

Recovery of molybdenum and rhenium in scrub liquors of fumes and dusts from roasting molybdenite concentrates

Hossein Salehi, Hamed Tavakoli, M.R. Aboutalebi, H.R. Samim

School of Metallurgy and Materials Engineering, Iran University of Science and Technology (IUST), Narmak, Tehran, Iran

ABSTRACT

The present work addresses the recovery of rhenium from scrub liquor of molybdenite concentrate roasting fume and dust by solvent extraction method. According to the results, recovery of rhenium from the scrub liquor is not practical unless molybdenum is removed in advance. The extraction of molybdenum was carried out using a D2EHPA-TBP system which resulted in up to 99.8% Mo extraction in a two-stage solvent extraction at $\text{pH} = 1$ and $\text{O/A} = 1$. Up to 99.6% of Re was extracted subsequently using TOA in a single-stage extraction at $\text{pH} = -0.3$ and $\text{O/A} = 1:20$. The organic phase was stripped by ammonium hydroxide 32% and the resultant liquor was further subjected to evaporation as a result of which, an enriched purified solution was obtained. Ammonium perrhenate was precipitated from the enriched liquor by adjusting the pH to 6.5–7.

1. Introduction

Rhenium is a precious metal with a wide variety of metallurgical as well as chemical applications. The main application of rhenium is in the production of nickel-based superalloys used in combustion turbines. Rhenium has several valences such as +7, +6, +5 and +4, and easily changes from one valence to another. This feature has made rhenium an ideal element for the manufacturing of reforming catalysts (Gunn, 2014). It is common to produce rhenium compounds as by-products in the extraction of molybdenum. Rhenium heptoxide can be recovered in venturi scrubbers from scrub liquor of fumes and dust from roasting molybdenite concentrate (Habashi, 1997). The scrubbing solution is acidic-based and contains high amounts of sulfate ion, with molybdenum as the major impurity. Since both of rhenium and molybdenum are existing in the form of oxyanions in a wide range of the solution pH , selective separation of rhenium over molybdenum has always been challenging (Srivastava et al., 2016). Ion exchange and solvent extraction are the most employed techniques by which rhenium is recovered from rhenium-bearing aqueous solutions industrially (Srivastava et al., 2015b; Truong et al., 2017; Virolainen et al., 2015; Zhang et al., 2017). High selectivity and recyclability of organic extractant with superior efficiency and low cost are the main advantages of solvent extraction process which have made it popular in commercial practice (Cheema et al., 2018; Srivastava et al., 2015a).

Solvent extraction of rhenium from acidic solutions is carried out using neutral extractants such as TBP (Tributyl phosphate) and TOPO

(Trioctylphosphine oxide) (Cheema et al., 2018; Hosseinzadeh et al., 2014; Keshavarz Alamdari et al., 2012; Sato and Sato, 1990; Schrötterová and Nekovář, 2006; Truong and Lee, 2017) as well as basic extractants such as tertiary amines (Fang et al., 2014; Kang et al., 2013; Kim et al., 2015; Shan et al., 2015). Cheema et al. studied the extraction of rhenium from leach liquor of molybdenite roasting flue-dust using TBP. Based on their findings, the extraction percentage of rhenium increased by decreasing the pH of the extraction to -0.3 , while extraction of molybdenum showed an opposite reverse trend (Cheema et al., 2018). Kang et al. reported similar results in the separation of rhenium over molybdenum from the leaching solution of molybdenite roasting dust using Trioctylamine (TOA) as the extractant (Kang et al., 2013).

The separation of molybdenum prior to rhenium is reported in the literature. Kim et al. studied the removal of molybdenum from molybdenite roasting fume leach solution using lime slurry. The rhenium content of the solution was then recovered by solvent extraction with Alamine 304-1 as the extractant. They produced high purity ammonium perrhenate after stripping the organic phase in ammonium hydroxide followed by selective precipitation (Kim et al., 2015). Keshavarz et al. studied separation of Re over Mo from leach liquor of roasting dust based on which rhenium was recovered after removing the major amount of molybdenum using TBP at $\text{pH} = 2$. Subsequently, rhenium was extracted selectively from the raffinate using TBP at $\text{pH} = 0$ in which co-extraction of molybdenum was negligible (Keshavarz Alamdari et al., 2012).

* Corresponding author.

E-mail address: mrezab@iust.ac.ir (M.R. Aboutalebi).

Olazabal et al. developed the molybdenum species distribution diagram in the aqueous solutions as a function of the pH using thermodynamic analysis. According to this study, there are several types of molybdenum species in acidic solutions. Molybdenum polynuclear anions such as $Mo_7O_{24}^{6-}$, $H_3Mo_7O_{24}^{3-}$ and $Mo_8O_{26}^{4-}$ are predominant at low acidities ($1 < \text{pH} < 6$), while molybdenum oxycations such as MoO_2^{2+} and $H_6Mo_2O_8^{2+}$ are predominant at high acidities ($\text{pH} < 1$). This has been reported in other studies as well (Cheema et al., 2018; Olazabal et al., 1992; Srivastava et al., 2015b). The molybdenum (VI) oxycations tend to form polynuclear ions by polymerization with the general form of $Mo_xO_{3x-1}^{2+}$. The polymerization degree (X) depends on the concentration of metal in the solution, mineral acid species and acidity of the solution which is mainly 2 for sulfate media at the sulfuric acid concentration higher than 0.5 M (Palant et al., 1998). These species form anionic complexes such as $Mo_2O_5(SO_4)_2^{2-}$ can be extracted by anion exchangers, (Palant et al., 1998), and neutral complexes such as $MoO_2(SO_4)$ are extractable by solvating extractants (Brassier, 1995; Tytko and Gras, 1988).

In Pars Molybdenum Co. of Yazd, Iran, molybdenite concentrate is roasted in order to produce molybdenum products. The roasting outgas is scrubbed using the venturi scrubbers, as a result of which an acidic liquor containing Mo and Re is produced. Due to high sulfate content of the scrub-liquor of molybdenite concentrate roasting fume and dust, which enters into the solution obtained from scrubbing the fume output of the roasting furnace, selective separation of rhenium from the scrub-liquor is not possible unless almost all of the Mo concentration of the solution be removed. In this study, separation of Mo over Re was carried out using the synergistic effect of TBP and D2EHPA as a different approach with high Mo extraction efficiency and low Re loss. Separation and purification of Re were then conducted using an anion exchanger, followed by stripping and production of ammonium perchlorate. The extraction mechanism of molybdenum was investigated and the effect of various parameters on the extraction was studied. Based on the experimental results, the overall flowchart of the process was devised.

2. Experimental

2.1. Materials and reagents

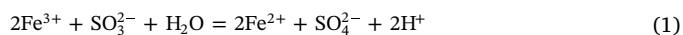
The scrubbing solution of molybdenite concentrate roasting fume and dust (venturi solution) was obtained from Pars Molybdenum Co. (Yazd, Iran). The chemical composition of the venturi solution is given in Table 1. It can be seen that Mo, Fe, and sulfur in the form of sulfate are the major impurities. Tributyl phosphate (TBP, supplied by Loba Chemie, of purity 99%), Di-(2-ethylhexyl) phosphoric acid (D2EHPA, Farapouyan Isatis-Iran, industrial grade) and Trioctylamine (TOA, Wako-Japan, of purity 97%) were used as organic extractants and 1-Decanol (Merck, of purity 99%) and Kerosene (ALFA Aesar, analytical grade) were used as TOA modifier and diluent, respectively. Analytical grade sodium sulfide was used as the reductant (Merck, 99.9%). The sulfuric acid and ammonium hydroxide used in the study were analytical grade and supplied by Parsoumash-Iran.

2.2. Methods

2.2.1. Solvent extraction

After adjusting the pH of the solution (inoLab pH 7110, WTW pH-meter), known volumes of the organic and aqueous phases were

equilibrated for 20 min in a 100 mL Erlenmeyer flask on a magnetic stirrer. The extraction of Mo from the venturi solution was conducted by a mixed organic phase of known volume fractions of TBP and D2EHPA. At the pH or acidity tested, D2EHPA would strongly extract Fe^{3+} , and this would be a problem in stripping and further purification of Mo. In order to overcome this problem, the sodium sulfite was added to the venturi solution before the molybdenum extraction, which reduces Fe^{3+} to Fe^{2+} . Na_2SO_3 was added at 1.5 times the stoichiometric value of total Fe to ensure the conversion of the whole Fe^{3+} content into Fe^{2+} . The main reaction during reduction is as follows:



Reduction of Fe^{3+} to Fe^{2+} is a simple and effective method to avoid contamination of the D2EHPA. By this way, Fe^{2+} as well as other impurities of the solution are partially extracted and can be scrubbed by dilute sulfuric acid. Rhenium was then extracted from the molybdenum extraction raffinate using a 10 vol% TOA mixed with 10 vol% Decanol modifier. Kerosene was used as the organic phase diluent and all the experiments were conducted at room temperature (298 K). Phase separation was performed using a 100 mL separatory funnel and the concentration of metals in all aqueous phases was determined using a GBC AVANTA atomic absorption spectrometer. FT-IR analysis of the organic phases in Mo extraction stage was conducted using an FT-IR spectrometer (FT-IR-8400S, Shimadzu) with a KBr cell. The concentrations of Re and Mo in all organic phases were calculated by mass balance. The stripping of Mo and Re was performed using a 0.5 M Na_2CO_3 solution and ammonium hydroxide 32%, respectively.

2.2.2. Precipitation of ammonium perchlorate (APR)

Based on the Stabcal modeling (Kim et al., 2015) Re concentration should be at least 30 g/L for efficient recovery of Re. Therefore, the concentration of Re in the stripped liquor was increased through evaporation. The pH of the concentrated solution was adjusted to 6–8 using H_2SO_4 at which APR starts precipitating. The filtrate APR was washed with distilled water as well as ethanol (Hamoon Teb-Iran, 99.7%) and dried in the oven at 90 °C for 1 h. An APR sample was dissolved in a 5% ammonium hydroxide, and chemical composition of the APR was determined using atomic absorption spectrometer. The crystal structure of the produced APR was also approved using X-Ray diffraction analysis (Bourestnik DRON-8, Russia, Cu K α , 40 kV, 30 Ma, step size = 0.04.).

3. Results and discussion

3.1. Separation of Mo

Based on the literature, by using TBP as the extractant high extraction percentages of rhenium are obtained at values of pH close to zero, and the extraction is decreased with increasing the pH (Cheema et al., 2018; Hosseinzadeh et al., 2014; Keshavarz Alamdari et al., 2012). Therefore, extraction of Re over Mo from solutions with high sulfate content is not practical since various types of molybdenum anionic and neutral complexes can be extracted using anion exchangers and solvating extractants, respectively. The extraction of Mo was conducted by exploiting the synergistic effect between TBP and D2EHPA at a certain pH. All experiments were done at O/A = 1 and room temperature (298 K).

The role of D2EHPA in the extraction process is to exchange the Mo (VI) oxycations while TBP extracts the Mo polynuclear anions, which are existing in the solution at the same time, by solvation mechanism.

Table 1

The chemical composition of the venturi solution.

Element	Re	Mo	Fe	Mg	S	As	Cu	Al	Ca	K	Na	Si	Zn
Concentration (mg/L)	289	3528	1196	371	3078	37	331	179	504	58	687	120	24.4

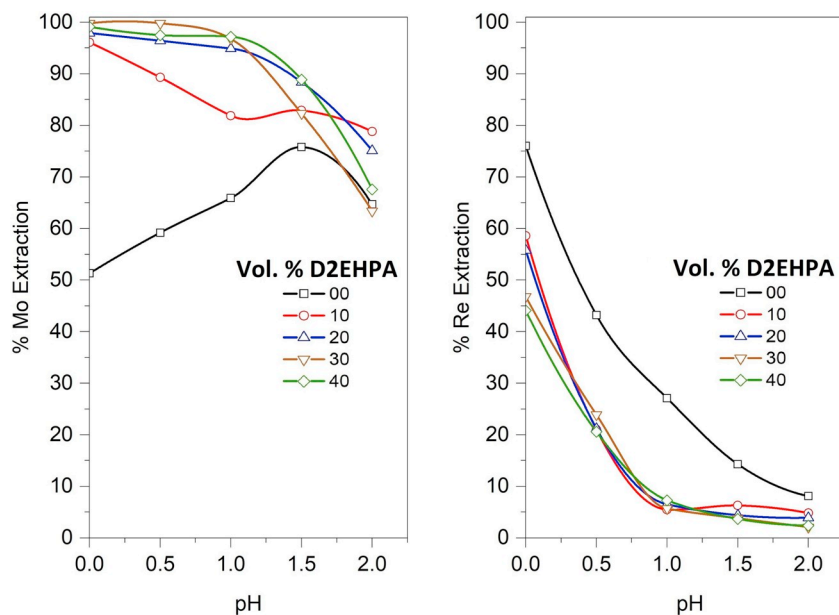


Fig. 1. The Mo and Re extraction isotherms with 20 vol% TBP and different amounts of D2EHPA.

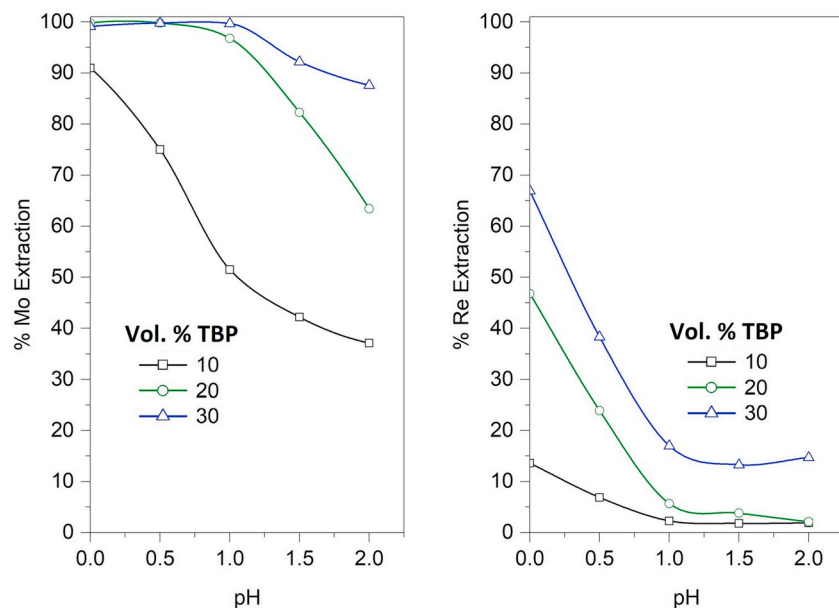


Fig. 2. Mo and Re extraction isotherms using the mixtures of 30 vol% D2EHPA and different amounts of TBP.

Table 2

Effect of reductant addition on iron extraction by 30% D2EHPA + 20% TBP system.

	Concentration (ppm)	Extraction (%)
Before Na ₂ SO ₄ addition	238	80.1
After Na ₂ SO ₄ addition	1131	5.4

Addition of Zn powder to the venturi solution results in the reduction of Fe³⁺ content to Fe²⁺. This would prevent contamination of D2EHPA with ferric ion that brings about problems in the stripping stage. Fig. 1 shows the extraction isotherms of Mo and Re against pH using the organic phases with 20 vol% TBP and 0-40 vol% D2EHPA. It can be seen that by using 20 vol% TBP alone, the Mo extraction efficiency reaches up to 76% at pH = 1.5 owing to Mo polynuclear anions extraction while Re co-extraction reaches to 14.3% at this condition. By using TBP

Table 3

Chemical composition of the raffinate after molybdenum extraction by 30% D2EHPA + 20% TBP system.

Element	Concentration (ppm)	Extraction (%)
Re	272.5	5.7
Mo	114.6	96.8
Fe	1131	5.4
Mg	353	4.9
Cu	322	2.7
Al	135	24.6
Ca	501	0.6

at high acidities, Re cannot be extracted selectively since molybdenum polynuclear anions, as well as Mo neutral complexes, are extracted.

Addition of D2EHPA to the organic phase shifted down the Re extraction curves, while Mo extraction curves shifted up drastically. This

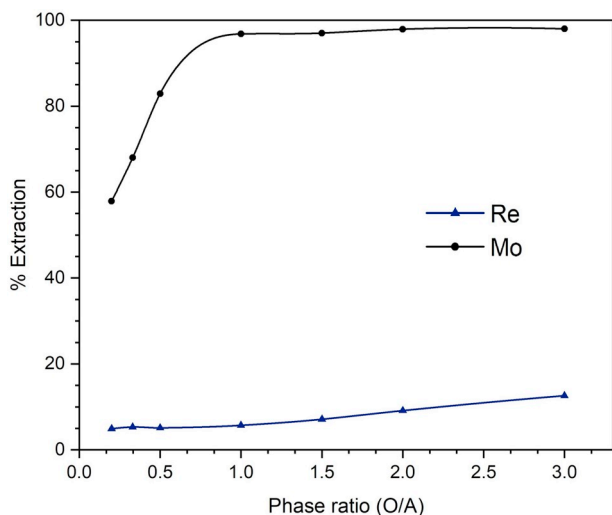


Fig. 3. The effect of phase ratio on extraction of Mo from the venturi solution using an organic phase of 30 vol% D2EHPA - 20 vol% TBP.

is due to extraction of Mo (VI) oxyocations by D2EHPA which increases the distribution coefficient of molybdenum ($D = Mo_{org}/Mo_{aq}$) using the mixed extractant. The Mo extraction efficiency is declined with increasing the pH as a result of the conversion of Mo(VI) oxyocations to Mo polynuclear anions. The most desirable condition is the highest extraction efficiency for Mo and the least co-extraction for Re. The Mo and Re extraction efficiencies were 96.7% and 5.5%, respectively, when using an organic phase with 30 vol% D2EHPA and 20 vol% TBP at pH = 1, which seem to be the optimum conditions for Mo removal from the solution.

Fig. 2 shows the extraction isotherms for Mo and Re with the mixture of 30 vol% D2EHPA and 10–30 vol% TBP, which confirms the results given in Fig. 1. It can be seen that high Mo extraction efficiency is achieved, while Re co-extraction is negligible using an organic phase of 30 vol% D2EHPA - 20 vol% TBP.

Using a mixed extractant with a high volume fraction of TBP brought about higher Re loss especially at high acidities. Since the sulfate content of the venturi solution is high, using TBP with a volume percent < 20 gives rise to the formation of a third phase owing to high organic phase loading with the acid. Therefore, when using an organic phase containing D2EHPA by itself, extraction of Mo from the venturi solution would not be practical. Also, as reported in the literature

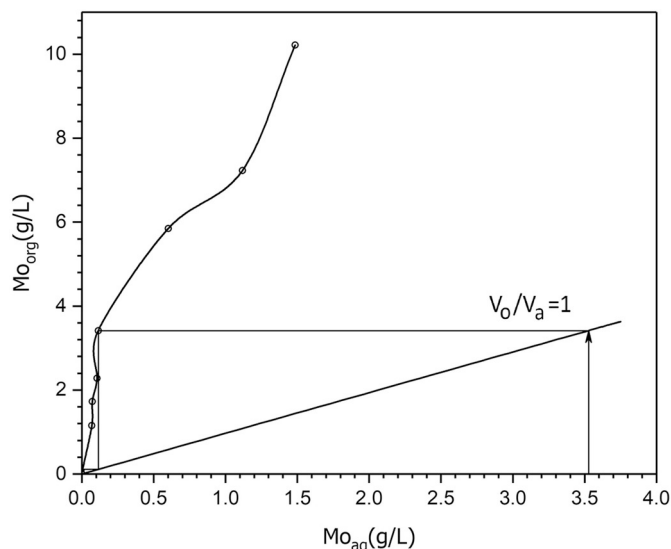


Fig. 5. McCabe-Thiele diagram for Mo extraction using a mixture of 30 vol% D2EHPA and 20 vol% TBP at pH = 1.

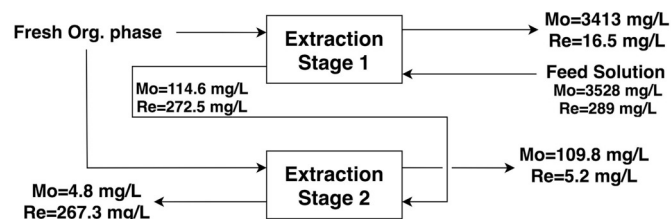


Fig. 6. The planned flowsheet for extraction of Mo from the venturi solution.

(Moyer, 2010), the crud can be formed due to the solid particles that have entered the solution while scrubbing the roasting fume and dust.

Sodium sulfite was added to the venturi solution as a reductant before the molybdenum extraction in order to reduce the ferric ion content to ferrous ion. Table 2 shows the effect of the addition of Na_2SO_3 on iron co-extraction by 30% D2EHPA + 20% TBP.

It can be seen that addition of sodium sulfite has remarkably decreased the iron co-extraction and only 5.4% of the iron content has been co-extracted, which is pertained to iron(II) and can be scrubbed further with dilute sulfuric acid. The chemical composition of the

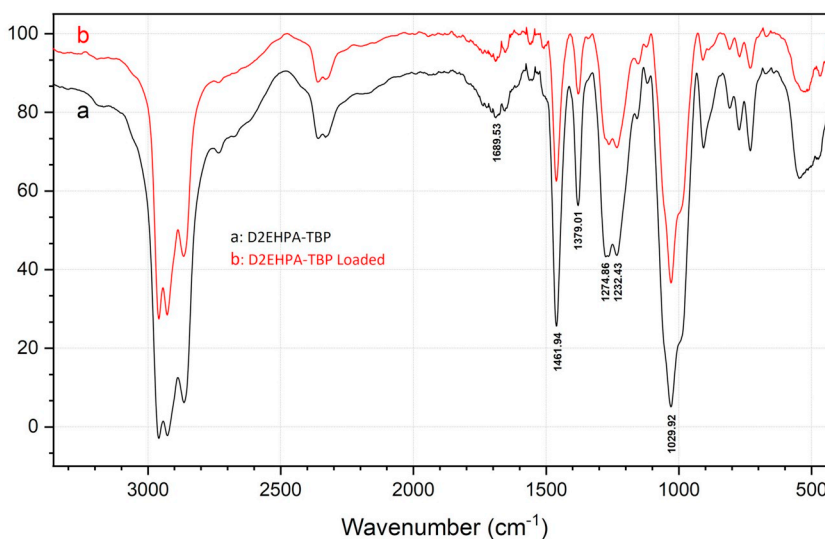


Fig. 4. FT-IR spectra of the mixture of 30 vol% D2EHPA and 20 vol% TBP fresh (a) and loaded (b).

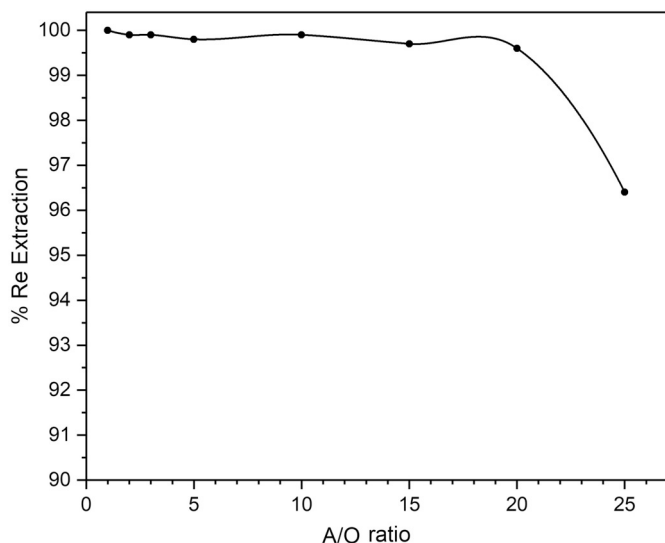


Fig. 7. Effect of A/O ratio on Re extraction percent using 10 vol% TOA - 10 vol% Decanol at pH = -0.3.

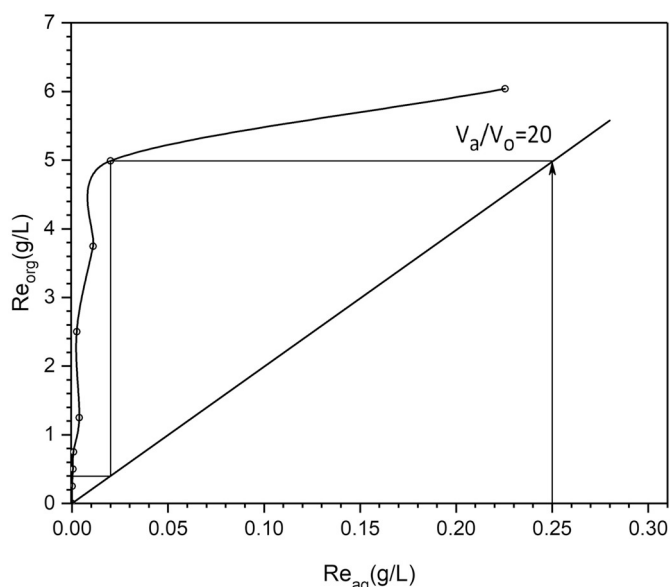


Fig. 8. McCabe-Thiele plot of Re extraction with an organic phase of 10 vol% TOA + 10 vol% Decanol at pH = -0.3.

Table 4
Results of the Re stripping tests at 32% ammonium hydroxide.

	Phase ratio (O/A)	Re concentration (g/L)	Re efficiency (%)
1	1	4.972	99.6
2	2	9.955	99.7
3	5	24.080	96.5

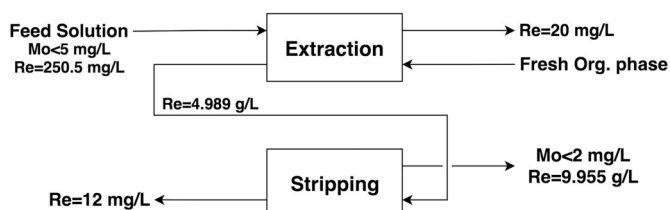


Fig. 9. The flowsheet of the Re extraction and stripping process.

raffinate after a one-step Mo solvent extraction is shown in Table 3. The co-extracted impurities can be scrubbed and stripped subsequently and the organic phase will be regenerated thereafter.

The effect of O/A on the extraction of Mo and Re is depicted in Fig. 3. The results confirm that at a phase ratio lower than 1, the Mo extraction percent is declined, and at a phase ratio higher than 1 Re co-extraction is increased. According to this, O/A = 1 is selected as optimum for Mo extraction.

In order to study the Mo extraction mechanism exploiting the synergistic effect between D2EHPA and TBP, the Fourier-transform infrared spectroscopy analysis (FT-IR) of the organic phase was carried out. The FT-IR spectra of a mixture of 30 vol% D2EHPA and 20 vol% TBP before and after the Mo extraction were compared in Fig. 4. Owing to the extraction of Mo (VI) oxycations, the intensity of P-OH stretching vibration at 1029 cm^{-1} and O-H bending vibration at 1689 cm^{-1} which both are the characteristic vibration bonds of D2EHPA, are decreased. Also, extraction of Mo polynuclear anions has decreased the P=O vibration bond interval at $1232\text{--}1274\text{ cm}^{-1}$. Accordingly, it can be concluded that the extraction mechanism was a combination of cation-exchange and solvation. Comparing the results shown in Figs. 1 and 4 indicates that the addition of D2EHPA to an organic phase containing TBP influences the P=O vibration bonds for both TBP and D2EHPA. The reason for this interaction maybe is the formation of new bonds between TBP and D2EHPA, therefore, polymerization of some extractant molecules through hydrogen bonds (Alamdari et al., 2002; Fatmehsari et al., 2009). Hence it seems that such interaction between D2EHPA and TBP is the reason for shifting the Re extraction isotherm curves down in Figs. 1 and 2 when mixed extractant is used.

The theoretical number of stages for maximum molybdenum extraction at $V_O/V_A = 1$ and pH = 1 using the mixture of 30 vol% D2EHPA and 20 vol% TBP was determined by constructing the McCabe-Thiele plot (Fig. 5). It can be seen that a two-stage solvent extraction is required for complete molybdenum separation.

The molybdenum content of the venturi solution should be removed completely since our previous studies demonstrated that selective separation of Re from the venturi solution using neutral extractants (TBP) and anion-exchangers (TOA) is not practical due to high Mo co-extraction.

The proposed process for Mo extraction in this study can be used through a multi-stage mixer-settler. Extraction of Mo was conducted according to the flowsheet presented in Fig. 6 based on which after a two-stage solvent extraction, molybdenum can be extracted up to 99.8% while total Re loss is 7.5%.

Complete stripping of Mo from the loaded organic phase was done using a 0.5 M solution of Na_2CO_3 with phase ratio of 1 followed by scrubbing using a 1 M sulfuric acid solution at O/A = 0.5 so that the final pH of the waste liquor be adjusted to 1.

3.2. Separation of rhenium

Separation of Re from the Mo extraction raffinate was carried out through solvent extraction at different phase ratios (O:A) from 1:25 to 1, pH = -0.3 using an organic phase with a mixture of 10 vol% TOA and 10 vol% Decanol modifier and 15 min contact time. All parameters were chosen based on the literature (Kang et al., 2013; Kim et al., 2015). Fig. 7 depicts the effect of A/O ratio on Re extraction efficiency based on which Re was extracted > 99.6% at A/O 1–20. Increasing the A/O leads to lower Re extraction percent. Therefore, A/O = 20 was chosen at which 99.6% of Re was extracted. The concentration of Mo in the raffinate was < 5 mg/L without a remarkable change.

McCabe-Thiele plot for Re extraction was constructed using 10 vol% TOA - 10 vol% Decanol organic phase at pH = -0.3 (Fig. 8), which clearly depicts that for complete Re separation, a two-stage solvent extraction is required.

Stripping of Re from the loaded organic phase was completed with 32% ammonium hydroxide at phase ratios from 1 to 5. Based on the

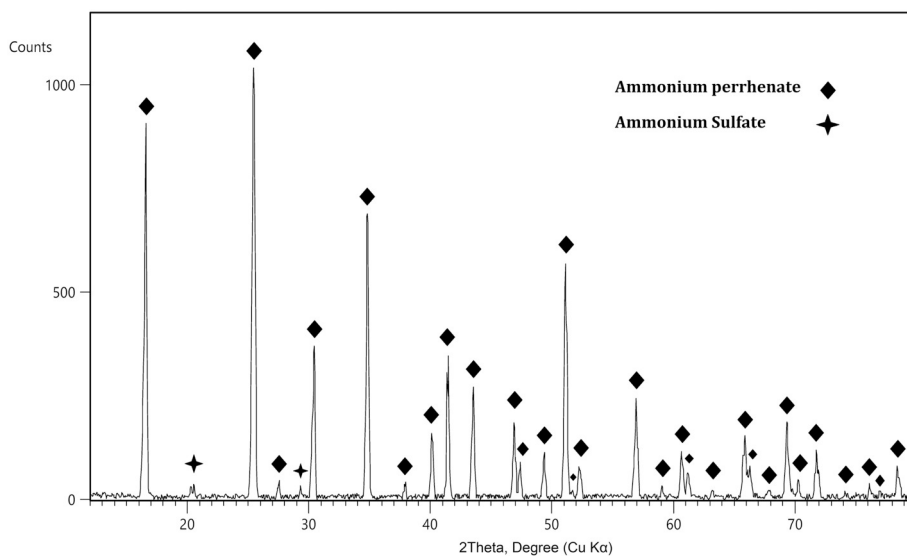


Fig. 10. The x-ray diffraction pattern of produced APR.

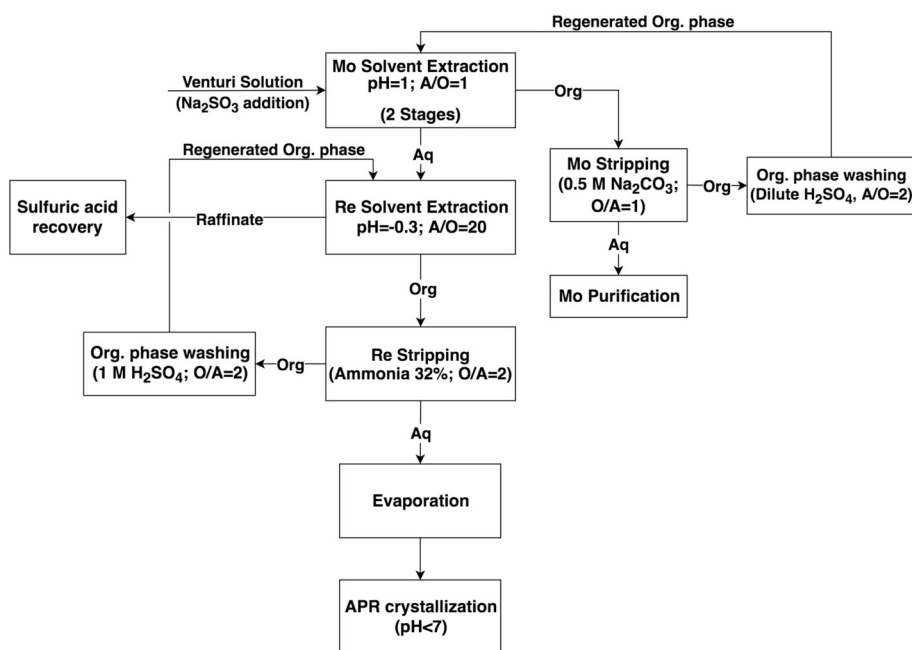


Fig. 11. Overall flow diagram of APR production from the venturi solution.

results shown in Table 4, Re stripping was done at $O/A = 2:1$ since a high stripping efficiency at a high O/A ratio was desired. Through a single-stage process, 99.7% of the loaded Re was stripped from the organic phase. The Mo concentration of the strip liquor was determined to be < 2 mg/L.

The flowsheet of the extraction of Re from the Mo extraction raffinate is represented in Fig. 9. Experimental results show that 91.8% of the Re was recovered from the venturi solution through purification followed by solvent extraction.

3.3. Precipitation of ammonium perrhenate

The stripped liquor was evaporated on a hot plate after which a concentrated liquor containing 29.9 g/L Re was obtained. The precipitation of APR was started right after the pH of the liquor was adjusted to 6.5–7. The x-ray diffraction pattern of the produced ammonium perrhenate is shown in Fig. 10. In accordance with XRD reference

patterns of ammonium perrhenate (JCPDs file no. 00-010-0252) and ammonium sulfate (JCPDs file no. 00-001-0363), Fig. 10 confirms that APR mixed with a little amount of ammonium sulfate is precipitated. To produce a high-grade APR (99% $<$) continued dissolution and recrystallization are necessary.

A sample of the final product was dissolved in a 5% ammonium hydroxide solution for assaying. The analysis showed that the purity of the final APR product was 95.8% with ammonium sulfate as the main contaminant. The composition of the evaporated strip liquor before and after precipitation showed that 89.4% of Re was precipitated as APR. Fig. 11 depicts the overall flow diagram for the production of APR from the scrub liquor of molybdenite concentrate roasting fume and dust, which shows that after a two-stage solvent extraction, Mo was separated using a mixture of 30 vol% D2EHPA and 20 vol% TBP at $O/A = 1$ and $pH = 1$. Re was then extracted using a mixture of 10 vol% TOA - 10 vol% Decanol at $O/A = 1:20$ and $pH = -0.3$. Stripping of the Re was carried out using a 32% ammonium hydroxide solution at $O/$

A = 2:1 and after evaporation of the strip liquor, APR was precipitated at pH 6.5–7. All of the organic phases were regenerated and reused after stripping.

4. Conclusions

Scrubbing the molybdenite concentrate roasting fume and dust using the venturi scrubbers leads to producing a high-sulfate-content liquor, which affects the solvent extraction of Re over Mo using neutral extractants as well as anion exchangers owing to the complexation of Mo polynuclear anions and Mo neutral complexes with the organic extractants. Since Mo anionic species are dominant at weak acidities and Mo (VI) cationic species are formed at $\text{pH} < 2$, by using a two-stage solvent extraction with a mixture of TBP and D2EHPA at $\text{pH} = 1$ the molybdenum anionic, cationic and neutral species were extracted up to 99.8% at the same time, while Re co-extraction was $< 7.5\%$. The Mo extraction raffinate was then subjected to solvent extraction followed by stripping to produce a purified liquor containing 9.955 g/L Re. After increasing the concentration of Re in the strip liquor through evaporation, ammonium perrhenate was precipitated at $6.5 < \text{pH} < 7$ as the final product with a purity grade of 95.8%. Consecutive dissolution and recrystallization are necessary for obtaining a high-grade APR.

References

- Alamdari, E.K., Darvishi, D., Sadrnezhaad, S., Shabestari, Z.M.H., O'hadizadeh, A., Akbari, M., 2002. Effect of TBP as a Modifier for Extraction of Zinc and Cadmium With a Mixture of DEHPA and MEHPA, Proc. Int. Conf. Solvent Extraction Conference. S. Afr. Inst. Min & Metall, Johannesburg, pp. 1052–1057.
- Brassier, C., 1995. Study of a process for upgrading molybdenum by organophosphorus solvent extraction (in French) In: Documentation and Multimedia Publishing Service. Saclay Study Center.
- Cheema, H.A., Ilyas, S., Masud, S., Muhsan, M.A., Mahmood, I., Lee, J.-C., 2018. Selective recovery of rhenium from molybdenite flue-dust leach liquor using solvent extraction with TBP. Sep. Purif. Technol. 191, 116–121.
- Fang, D.-W., Shan, W.-J., Yan, Q., Li, D., Xia, L.-X., Zang, S.-L., 2014. Extraction of rhenium from sulphuric acid solution with used amine N235. Fluid Phase Equilib. 383, 1–4.
- Fatmehsari, D.H., Darvishi, D., Etemadi, S., Hollagh, A.E., Alamdari, E.K., Salardini, A., 2009. Interaction between TBP and D2EHPA during Zn, Cd, Mn, Cu, Co and Ni solvent extraction: a thermodynamic and empirical approach. Hydrometallurgy 98 (1), 143–147.
- Gunn, G., 2014. Critical Metals Handbook. American Geophysical Union.
- Habashi, F., 1997. Handbook of Extractive Metallurgy, Precious Metals, Refractory Metals, Scattered Metals, Radioactive Metals, Rare Earth Metals. 3 Wiley-VCH.
- Hosseinzadeh, M., Alizadeh, M., Ranjbar, M., 2014. Optimization of Re solvent extraction from molybdenite roasting dust leaching solution and the performance evaluation of extraction in a multi-stage mixer-settler. Int. J. Miner. Process. 130, 88–94.
- Kang, J., Kim, Y.-U., Joo, S.-H., Yoon, H.-S., Rajesh Kumar, J., Park, K.-H., Parhi, P.K., Shin, S.M., 2013. Behavior of extraction, stripping, and separation possibilities of rhenium and molybdenum from molybdenite roasting dust leaching solution using amine based extractant tri-*n*-butyl-amine (TOA). Mater. Trans. 54 (7), 1209–1212.
- Keshavarz Alamdari, E., Darvishi, D., Haghshenas, D.F., Yousefi, N., Sadrnezhaad, S.K., 2012. Separation of Re and Mo from roasting-dust leach-liquor using solvent extraction technique by TBP. Sep. Purif. Technol. 86, 143–148.
- Kim, H.S., Park, J.S., Seo, S.Y., Tran, T., Kim, M.J., 2015. Recovery of rhenium from a molybdenite roaster fume as high purity ammonium perrhenate. Hydrometallurgy 156, 158–164.
- Moyer, B.A., 2010. Ion Exchange and Solvent Extraction: A Series of Advances. 19 CRC Press, USA.
- Olazabal, M., Orive, M., Fernandez, L., Madariaga, J., 1992. Selective extraction of vanadium (V) from solutions containing molybdenum (VI) by ammonium salts dissolved in toluene. Solvent Extract. Ion Exchange 10 (4), 623–635.
- Palant, A.A., Iatsenko, N.A., Petrova, V.A., 1998. Solvent extraction of molybdenum (VI) by diisododecylamine from sulphuric acid solution. Hydrometallurgy 48 (1), 83–90.
- Sato, T., Sato, K., 1990. Liquid-liquid extraction of rhenium (VII) from hydrochloric acid solutions by neutral organophosphorus compounds and high molecular weight amines. Hydrometallurgy 25 (3), 281–291.
- Schrötterová, D., Nekovář, P., 2006. Extraction of Re(VII) by neutral and basic extractants. Chem. Pap. 60 (6).
- Shan, W.-J., Cheng, P., Li, J., Xiong, Y., Fang, D.-W., Zang, S.-L., 2015. Solvent extraction of perrhenate from sulfuric acid medium by trioctylamine. J. Chem. Eng. Data 60 (10), 2843–2847.
- Srivastava, R.R., Kim, M.-S., Lee, J.-C., Ilyas, S., 2015a. Liquid-liquid extraction of rhenium(VII) from an acidic chloride solution using Cyanex 923. Hydrometallurgy 157, 33–38.
- Srivastava, R.R., Lee, J.-C., Kim, M.-S., 2015b. Complexation chemistry in liquid-liquid extraction of rhenium. J. Chem. Technol. Biotechnol. 90 (10), 1752–1764.
- Srivastava, R.R., Kim, M.-S., Lee, J.-C., 2016. Novel aqueous processing of the reverted turbine-blade superalloy for rhenium recovery. Ind. Eng. Chem. Res. 55 (29), 8191–8199.
- Truong, H.T., Lee, M.S., 2017. Separation of rhenium (VII), molybdenum (VI), and vanadium (V) from hydrochloric acid solution by solvent extraction with TBP. Geosyst. Eng. 1–7.
- Truong, H.T., Nguyen, T.H., Lee, M.S., 2017. Separation of molybdenum (VI), rhenium (VII), tungsten (VI), and vanadium (V) by solvent extraction. Hydrometallurgy 171, 298–305.
- Tytko, K.-H., Gras, D., 1988. Mo Molybdenum: Oxomolybdenum Species in Aqueous Solutions (Continued) Oxomolybdenum Species in Nonaqueous Solvents Oxomolybdenum Species in Melts Peroxomolybdenum Species. Mo. Molybdän. Molybdenum (System-Nr. 53). Springer-Verlag Berlin Heidelberg.
- Virolainen, S., Laatikainen, M., Sainio, T., 2015. Ion exchange recovery of rhenium from industrially relevant sulfate solutions: single column separations and modeling. Hydrometallurgy 158, 74–82.
- Zhang, B., Liu, H.-Z., Wang, W., Gao, Z.-G., Cao, Y.-H., 2017. Recovery of rhenium from copper leach solutions using ion exchange with weak base resins. Hydrometallurgy 173, 50–56.