEUF molybdenum is removed maximum up to 92% from waste water streams.

References

- Adakole J A & Abolude D S, *Res J Environ Earth Sci*, 1 (2) (2009) 54.
- US Department of Health and Human Services, (1978) Available from <http://www.osha.gov/dts/sltc/methods/toc.html>
- Matlock M M, Howerton B S & Atwood D A, *Water Res*, 36 (2002) 4757.
- Souag R, Touaibia D, Benayada B & Boucenna A, *European J Sci Res*, 35 (2009) 416.
- Mehmet E & Fikret T, *J Hazard Mater*, B 109 (2004) 71.
- Manos M J, Malliakas C D & Kanatzidis M G, *Chemistry-A European J*, 13 (2007) 51.
- Weon B, Chen W, Mehra R & Mulchandani A, *Chemistry-A European J*, 40 (2000) 793.
- Leung P S, *Ultrafiltration Membranes and Applications*, edited by Cooper (Plenum Press, New York) 1979, pp. 415.
- Dunn R O, Scamehorn J F & S D Christian, *Sep Sci Technol*, 20 (1985) 257.

- 10 S D Christian & J F Scamehorn, *Surfactant - Based Separation Processes*, edited by J F Scamehorn & J H Harwell, (Marcel Dekker, New York) 1989, pp. 3.
- 11 Scamehorn J F, Christian S D & Ellington R T, *Surfactant-Based Separation Processes*, edited by J F Scamehorn & J H Harwell, (Marcel Dekker, New York) 1989, pp. 29.
- 12 Huang Y C, Batchelor B & Koseoglu S S, *Sep Sci Technol*, 29 (1994) 1979.
- 13 Sadaoui Z, Azoug C, Charbit G & Charbit F, *J Environ Eng ASCE*, 124 (1998) 695.
- 14 A S Jonsson & G Tragardh, *Desalination*, 77 (1990) 135.
- 15 M Cheryan, *Ultrafiltration and Microfiltration Handbook*, (Technomic Publishing Co., Lancaster) (1998).
- 16 Juang R S, Xu Y Y & Chen C L, *J Memb Sci*, 218 (2003) 257.
- 17 Afkhami A & Conway B E, *J Colloid Interf Sci*, 251 (2003) 248.
- 18 Afkhami A, Madrakian T & Amini A, *Desalination*, 243 (2009) 258.
- 19 Xu N, Christodoulatos C & Braida W, *Chemosphere*, 62 (2006) 1726.
- 20 Ryden J C, Syers J K & Tillman R W, *J Soil Sci*, 38 (1987) 211.
- 21 Wu C H, Lo S L & Lin C F, *Colloids Surf A*, 166 (2000) 251.
- 22 Faghihian H, Malekpour A & Maragheh M G, *Int J Environ Pollut*, 18 (2002) 181.
- 23 Bostick B C, Fendorf S & Helz G R, *Environ. Sci Technol*, 37 (2003) 285.
- 24 Saberyan K, Maragheh M G & Ganjali M R, *Korean Chem Soc*, 25 (2004) 460.
- 25 Zhang P, Inoue K, Yoshizuka K & Tsuyama H, *Hydrometallurgy*, 41 (1996) 45.
- 26 Asresahegnova Z & Jelinek L, *Ion Exchange Lett*, 2 (2009) 38.
- 27 Lazaridis N K, Jekel M & Zouboulis A I, *Sep Sci Technol*, 38 (2003) 2201.
- 28 Swinkels P L J, Van Der Weijden R D, Ajah A N, Arifin Y, Loe H L, Manik M H, Siriski I & M A Reuter, *Minerals Eng*, 17 (2004) 205.
- 29 Huang J H, Kargl-Simard C, Oliazadeh M & A Alfantazi M, *Hydrometallurgy*, 75 (2004) 77.
- 30 Cheryan M, *Ultrafiltration and microfiltration handbook*, 2nd Edn, (CRC press, US) pp.386.
- 31 Karate V D & Marathe K V, *J Hazard Mater*, 157 (2008) 464.
- 32 Kamble S B & Marathe K V, *Sep Sci Technol*, 40 (2005) 3051.
- 33 Chhatre A J & Marathe K V, *Sep Sci Technol*, 40 (2006) 3051.
- 34 Liu C-K & Li C-W, *Sep Purifi Technol*, 43 (2005) 25.
- 35 Baek K, Kim B-K & Yang J-W, *Desalination*, 156 (2003) 137.
- 36 Blocher C, Dorda J, Mavrov V, Chmiel H, Lazaridis N K & Matis K A, *Water Res*, 37 (2003) 4018.
- 37 Ahmadi S, Huang Y C & Batchelor B, *J Environ Eng*, 121 (1995) 645.
- 38 C-Y Lin, Master thesis, Department of Water Resources and Environ. Eng., TamKang University, 2003.
- 39 D T Wasan, M E Ginn & D O Shah, *Surfactants in Chemical / Process Eng, Surfactant Sci Series*, US, Vol. 28, pp. 81.
- 40 Huang J-h, Zeng G-m, Fang Y-y, Qu Y-h & Li X, *J Memb Sci*, 326 (2009) 303.