

# Selective recovery of nickel and cobalt from cobalt-enriched Ni–Cu matte by two-stage counter-current leaching

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## Abstract

This work presents investigations on the selective recovery of Ni and Co from Ni–Cu matte by two-stage counter-current leaching. The investigations indicated that the sulphuric acid used during leaching can be fully replaced by sulphur. The leaching behavior of nickel and cobalt were determined and the influences of temperature, the amount of sulphur and oxygen pressure on leaching process were also investigated. A pilot plant experiment was carried out to confirm the developed process. It is found that, under two leaching conditions: (1) *Ambient pressure leaching*: sulphur coefficient = 1.15,  $T = 85 \pm 5^\circ\text{C}$  and time = 2.5 h with a liquid to solid ratio of 5:1 (i.e.,  $L/S = 5:1$ ), and (2) *Elevated pressure leaching*:  $L/S = 5:1$ ,  $T = 150 \pm 5^\circ\text{C}$ , pressure = 1.45 MPa, air flowrate =  $1500 \pm 50 \text{ N m}^3/\text{h}$  and time = 6 h; the achieved recoveries of Ni and Co were >96.02%. The ratio of Cu/Ni is higher than 45 in the resulting residue, which is favorable for effective recovery Cu by simple  $\text{H}_2\text{SO}_4$  leaching followed by electrowinning step to obtain copper metal. Therefore, the leaching liquor can be used to recover Ni and Co after removal of iron and Cu can be extracted from the residue.

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**Keywords:** Ni–Cu matte; Sulphur; Counter-current leaching; Recovery; Nickel; Cobalt

## 1. Introduction

In general, primary nickel is extracted from either sulphide or oxide ores and cobalt is usually produced as byproduct. Although pyrometallurgical processes are an integral part of most flowsheets which outline primary nickel production, the processes for primary nickel production are diverse because of the variability of raw materials and end-use applications [1]. Due to increasing industrial activities, air pollution is increasingly becoming a serious environmental problem worldwide, especially in the developing countries like China. Most cities suffer from poor air quality, which has received increasing attention in the past decade [2]. Therefore, hydrometallurgical processes gradually gain an advantage for reducing the environmental impact of industrial activities and recovering valuable metals from ores and slag in recent years. These include leaching using

lixiviant such as acidic ferric sulphate, ammonium sulphate, ferric chloride, sulphuric acid and sulphurous acid/oxygen [3–10]. Among them, the  $\text{CuSO}_4\text{--H}_2\text{SO}_4\text{--O}_2$  pressure leaching technology has become the preferred choice for the treatment of Ni–Cu matte and allowed the extraction of Ni, Cu and Co in a number of metallurgical plants [11–15]. More recently, chloride media such as  $\text{CuCl}_2$  and  $\text{FeCl}_3$  have been used for leaching of a synthetically prepared Cu–Ni–Co–Fe matte, due to some advantages of chloride based system over sulphate based leaching [16,17]. On the other hand, the chemistry of the sulphide minerals present in the Ni–Cu matte is extremely complex which stimulates many research groups worldwide to investigate the fundamental mechanisms in the pressure leaching system under different reaction conditions [12–14].

The Jinchuan ore deposit is the largest nickel and cobalt mineral resource in China, where cobalt enriched Ni–Cu matte, produced from nickel sulphide concentrate treated by converter roasting followed water quenching, consists principally of synthesized nickel and copper sulphide minerals and minor quantity of alloys. Since 1985, pressure leaching technology has been

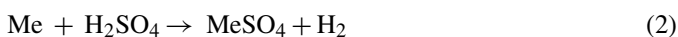
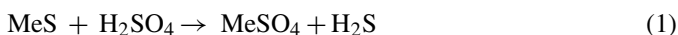
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Table 1  
Initial chemical composition of Co enriched Ni–Cu matte

	Constituent									
	Ni	Co	Cu	Fe	Mn	Zn	Pb	CaO	MgO	S
Amount (%)	38.20	2.11	18.59	14.76	0.02	0.03	<0.01	0.03	0.06	26.14

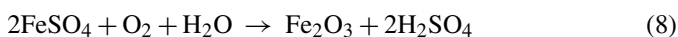
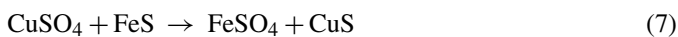
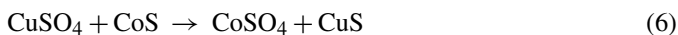
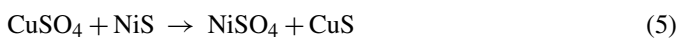
put into practice in Jinchuan refinery to extract Ni, Co and Cu from Co enriched Ni–Cu matte. However, some difficulties were incurred in production using sulphuric acid as lixiviant. First, the autoclave suffered corrosion in spite of it lined with acid-resistant ceramic tile. Second, the emission of H<sub>2</sub>S during leaching, when released into the environment, can be harmful to humans, animals and plants.

In industry production of Jinchuan refinery, sulphuric acid used as leachant in pressure leaching, the matte was mixed with H<sub>2</sub>SO<sub>4</sub> using a stoichiometric ratio of 5:6 in a slurry tank and stirred for 1.5 h and then the resulting pulp was heated up to 95 ± 5 °C. It was found the content of H<sub>2</sub>S in per tonne slurry was about 52 mg and that was hazardous for the environment though some of which were used up during leaching. Besides, hydrogen gas, which is harmful gas for the subsequent leaching, was also formed for the following reactions took place during the process:



where Me presents Ni, Co and Fe. Rademan et al. [12] stated that the detected H<sub>2</sub>S in the tests was due to the very low cupric ion concentration in solution and the reaction between H<sub>2</sub>S and Cu<sup>2+</sup> could not proceed to consume the produced H<sub>2</sub>S.

The heated pulp was added into autoclave with a capacity of 48 M<sup>3</sup> and the valuable metals such as Ni, Co and Cu, as well as their respective sulphide could be transformed into sulphate in the existence of oxygen and sulphuric acid under a pressure of 1.45 MPa. The process can be described using Eqs. (3)–(8):



here Me presents elements Ni, Co, Cu and Fe. The above reactions clearly indicate that nickel, cobalt and copper can be leached out to form respective sulphate while iron is continually precipitated and redissolved in the leaching process and acts as an electron carrier from sulphide phase to the dissolved oxygen (Eqs. (4), (7) and (8)), i.e., iron remains in residue after leaching operation.

Accordingly, the leaching procedure was conducted at an L/S ratio of 6:1 with air flowrate of 1500 ± 50 N m<sup>3</sup>/h at pressure

1.45 MPa and a temperature of 150 ± 5 °C for 6 h. Under these conditions, the compositions of the resultant leach liquor, data from production for a continual two weeks, were found to be in a range of, in g/L, 55.39–64.27 Ni, 3.53–4.72 Co, 27.35–30.42 Cu and 1.14–1.59 Fe with pH value of 1.03–2.51, and those of residue were (wt.%): 4.27–5.61 Ni, 0.18–0.39 Co, 2.65–6.82 Cu and 44.87–56.39 Fe. In comparison with the chemical composition of Ni–Cu matte (shown in Table 1), about 96% of Ni, 96% of Co and 90% of Cu could be extracted from the matte.

The main objective of this paper is present a process for selective recovery nickel and cobalt from cobalt enriched Ni–Cu matte by counter-current leaching, and the effect of the amount of sulphur as well as oxygen pressure on the leaching results are also explored.

## 2. Experimental

### 2.1. Laboratory experiments

At ambient pressure, the effect of temperature was tested in the range of 25–100 °C. The temperature tests were carried out in a reactor consisted of a four-necked 5 L round-bottom glass flask in a thermostated bath. The reactor was equipped with an overhead stirrer driven by a variable speed motor, water-cooled condenser, sample outlet and thermometer. The reactor was charged with 3 L of solution which was collected from pressure leaching, the 600 g Ni–Cu matte and a measured amount of sulphur (typically 64 g) and then heated. The sulphur used was produced from Jinchuan refinery of which the chemical compositions were found to be (wt.%): S ≥ 99.62%, H<sub>2</sub>O ≤ 0.29% and organic phase ≤ 0.03%. The agitation speed was maintained at 500 rpm, which was enough to suspend the mixture of matte and sulphur particles during the leaching process. The duration time for each leaching test was maintained for 2.5 h for the final pH 1.50–2.50 and then the mixture was filtered. The filtrate was washed and oven-dried at 70 °C. The samples collected from solid and leach liquor were respectively analyzed for Ni, Co, Cu and Fe.

Elevated pressure leaching experiments were performed in a 10 L vertical titanium autoclave consisting of a reactor chamber and a head assembly, both of which could be combined and tightened with a leak-proof closure, with provisions for gas inlet/outlet, sampling and agitation. The autoclave was directly connected to an oxygen cylinder in order to pressurize it to the required oxygen pressure conveniently. The residue of ambient pressure leaching and water were mixed with an L/S ratio of 5:1 and then placed in titanium container. Before tightened, the stainless screws were wrapped with Teflon tape to avoid corrosion. The contents were heated to the desired temperature while

the agitation rate was maintained at 500 rpm and then the reaction time was counted once the oxygen pressure was adjusted to the desired value. The more detailed operation procedure can be found in Ref. [18].

## 2.2. Pilot plant tests

Ambient pressure leaching was conducted in a 1 M<sup>3</sup> ceramic-tile lined reactor equipped with stirrer and thermocouple, and the temperature was controlled at  $85 \pm 5^\circ\text{C}$  by an external temperature controller. In each experiment, the matte with an average particle size of 43  $\mu\text{m}$  and sulphur ( $d = 74 \mu\text{m}$ ) were mixed with solution from pressure leaching at L/S ratio of 5:1 and then added into the reactor, and the leaching process lasted for 2.5 h. Elevated pressure leaching operations were carried out in a pressure leaching system, which was made in Japan and consisted of a horizontal autoclave, a measurable force pump, a bundle of tubular heaters, a decompression chamber and a series of computer control system, with a design operating volume of 34 M<sup>3</sup>. The residue of ambient pressure leaching (typically 3000 kg) was pulped with L/S ratio of 5:1 and then added into autoclave. The total pressure in autoclave was 1.45 MPa with an air flowrate of  $1500 \pm 50 \text{ N m}^3/\text{h}$ . The reaction mixture was collected by a pipe attached to sampling tube at regular time intervals of 2 h. The solution and residue samples were respectively analyzed for Ni, Co, Cu, and Fe while the acidity of the filtrate samples was determined by titration of diluted filtrate using sodium hydroxide and a mixed 50:50 neutral red/bromothymol blue indicator, together with a PHS-3B digital acidity meter used to check the endpoint pH value. The slurry was kept in the autoclave for 6 h at a temperature of  $150 \pm 5^\circ\text{C}$  and then the resulting mixture was filtered.

The analysis of phase of matte and residue was conducted by X-ray diffraction. The content of ions in the aqueous phases was detected with the Perkin-Elmer Model 800 Atomic Absorption Spectroscopy (AAS). Qualitative XRD measurements of the mattes and some typical leach residues were carried out on a Rigaku D/max 2400 X-rays diffractometer with Cu K $\alpha$  radiation. X-ray wave-lengths  $\lambda_{\text{K}\alpha 1} = 1.54056 \text{ \AA}$  and  $\lambda_{\text{K}\alpha 2} = 1.54439 \text{ \AA}$  were selected by using a graphite monochromator with a scanning speed of  $2^\circ(2\theta)/\text{min}$  in the range  $6\text{--}70^\circ$ . The XRD peaks were matched with powder diffraction file data to identify the various minerals phases. Thereafter, the morphology of matte was further characterized by means of optical microscopy (Leica DFC280) analyses.

## 3. Results and discussion

### 3.1. Mineralogy of Co enrichment Ni–Cu matte

The X-ray diffraction pattern of matte is shown in Fig. 1(a). It is found that nickel in the matte is present predominantly as nickel-pyrite  $\text{NiFeS}_2$  (5%) and pentlandite  $(\text{Ni,Fe})_9\text{S}_8$  (11%) as well as heazlewoodite  $\text{Ni}_3\text{S}_2$  (39%), and copper occurs originally in the form of chalcocite  $\text{Cu}_2\text{S}$  (18%) and chalcopyrite  $\text{CuFeS}_2$  (10%) while cobalt is entrained in the pentlandite and as alloy phase (i.e.,  $\text{CuFeNi}_{8-10}$ , 7%) in the matte. The rem-

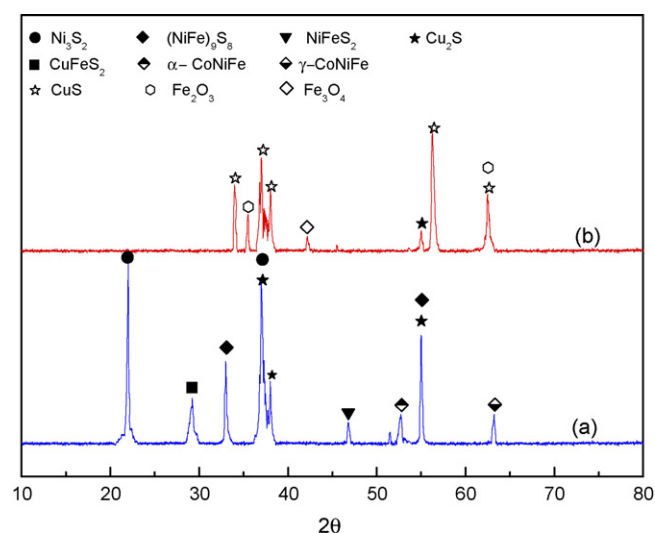


Fig. 1. X-ray diffraction patterns for Co enriched Ni–Cu matte (a) and the residue of elevated pressure leaching (b).

Table 2

Phase percentage of each primary element in Co enriched Ni–Cu matte

	Constituent			
	Ni	Co	Cu	Fe
Sulphide phase (%)	92	95	97	62
Oxide phase (%)	1	3	2	32
Metal and alloy phase (%)	7	2	1	6

nant was balanced by metal oxides and a chemical composition of matte is presented in Table 1, while the phase ratio of each primary element distribution is listed in Table 2. A clear morphology of the matte has been provided by optical microscopy observation (Fig. 2). As indicated by Fig. 2, the azury chalcocite  $\text{Cu}_2\text{S}$  and the white chalcopyrite  $\text{CuFeS}_2$  are deposited on the rims of the heazlewoodite  $\text{Ni}_3\text{S}_2$  matrix, and a number of small alloy particles intersperse among the matrix. Meanwhile, it is also interesting to notice that a few lattice like structures

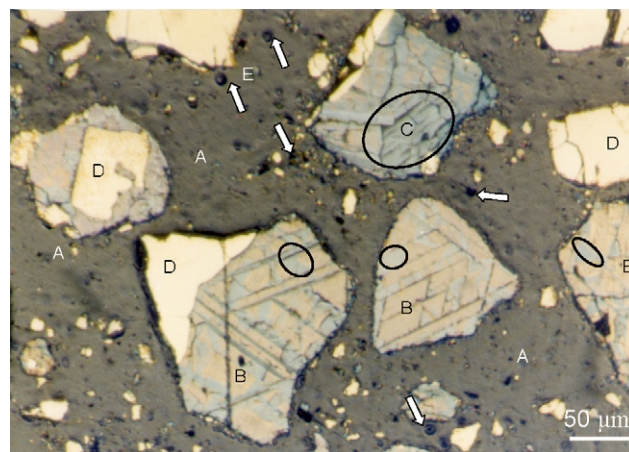
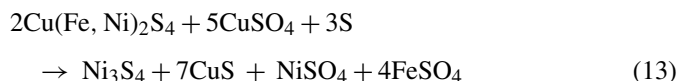
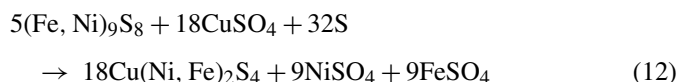
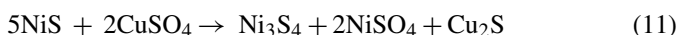
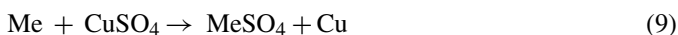


Fig. 2. Optical micrograph of Co enriched Ni–Cu matte. (A)  $\text{Ni}_3\text{S}_2$  matrix; (B)  $(\text{Ni,Fe})_9\text{S}_8$ ; (C)  $\text{Cu}_2\text{S}$  (indicated by ellipses); (D)  $\text{CuFeS}_2$ ; and (E) alloys (indicated by arrows).

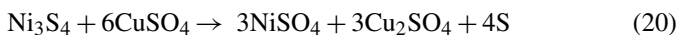
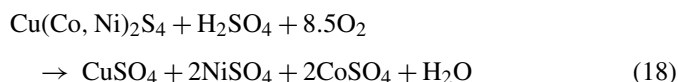
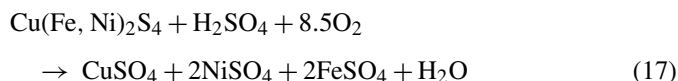
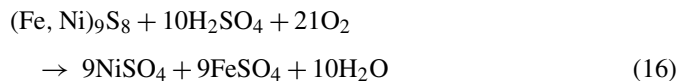
have been formed for the coexistence of the canary pentlandite  $(\text{Ni,Fe})_9\text{S}_8$  and the azury chalcocite  $\text{Cu}_2\text{S}$ .

### 3.2. Chemical reactions in two-stage counter-current leaching

In a series of pilot plant experiments, sulphur replaced sulphuric acid as leachant to avoid equipments from corrosion. The two-stage counter-current leaching technique, in which sulphur and Ni–Cu matte were contacted with the leach liquor resulted from elevated pressure leach process to remove Cu from the solution while the resulting residue was returned to the pressure leach process, was used to selectively extract Ni and Co from Ni–Cu matte. In two-stage counter-current oxidative leaching of Ni–Cu matte, nickel and cobalt are dissolved in the first stage (ambient pressure leach at room temperature) via metathesis or oxidation. The chemistry of the leaching process can be summarized as follows (Me representing Ni, Co and Fe in Eq. (9)):



No copper is leached from the residue in this stage. On the contrary, the copper in solution is precipitated by replacing the nickel in the residue and cemented out as copper sulphides. In the initial process of the second-stage leach, under elevated pressure and temperature, sulphur is oxidized to form sulphuric acid, and then the nickel remained in the partially leached residue of the first stage is further dissolved by metathesis and oxidation according to the following equations in addition to Eqs. (1)–(3) as well as Eqs. (4)–(7):



In the process of pressure leaching, sulphur can be oxidized to form sulphuric acid according to Eq. (15) as the mixture is heated up to  $150 \pm 5^\circ\text{C}$ , accompanied by a proper oxygen potential with increasing pressure in the interior of autoclave. Thereafter, the copper in the residue resulted from the first leach stage is leached out of the solids by the produced sulphuric acid. With increasing copper content in solution, the chemical driving force for the cementation of copper with nickel sulphide is increased. Thus, copper in the solution is preferably cemented and at the same time nickel and cobalt are leached out of the solids. Iron dissolved into the solution is continually precipitated in the form of hematite according to Eq. (8). It is believed that the processes have significant impact performance of the leaching in terms of the acid consumed and then released via reactions involving Fe in various oxidation states in both solid and aqueous phases, i.e., Fe has a catalytic effect on the leaching of Ni and Co in this system [12,14,15].

### 3.3. Effect of temperature

To determine the effect of temperature on extraction rate of metals, leaching experiments were conducted by varying temperatures from  $50$  to  $90^\circ\text{C}$  under the ambient pressure. The results indicate that the leaching temperature does significantly affect the precipitation rate of Cu, although it has little effect on the extraction of Ni and Co. For instance, the  $\text{Cu}^{2+}$  concentration is  $2.71\text{ g/L}$  in leach liquor at a temperature of  $50^\circ\text{C}$ , but it decreases to only  $0.02\text{ g/L}$  at  $90^\circ\text{C}$  (Fig. 3). However, in comparison with the evident variation of cupric concentration, the extraction rate of Ni and Fe only increased slightly, from  $12\%$  to  $31\%$  and  $9\%$  to  $26\%$ , respectively, with the same temperature variation. In contrast, no obvious variation is detected for Co concentration in solution before and after each leaching test as leaching temperature increases. Therefore, the preferable temperature is  $85 \pm 5^\circ\text{C}$  in order to obtain a high ratio

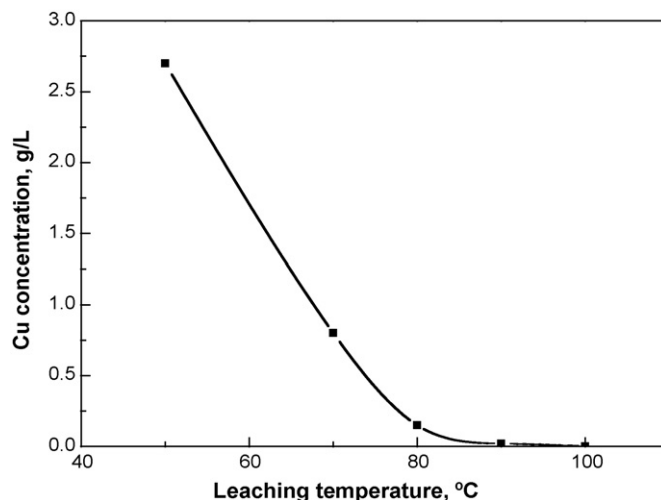


Fig. 3. Effect of temperature on cupric concentration in the leach liquor.



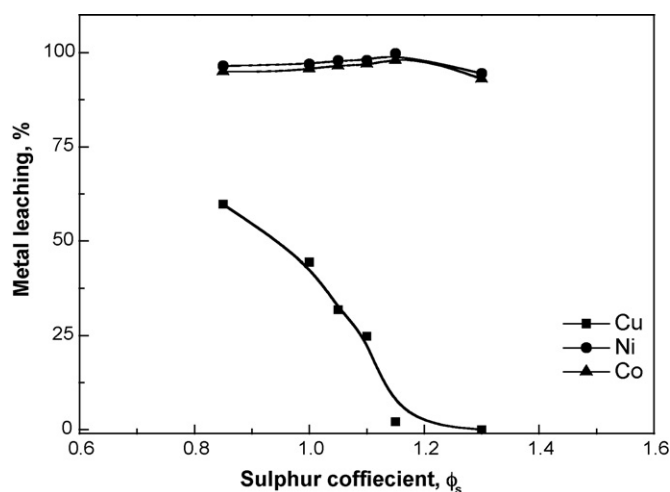


Fig. 4. Effect of the amount of sulphur on metals extraction.

of Ni/Cu in leach liquor and hence a high ratio of Cu/Ni in residue.

### 3.4. Effect of amounts of sulphur addition

The sulphur was added to alleviate the corrosion of equipment by sulphuric acid during leaching. The amount of the sulphur added is represented by sulphur coefficient,  $\phi_s$ , which is a ratio of the amount of sulphur added in experiment to that needed by calculation in order to achieve a total transformation for metal sulphides to respective sulphates. At a temperature of  $150 \pm 5^\circ\text{C}$  and oxygen pressure of 100 kPa, the effect of sulphur was investigated. It can be seen from Fig. 4 that the sulphur coefficient has a remarkable influence on the cupric content of the final leach liquor, as well as the Ni and Co recovery in total. As shown in Fig. 4, the leaching percentage of Cu decreases gradually with an increasing sulphur coefficient, reaching 0.64% at  $\phi_s = 1.27$ , whereas the Ni and Co recoveries present a reverse trend with the variation of  $\phi_s$  within 0.85–1.15. The final extraction rates can be as high as 99.36% and 98.61% for Ni and Co, respectively, with  $\phi_s = 1.15$ ; then the extraction rates slightly decreases with the further increasing  $\phi_s$ .

It is well known that an increasing reactants concentration facilitates the forward reaction. With existence of sulphur, as described above, the formation of sulphuric acid can be favored by increasing temperature and oxygen potential in the process of leaching (Eq. (15)). The resulting acid will be continuously consumed by metal oxides and their salts. Once this process is halted, the forward reaction of Eq. (15) will be arrested with an increasing sulphuric acid concentration. In the end of leach process, the dominate reactions will be the metathesis reactions between nickel sulphides and cupric or cuprous cation. Consequently, the corrosion of equipment by acid can be suppressed and the formation of  $\text{H}_2$  and  $\text{H}_2\text{S}$ , which occur under a relatively low oxygen potential, is also effectively restrained.

On the other hand, it is also noticed that the Ni and Co recoveries decrease at higher S coefficient of  $>1.15$ . This may be due to the fact that a superfluous amount of S suppressed the reaction indicated by Eq. (20), which restrained the leach out of Ni from

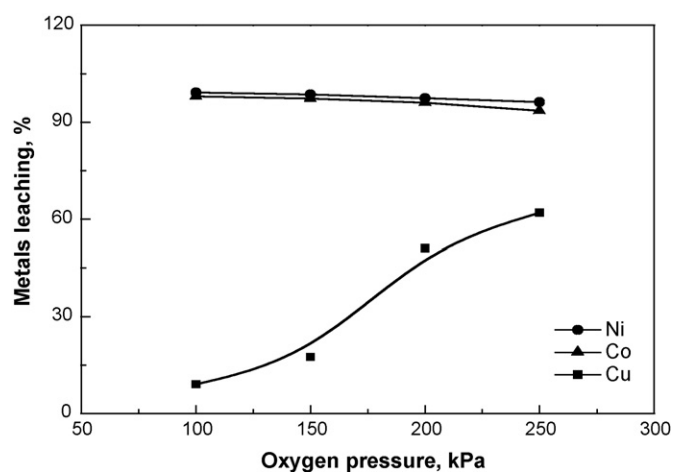


Fig. 5. Effect of oxygen pressure on metals extraction.

the matte and also favored the transformation of  $\text{Cu}^+$  into  $\text{Cu}^{2+}$ . Thus, the decreasing Ni and Co recoveries were resulted in (Eq. (18)).

### 3.5. Effect of oxygen pressure

In order to determine the effect of oxygen pressure on removal of copper, further leaching experiments were carried out at  $\phi_s = 1.15$  and  $150 \pm 5^\circ\text{C}$  for 2.5 h. The results are shown in Fig. 5. One can see from Fig. 5 that the extraction percentages of both Co and Ni are higher than 96.02%, and decrease slightly with increasing oxygen pressure within the range of 100–250 kPa, whereas that of Cu is significantly lower and increases from 8% to 62% in the same range of oxygen pressure. It can be inferred that the preferable conditions for high Ni and Co extractions were: temperature  $150 \pm 5^\circ\text{C}$ ,  $\phi_s = 1.15$ , oxygen pressure 100 kPa and time 2.5 h.

### 3.6. Results of two-stage counter-current leaching

In the pilot experiment, the compressed air was used to replace the oxygen and it was found that oxygen efficiency was only 39% with an air flowrate of  $1500 \pm 50 \text{ N m}^3/\text{h}$  at 1.45 MPa. Therefore, the leach time was adjusted to 6 h to maintain a leach rate the same as that obtained with oxygen. However, the prolonged leaching time may retard the industrial applicability of the process. Consequently, an investigation on improving oxygen efficiency must be further carried out. By two-stage counter-current leaching, leaching of nickel matte for selective extraction of nickel is operated under controlled oxidation conditions to ensure that the leach liquor is copper-free. The results show that the majority of original copper present in the matte remains intact through the selective oxidative leaching. The operation conditions can be summarized as follows:

*Ambient pressure leaching:*  $\text{L/S} = 5:1$ ;  $\phi_s = 1.15$ ;  $T = 85 \pm 5^\circ\text{C}$ ; stirring speed = 500 rpm and time = 2.5 h.

Table 3

Pilot plant production results of two stages counter-current leaching process for the recovery Ni and Co from the Co enriched Ni–Cu matte

No.	Leach liquor (g/L)					Residue (%)						Recovery (%)	
	Ni	Co	Cu	Fe	pH	Ni	Co	Cu	Fe	S	Cu/Ni	Ni	Co
1	74.49	4.14	0.07	7.41	2.53	0.83	0.06	38.82	22.67	19.42	47	97.48	98.61
2	75.94	4.12	<0.01	11.08	1.48	0.58	0.08	46.49	23.61	20.79	80	99.36	98.14
3	75.64	4.10	<0.01	8.19	2.02	0.69	0.09	46.07	24.43	23.31	67	99.03	97.59
4	74.26	4.05	0.02	9.17	1.51	0.86	0.12	42.41	16.98	23.83	49	97.15	96.46
5	73.35	4.02	<0.01	8.62	1.49	0.98	0.14	44.06	16.84	24.89	45	96.27	96.02

The leaching conditions are as follows: (1) *Ambient pressure leaching*: L/S = 5:1;  $\phi_s = 1.15$ ;  $T = 85 \pm 5^\circ\text{C}$ ; stirring speed = 500 rpm and time = 2.5 h. (2) *Elevated pressure leaching*: L/S = 5:1;  $T = 150 \pm 5^\circ\text{C}$ ; stirring speed = 500 rpm; pressure = 1.45 MPa; air flowrate =  $1500 \pm 50 \text{ N m}^3/\text{h}$  and time = 6 h.

*Elevated pressure leaching*: L/S = 5:1;  $T = 150 \pm 5^\circ\text{C}$ ; stirring speed = 500 rpm; pressure = 1.45 MPa; air flowrate =  $1500 \pm 50 \text{ N m}^3/\text{h}$  and time = 6 h.

Under above conditions, the typical results from continual 2 weeks pilot plant production are presented in Table 3. It can be seen that Ni and Co extractions are higher than 96.02% and the contents of copper in solutions are less than 0.07 g/L, while the iron concentrations are unfavorably high as 7.41 to 11.08 g/L under the present leaching conditions. Therefore, the further purification for removal of iron must be operated using jarosite or hematite before separation of Ni and Co. Elimination of iron was carried out by heating the solution up to  $90^\circ\text{C}$  with air agitation for 2 h. It is essential to use sodium carbonate solution as neutralizer adjusting pH 1.95–3.05 and sodium chlorate as oxidizer so that the separation of iron from nickel and cobalt is possible. It is noticed that hydrolysis of iron yields jarosite and an increased pH value results in decreased iron concentrations, which is consistent with results obtained by Whittington et al. [19].

The resulting solution contained, in g/L, 75.92 Ni, 4.11 Co, 0.01 Cu and 0.01 Fe with pH 2.98, and the compositions of residue were (wt.%): 30.67%Fe, 0.01% Ni and <0.01% Co. Thus, the solution obtained can be used to recover Ni and Co by solvent extraction process.

At the same time, it can be found from Table 3 that the contents of Ni and Cu are about  $\leq 0.98\%$ , and  $\geq 38.82\%$  in residues, respectively, with a ratio of Cu/Ni higher than 45, which is favorable for the effective recovery of copper.

The XRD analysis indicates that the residue of ambient pressure leaching consists of covellite CuS, heazlewoodite  $\text{Ni}_3\text{S}_2$ , pentlandite  $(\text{Ni,Fe})_9\text{S}_8$ , magnetite  $\text{Fe}_3\text{O}_4$  and intermediate  $\text{Cu}(\text{NiFe})_2\text{S}_4$  as well as  $\text{Cu}(\text{NiCo})_2\text{S}_4$ , while the residue of elevated pressure leaching (Fig. 1(b)) mainly consists of covellite CuS (62%) and hematite  $\text{Fe}_2\text{O}_3$  (30%), as well as a few of chalcocite  $\text{Cu}_2\text{S}$  (4%) and magnetite  $\text{Fe}_3\text{O}_4$  (3%).

The complete process flow sheet for the selective leaching of Ni and Co from Ni–Cu matte is illustrated in Fig. 6, from which material balance, technique parameters and the

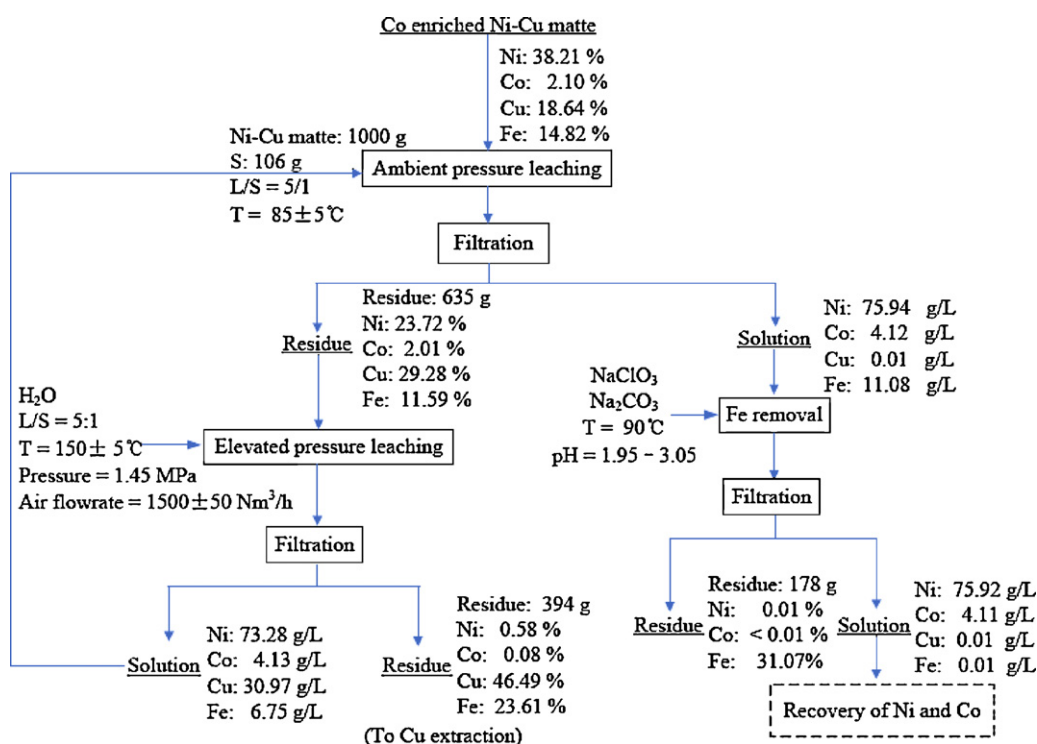


Fig. 6. Flowsheet of the process for the recovery of nickel and cobalt from the Ni–Cu matte using two-stage counter-current leaching.

corresponding chemical compositions can also be seen in detail.

#### 4. Conclusions

Selective leaching process was developed for the extraction of nickel and cobalt from cobalt-rich Ni–Cu matte. Investigations indicate that sulphur can be used to fully replace sulphuric acid during leaching in the industry production. The leaching behaviors of Ni and Co were studied. Several critical factors, such as the amount of sulphur, temperature and oxygen, were investigated in order to optimize the leaching conditions. Consequently, a two-stage counter-current leaching process was developed and carried out in a pilot plant for recovery Ni and Co from the cobalt enriched Ni–Cu matte. The results indicate that both the extraction percentages of Ni and Co are more than 96.02%, and the copper can remain successfully in the residue under proper leaching conditions, resulting in a Cu/Ni ratio in the residue higher than 45. Thus, the leaching liquor, after removal of iron, can be used to recover Ni and Co, and copper can be effectively extracted from the residue.

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