Kinetics of simultaneous recovering of Au and Ag from CTs by chloridizing volatilization methods

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Abstract: Cyanide Tailings (CTs) are known as hazardous resources that accumulate hundreds of millions of tons, threatening the ecological environment. This work proposes an eco-friendly and efficient way to recover gold and silver from CTs. The effects of calcium chloride dosage, silicon dioxide dosage, pellet moisture content, roasting temperature, and roasting time on Au and Ag chloridizing volatilization were studied. The kinetics of simultaneously recovering of gold and silver from cyanide Tailings by chlorination roasting was investigated. It was determined that the chloridizing volatilization rates increased with increasing calcium chloride dosage, temperature and decreasing silicon dioxide dosage, pellet moisture content. The chloridizing volatilization kinetics followed a shrinking core model, with inter-diffusion through gangue layer as the rate determining step. This finding is in accordance with the apparent activation energy (Ea) of 24.01 kJ·mol^{-1} (Au) and 24.62 kJ·mol^{-1} (Ag). The orders of reaction with respect to moisture content, temperature, calcium chloride dosage and silicon dioxide dosage were also achieved. The rate of reaction based on diffusion-controlled process can be expressed by semi-empirical equations. The control steps of the gold and silver recovery process were investigated by the kinetic study, which provided theoretical guidance for the optimization of the method.

Keywords: cyanide tailings, chloridizing volatilization, gold, silver, kinetics

1. Introduction

Gold and silver are indispensable metal resources for national economy. Gold reserve plays an important role in international relations, and is also a key gold group that is indispensable or absent for the rise of strategic new industries. How to develop gold and silver associated resources in a high efficiency is important for guaranteeing national strategic and financial security Meaning. Our silver source and storage is large, but the high-quality silver ore is less. Therefore, the previously difficult silver source, such as fine-grained silver ore, complex co-associated silver ore and secondary source comprehensive utilization, has gradually become an important source of silver (Huang et al., 2015; Qin et al., 2019; Chen et al., 2021).

Cyanide leaching is still the main method of gold extraction in gold smelting enterprises because of its advantages of mature technology and low cost (Sun et al., 2014;Li et al., 2016). Cyanide tailings produced by cyanide leaching technology contain considerable amount of gold, silver, iron, lead and other minor valuable constituents (Long et al., 2021). With the depletion of gold ores and rapid rising of the metal price, the processing of cyanide tailings as different secondary resource rather than waste for sustainable production because of the high metal content has become a more attractive route for sustainable production(Zhang et al., 2022). The gold and silver in cyanide tailings is usually encapsulated in refractory minerals in the form of micro or ultra microscopic inclusions, which is difficult to be effectively extracted(Wang et al., 2020). Up to now, many researchers have carried out a

lot of studies to treat the cyanide tailings for recovering gold as well as silver and iron. The mineral and metallurgy processes are operated (Liu et al., 2011; Huang et al., 2011; Wei et al., 2014; Sun et al., 2012; Wang et al., 2015; Zhang et al., 2015). They focus on the metallurgical technique especially, which can be either pyrometallurgical or hydrometallurgical routes. Scholars have carried out several studies on the recovery of gold and iron from cyanide tailings, mainly focusing on the recovery of gold and silver by reductive roasting-acid dissolution (Shang et al., 2011), and recovery of gold and iron by reduction roasting-acid leaching-cyanide leaching (Qin et al., 2020). However, it is difficult to deal with a large amount of acid waste liquid produced in the process.

Chlorination metallurgy technology has the characteristics of fast reaction speed, selective recovery and strong adaptability to ores (MUKHERJEE et al., 1983). It can chlorinate, separate, purify, reduce and refine valuable metals in cyanide tailings. The chlorination technology of cyanide tailings is usually divided into fire method and wet method, and fire method mainly refers to high temperature chlorination (Li et al., 2018). Due to the inert nature of precious metals, researchers generally believe that the active ingredient promoting chlorination of precious metals is Cl_2, which has strong oxygenation. Due to the toxicity and strong corrosion of gaseous Cl_2, NH_4Cl is highly decomposed at low temperature, NaCl is suitable for medium temperature roasting, while SO_2 and SiO_2 can promote the decomposition of solid chlorinated agents at low temperature (Chang et al., 2015). For chlorinated agents, solid $CaCl_2$ is usually used. Some researchers have studied the recovery of gold and silver from cyanide tailings by chlorination volatilization, and mainly investigated the influence of roasting temperature, roasting time and dosage of chlorination agent on the chlorination volatilization rates (Zhang et al., 2022). However, there are few reports on the influencing factors such as SiO_2 content and pellet water content. In this work, the factors (calcium chloride dosage, silicon dioxide dosage, pellet moisture content, roasting temperature, and roasting time) influencing the simultaneous recovery of gold and silver from cyanide tailings by chlorination roasting were systematically studied, the kinetics of chlorination roasting of cyanide tailings was studied in order to provide theoretical basis for further strengthening the extract of gold and silver in the process.

2.   Materials and methods

2.1. Materials

A gold smelting company (Shandong Province, China) provided representative samples of cyanide tailings. The samples were dried and sieved to obtain the necessary fraction prior to being used in this research. Before experiments, these samples were submitted for thorough analyses. Table 1 lists the chemical makeup determined by atomic absorption spectroscopy (AAS) and plasma atomic emission spectroscopy (ICP-AES), and Tables 2 and 3 display the chemical phase compositions of gold and silver. Fig. 1 displays the X-ray diffraction analysis (XRD) pattern. The cyanide tailings comprise 7.69 gram per ton(g/t) Au, 19.60 g/t Ag, 35.76 wt% Fe, 27.35 wt% SiO_2, and 5.38 wt% Al_2O_3, according to the ICP-AES and AAS analyses. Iron oxide (Fe_2O_3) and quartz (SiO_2) are the two main components, according to XRD analysis; gold metal and silver metal, which are present in trace amounts in the residues, do not exhibit any noticeable diffraction peaks. The Sinopharm Group Chemical Reagent Co., Ltd.'s chemically pure calcium chloride was chosen as the chlorination substance.
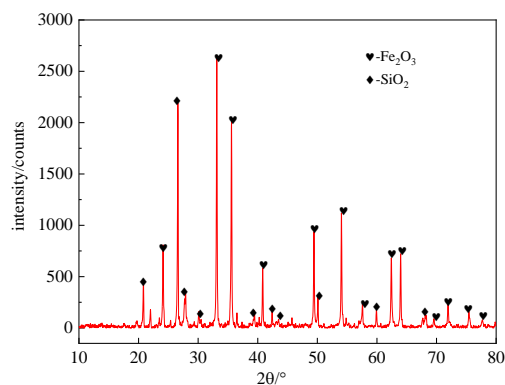

Fig. 1. Results of XRD analysis of cyanide tailings

Table 1. Results of main chemical composition analysis on cyanide tailings

Element	Au*	Ag*	Cu	Pb	Zn	Fe	S
Content (wt%)	7.69(g/t)	19.60(g/t)	0.11	0.14	0.13	35.76	0.54
Element	MgO	Al2O3	K_2O	Na_2O	P	CaO	SiO_2
Content (wt%)	0.81	5.42	1.87	1.36	0.53	2.97	27.35

Table 2. Mineral phase constitutes of gold

Components	Repartition of gold/ (g/t)	Distribution (%)
Bare	0.29	3.77
Gold enclosed by sulfide	0.56	7.28
Gold enclosed by iron oxide	6.01	78.16
Rests	0.83	10.79
Total	7.69	100.00

Table 3. Mineral phase constitutes of silver

Components	Repartition of silver / (g/t)	Distribution (%)
Bare	1.06	5.41
Silver enclosed by sulfide	1.14	5.82
Silver enclosed by iron Oxide	13.51	68.93
Rests	3.89	19.85

2.2. Experimental procedure

Cyanide tailings were evenly combined with calcium chloride in a weight ratio of test conditions. The mixture was shaped into 20 mm pellets using a pressure pellet machine. The pellets were then left to dry in a drying box (SC101-Y). In the tube furnace, cyanide residues were chlorinated and roasted (Fig. 2). A 10 °C/min heating rate was used to raise the tube furnace's temperature to the fixed level. For chlorination roasting, the pellets were loaded into a combustion boat fabricated from porcelain and put in the tube furnace. The hot ceramic combustion boat was allowed to cool to room temperature in the air after the roasting process. The preparation and analysis of the pellets were done for the presence of Au and Ag.
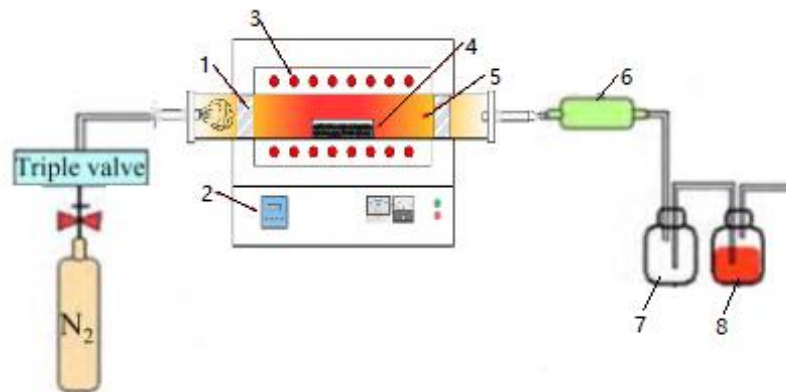

Fig. 2. Diagram of experimental device of chlorination roasting (1−Insulating brick; 2−Temperature control system; 3−Silicon molybdenum bar; 4−Sample and steel boat; 5−Tube furnace; 6−Condensing apparatus; 7−Safety bottle; 8−Offgas absorption bottle)

For gold, the high-temperature chlorination efficiency (ψ_{Au}) is expressed as:

$$\psi_{Au} = 100\% - \frac{\omega_{Au1}\xi_{Au1}}{\omega_{Au0}\xi_{Au0}} \times 100\% \tag{1}$$

where the grade of gold in roasted products is denoted by ξ_{Au1}, the mass of roasted products is given by ω_{Au1}, ξ_{Au0} is the grade of gold in cyanide tailings and ω_{Au0} stands for the mass of cyanide tailings.

For silver, the high-temperature chlorination efficiency (ψ_{Au}) is given by:
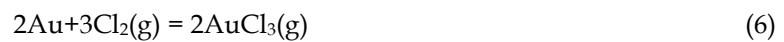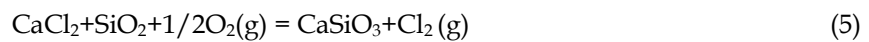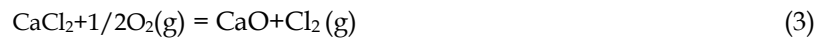
$$\psi_{Ag} = 100\% - \frac{\omega_{Ag1}\xi_{Ag1}}{\omega_{Ag0}\xi_{Ag0}} \times 100\% \qquad (2)$$

where ξ_{Ag0} and ξ_{Ag1} respectively denote the grade of gold in cyanide tailings and roasted products, ω_{Ag0} and ω_{Ag1} is mass of gold in cyanide tailings and roasted products respectively

3.   Results and discussion

3.1.   Chlorination roasting kinetics analysis

The chlorination roasting of the secondary residue after gold extraction with calcium chloride is a typical gas-solid heterogeneous reaction. The main chemical reactions that occur between residue and calcium chloride are (Sun et al., 2008):

$$CaCl_2 + 1/2O_2(g) = CaO + Cl_2(g) \qquad (3)$$
$$CaCl_2 + H_2O(g) = CaO + 2HCl(g) \qquad (4)$$
$$CaCl_2 + SiO_2 + 1/2O_2(g) = CaSiO_3 + Cl_2(g) \qquad (5)$$
$$2Au + 3Cl_2(g) = 2AuCl_3(g) \qquad (6)$$
$$2Ag + Cl_2(g) = 2AgCl(g) \qquad (7)$$

In the test, the reaction zone in the furnace of the tubular furnace is heated as a whole, the solid particles are mixed evenly, and the heating temperature gradient of the material is small, so it can be considered that the heating temperature of the solid particles is evenly distributed. Calcium chloride and cyanide tailings are uniformly mixed in the form of solid particles, so gold and silver solid particles are chlorinated layer by layer from the outside to the inside in the reaction process. First, the solid calcium chloride decomposes to generate chlorine to react with gold and silver. Then, after the exposed gold and silver are chlorinated, the chlorine is difficult to enter other minerals to react with gold and silver. At this time, the chlorine mainly passes through the product layer and enters the mineral particles for further chlorination reaction. The main steps are: (1) chlorine diffuses to the surface of gold and silver particles. (2) Chlorine reacts on the surface of gold and silver particles. (3) The gaseous reaction products diffuse from the surface of gold and silver to the gas phase. Due to the gradual shrinkage of reactant particles during chlorination roasting, the unreacted core shrinkage model can be used for treatment. According to the kinetic principle, the total reaction rate of gas-solid reaction is determined by the slowest link, which is called the control step of the reaction. Assuming that cyanide tailings is a dense solid particle with the same chemical activity everywhere on the surface. The chlorination reaction of Au and Ag will be controlled by one of diffusion and interface chemical reactions.

3.2. Effect of pellet moisture content

It can be seen from formula (3-2) that moisture content will promote the decomposition of calcium chloride and ultimately affect the chlorination volatilization rate of gold and silver. Under the condition that the amount of $CaCl_2$ was 8wt%, the drying time of the pellets was changed at 100 °C to make the water content of the pellets different. Then, the pellets with different moisture content were Chlorination roasted at 1000°C for 50 min to investigate the influence of moisture content of the pellets on the chlorination volatilization rate of gold and silver. The results are shown in Fig.3.

It can be seen from Fig. 3 that with the decrease of pellet water content, chlorination volatilization rate of gold and silver increases. When the moisture content of pellet is 1.09wt%, The chlorination volatilization rate of gold and silver is 89.15% and 63.19%, respectively, while when the moisture content of pellet is 16.39 wt%, the volatilization rate of gold and silver is only 72.35% and 40.76%, respectively. When the content of water in pellets is high, the water vapor in the gas phase increases, and the reacts with $CaCl_2 + H_2O(g) + SiO_2 = CaSiO_3 + 2HCl(g)$, promoting the rapid decomposition of $CaCl_2$ at low temperature, which is not conducive to the chlorination volatilization of gold and silver at high temperature. As a result, the volatilization rate of gold and silver is low when the moisture content is high. As can be seen from Table 4, the drying time of pellets increased by 60 min when the

moisture content decreased from 1.09 wt% to 0.53 wt%. Considering the economic problems, the drying time of pellets was determined to be 50 min.
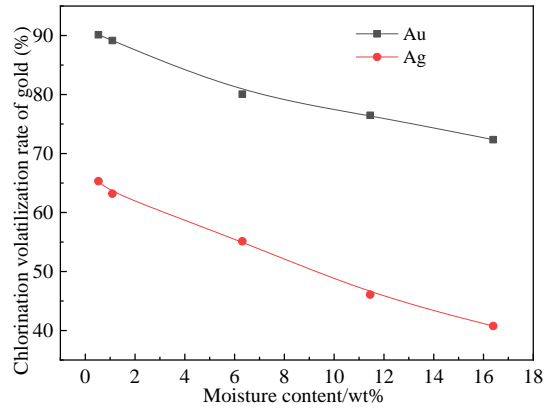

Fig. 3. Effect of moisture content on chlorination volatilization rate

The moisture content of CTs is expressed as:

$$Moisture\ content = \frac{M_{CT0} - M_{CTt}}{M_{CT0}} \times 100\% \tag{8}$$

where the mass of CTs in initial state by M_{CT0}, the mass of CTs after drying for different times by M_{CTt}.

Table 4. Effect of drying time on moisture content

Drying time(min)	0	10	30	50	120
Moisture content(wt%)	16.39	11.45	6.31	1.09	0.53

3.3. Effect of silicon dioxide dosage

The silicon dioxide dosage was varied in a range from 27.35 wt% to 35 wt% while keeping roasting temperature, roasting time, moisture content, and calcium chloride dosage at 1000 °C, 50 min, 1.09 wt%, and 8 wt%, respectively. Figs.4 illustrate the influence of silicon dioxide dosage on chlorination volatilization rate. It is indicated that increasing silicon dioxide dosage could inhibit the chlorination efficiency of gold and silver. The main reason is that the decomposition of $CaCl_2$ is promoted by SiO_2 in the raw material during chlorination roasting, and the reaction is $2CaCl_2+O_2(g)+2SiO_2=2CaSiO_3+2Cl_2(g)$.Therefore, the higher the content of SiO_2, the better the decomposition of $CaCl_2$, which will lead to the final high-temperature chlorination volatilization of $CaCl_2$ in the residue has been less, cannot meet the needs of further chlorination of gold and silver, thus, the volatilization rate of gold and silver is reduced (Xue et al., 2012; Zhang et al., 2007). Therefore, in order to ensure sufficient
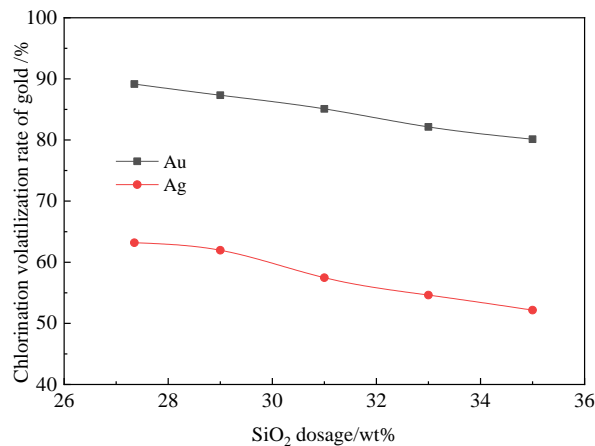

Fig. 4. Effect of calcium chloride dosage on the separation of gold-iron

chlorine gas in the process of high temperature chlorination of gold and silver, SiO_2 is not added alone during the test.

3.4. Effect of calcium chloride dosage

The calcium chloride dosage was varied in a range from 2 wt% to 8 wt% while keeping roasting temperature, roasting time, pellet moisture content, and silicon dioxide dosage at 1000 °C, 50 min, 1.09%, and 27.35 wt%, respectively. Figs. 5(a) and (b) illustrate the influence of calcium chloride dosage on chlorination volatilization rate. It is indicated that increasing calcium chloride dosage could promote high temperature chlorination of gold and silver. Excess calcium chloride is necessary to maintain higher volatilization rate and ensure sufficient reactions, yet the extra calcium chloride is not economical in industrial production practice. Therefore, to investigate the effects of other parameters, 8wt% was chosen.

When the diffusion through the gangue layer is rate controlling, the kinetics may be correlated graphically using the equation (Eq.7) (Li et al., 2008; Fouge et al., 2007):

$$k_1t=1-2/3x-(1-x)^{2/3} \tag{9}$$

When the reaction rate is controlled by chemical reaction, the following expression of shrinking core model can be used to describe the kinetics:

$$k_2t=1-(1-x)^{1/3} \tag{10}$$

where k_1, k_2=chemical rate constant (min^{-1}); t = time(min); x= fraction reaction of Au or Ag.

On the basis of the experimental data in Figs. 5 (a) and (b), the rate constants and their correlation coefficients are given in Tables 5 and 6 for the diffusion through the product layer and the chemical reaction controlled model. Also, Figs. 6 (a) and (c) show the data plots according to chemical reaction control process. Figs. 6 (b) and (d) show the data plots according to diffusion control process. The results in Tables 4 and 5 reveal that the values of the correlation coefficients for the diffusion through the product layer are closer to 1 than those of the chemical reaction controlled model. Therefore, Eq. (8) was found to fit the data best. Figs. 6 (b) and (d) show that, during the whole reaction time, the data are linear, and zero point intercepts are obtained. The linear relationship between $1-2/3x-(1-x)^{2/3}$ and roasting time is significant and indicates that the rates of chlorination volatilization reactions are controlled by diffusion through the gangue layer (Lei et al., 2022). The slope of these straight lines is
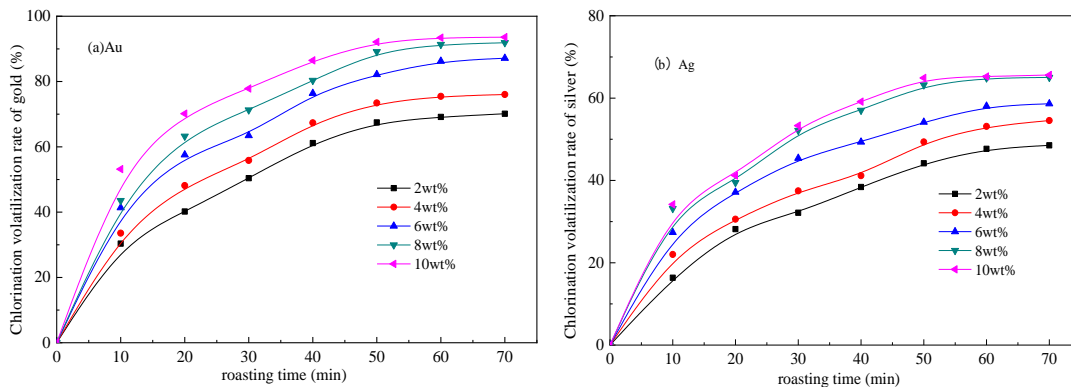

Fig. 5. Effect of calcium chloride dosage on chlorination volatilization rate

Table 5. Apparent rate constant and correlation coefficient values (R^2)

Reaction condition	Chemical reaction (Au)		Diffusion through the gangue layer (Au)	
	Ka/min^{-1}	R^2	Ka/min^{-1}	R^2
2	0.0046	0.913	0.0014	0.964
4	0.0052	0.905	0.0017	0.964
6	0.0068	0.931	0.0025	0.981
8	0.0080	0.931	0.0031	0.974
10	0.0082	0.888	0.0039	0.955

k1. Plots of lnk1 versus lnC$_0$ are shown in Figs. 6 (e) and (f). The reaction orders are calculated to be 0.6131 for Au and 0.3777 for Ag, which indicates that the dependency of Ag chlorination volatilization on calcium chloride dosage is less than that of Au. However, all the dependency is slight, as can be seen in Fig. 6, which indicates that a solid gangue layer forms and prevents the mobilization of Au and Ag from tailings.

Table 6. Apparent rate constant and correlation coefficient values (R^2)

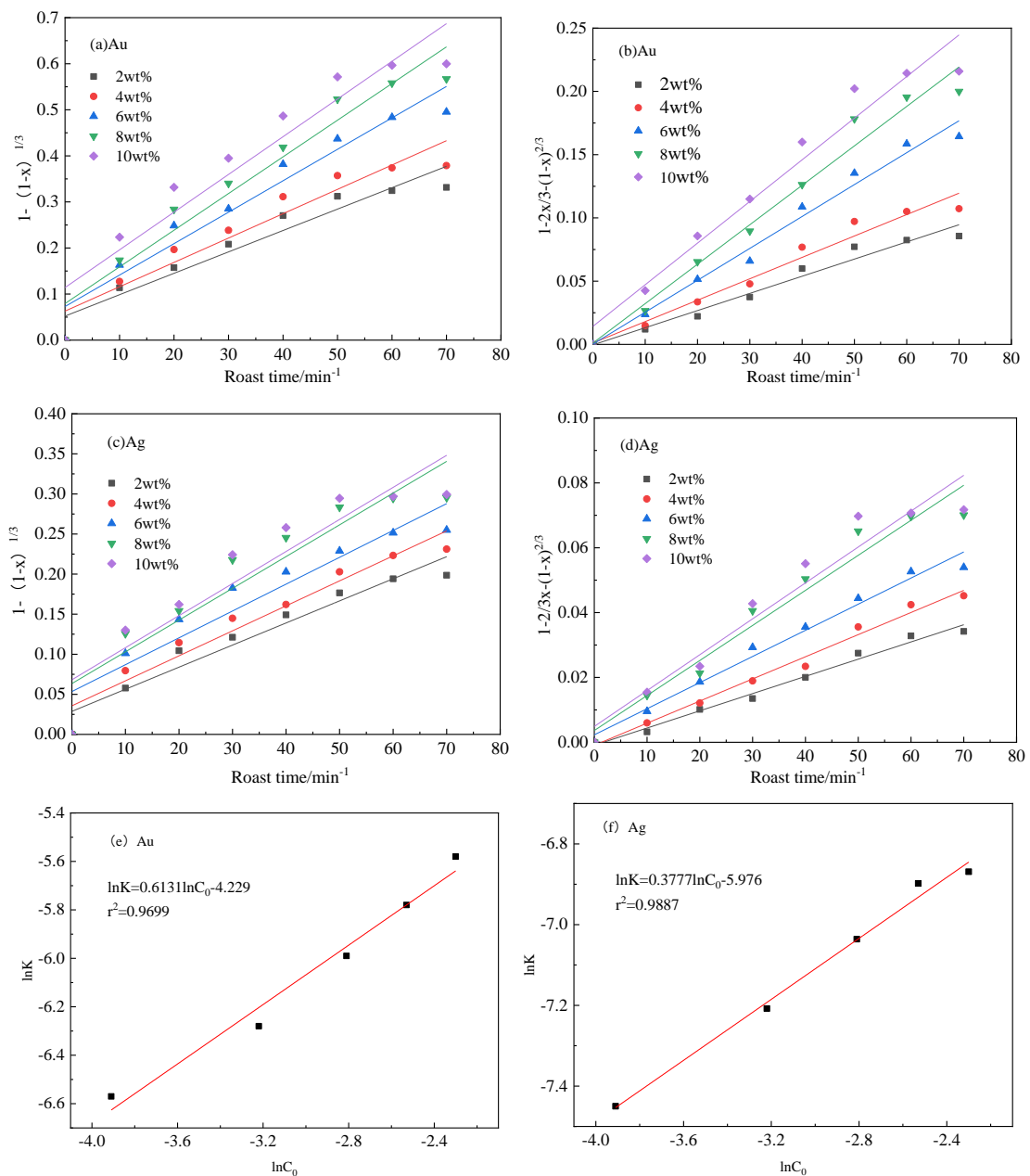| Reaction condition	Chemical reaction (Ag)		Diffusion through the gangue layer (Ag)	
	Ka/min^{-1}	R^2	Ka/min^{-1}	R^2
2	0.0028	0.939	0.00058	0.950
4	0.0031	0.940	0.00067	0.955
6	0.0034	0.890	0.00088	0.944
8	0.0040	0.879	0.00101	0.911
10	0.0040	0.863	0.00104	0.880

Fig. 6. Plots of kinetics at different chloride dosage(a),(b),(c) and (d) and plots of lnK$_1$ against lnC$_0$ (e) and (f)

3.5. Effect of roasting temperature

The roasting temperature was varied in a range from 700 °C to 1100 °C while keeping calcium chloride dosage, roasting time, pellet moisture content, and silicon dioxide dosage at 8 wt%, 50 min, 1.09 wt%, and 27.35 wt%, respectively. The results are presented in Figs.7 (a) and (b). The rate constants and their correlation coefficients are given in Tables 7 and 8 for the diffusion through the product layer and the chemical reaction controlled model. The plots against time are obtained by substituting the experimental data into Eq. (6) and given in Figs. 8 (b) and (d). The plots against time are obtained by substituting the experimental data into Eq. (7) and given in Figs. 8 (a) and (c). It can be seen in Figs. 7 (a) and (b) that the temperature has a noticeable influence on the extraction of Au and Ag. About 47.15% for gold and 69.12% for silver in the tailings are volatilized after 50 min at a roasting temperature of 700°C; at 1000 °C, the volatilization rate are 89.15% for gold and 63.19% for silver. The metal extraction increased with increasing the temperature, which is mainly because high temperature can increase the numbers of activated molecule and diffusion coefficient, the metal gasification can be improved. The experimental data in Fig.8 (b) and (d) are more approximately linear compared with Fig.8 (a) and (c), which also suggests that an inner diffusion-controlled model is suitable for this reaction process, as can be also seen from the value of correlation coefficient values in Tables 7 and 8.
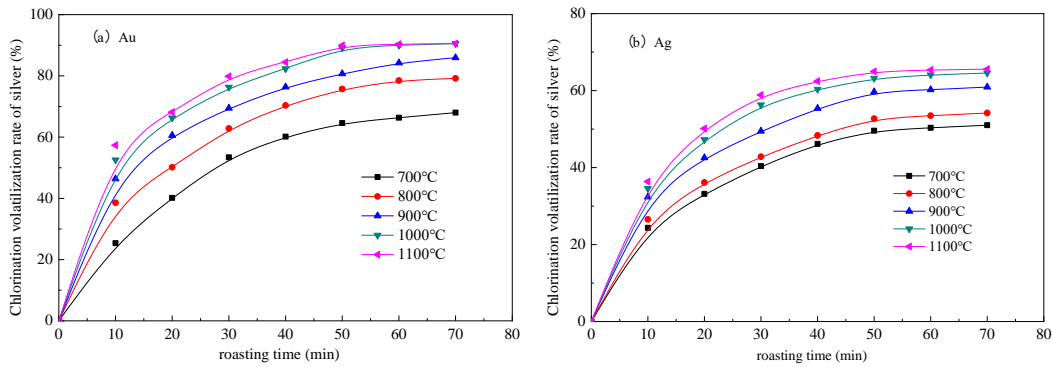

Fig. 7. Effect of roasting temperature on chlorination volatilization rate

Table 7. Apparent rate constant and correlation coefficient values (R^2)

Reaction condition	Chemical reaction (Au)		Diffusion through the gangue layer (Au)	
	Ka/min^{-1}	R^2	Ka/min^{-1}	R^2
700	0.0044	0.907	0.0012	0.966
800	0.0056	0.908	0.0019	0.974
900	0.0062	0.899	0.0023	0.983
1000	0.0073	0.888	0.0028	0.960
1100	0.0071	0.850	0.0029	0.943

Table 7. Apparent rate constant and correlation coefficient values (R^2)

Reaction condition	Chemical reaction (Ag)		Diffusion through the gangue layer (Ag)	
	Ka/min^{-1}	R^2	Ka/min^{-1}	R^2
700	0.0028	0.852	0.0005	0.986
800	0.0030	0.852	0.0007	0.987
900	0.0035	0.833	0.0008	0.984
1000	0.0037	0.800	0.0011	0.960
1100	0.0038	0.770	0.0012	0.945

3.6 Calculation of apparent activation energy

The activation energy (Sun et al., 2008) of an inner diffusion-controlled process is characterized to be 8-30 kJ·mol^{-1}, while for a chemically controlled process, it is usually greater than 40 kJ·mol^{-1}. The apparent activation energy was determined based on Arrhenius equation (Mohammad et al., 2009):

$$K = Ae^{\frac{-E_a}{RT}} \tag{11}$$

where: A is frequency factor (min⁻¹), E_a is apparent activation energy (kJ·mol⁻¹), R is ideal gas constant (8.314 J·mol·K⁻¹), T is roasting temperature (K).

To calculate the apparent activation energy, the values of lnk1 against 1000/T are plotted in Figs. 7 (e) and (f). The activation energy of the overall reaction is calculated to be about 24.01 kJ mol⁻¹ for Au and 24.62 kJ mol⁻¹ for Ag. The frequency factor (A) is calculated to be about 0.0261 for Au and 0.0106 for Ag. The energy values fall in the range of typical inner diffusion controlled process, which supports the conclusion that the chlorination roasting process is controlled by the mass transfer through the gangue product layer.

Calculations show that activation energy and the orders of reaction values with respect to Calcium chloride dosage and temperature confirm to the shrinking core model for a diffusion controlled process. K can be expressed as the following equation (Mohammad et al., 2009):

$$K = AC_1^\alpha \cdot C_2^\beta \cdot \exp\left(\frac{-E_a}{RT}\right) \tag{12}$$

where: C_i is dosage (wt%); α, β is reaction order of variable C_1, C_2 respectively.

Thus, the kinetic equation of Au and Ag can be presented by Eqs. (11) and (12):

$$1 - \frac{2}{3}x - (1-x)^{\frac{2}{3}} = 0.0261C^{0.6131} \exp\left(\frac{-24010}{RT}\right)t \tag{13}$$

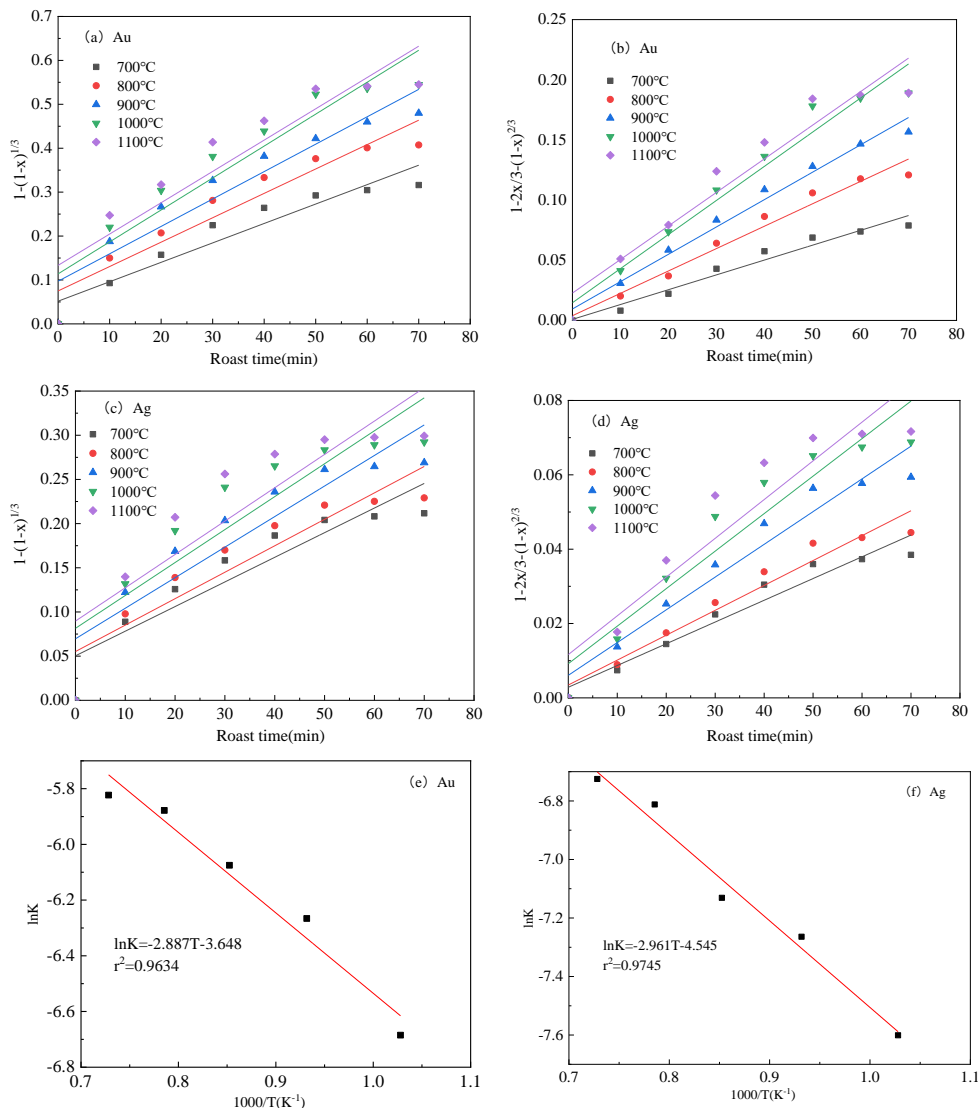$$1 - \frac{2}{3}x - (1-x)^{\frac{2}{3}} = 0.0106C^{0.3777} \exp\left(\frac{-24620}{RT}\right)t \tag{14}$$

Fig. 8. Plots of kinetics at different roasting temperature (a),(b),(c) and (d) and plots of lnK₁ against lnC₀ (e) and (f)

3.7. Characterization of solid residuals after chlorination roasting

The solid residuals reacted at 1000 °C for 50 min under the conditions of calcium chloride dosage of 8 wt%, pellet moisture content of 1.09 wt%, and silicon dioxide dosage at 27.35 wt%, were characterized by XRD. Experimental results is shown in Table 8. Compared with Table 1, it can be seen that the content of Au varied from 7.69(g/t) to 0.42(g/t), and the content of Ag decreased to 7.77(g/t) from 19.60(g/t). The chlorination volatilization rates of Au and Ag can reach 90.08% and 63.51%. The XRD (Fig.9) patterns of solid residuals after chlorination roasting indicate that the major mineral phase are quartz (SiO_2) and ferric oxide (Fe_2O_3). Calcium silicate ($CaSiO_3$) and silicate iron (Fe_2SiO_4) are the minor phases. It is worth noting that the chlorination volatilization rate of iron is only 2.98% during the whole chlorination roasting process, and most of the iron remains in the solid residuals, which can be further recycled.

Table 9. Experimental results of comprehensive conditions

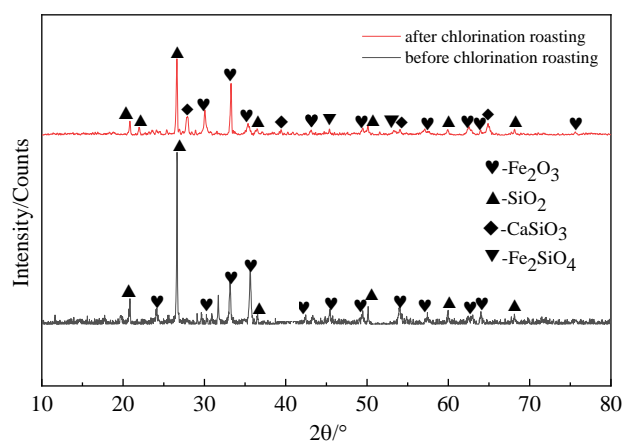| Sample	solid residuals			CTs			chlorination volatilization rate		
	Au(g/t)	Ag(g/t)	Fe(wt%)	Au(g/t)	Ag(g/t)	Fe(wt%)	Au(%)	Ag(%)	Fe(%)
1	0.44	7.85	34.61	7.69	19.60	35.69	89.13	63.14	2.89
2	0.40	7.79	34.82	7.69	19.60	35.69	91.06	64.52	3.12
3	0.42	7.67	34.75	7.69	19.60	35.69	90.05	62.88	2.93
average value	0.42	7.77	34.73	7.69	19.60	35.69	90.08	63.51	2.98
Liu et al., 2011	0.36	10.69	-	3.45	22.97	25.59	89.57	53.46	-

Fig. 9. XRD pattern of residue before and after chlorination roasting

4. Conclusions

The attempt to recover silver and gold from cyanide tailings through chlorination roasting was investigated in this work. The technical indices of volatilization rate were 90.08% for gold and 63.51% for silver under the conditions of calcium chloride dose of 8 wt%, silicon dioxide dosage of 27.35 wt%, pellet moisture content of 1.09 wt%, roasting temperature of 1000 °C, and roasting duration of 50 minutes. The results of this study provide an economical process for the recover silver and gold from cyanide tailings.A kinetic model has been most suitably utilized to describe the simultaneous recovery of Au and Ag from cyanide tailings by chloridizing volatilization, taking into account the experimentally employed parameters of moisture content, temperature, calcium chloride dosage, and silicon dioxide dosage as well as their levels. This model is found to corroborate well with the shrinking core model for an inner diffusion through the gangue layer-controlled process. Au and Ag have respective activation energies of 24.01 kJ·mol^{-1} and 24.62 kJ·mol^{-1}. Eqs. (3-11) and (3-12), which represent a semi-empirical mathematical model symbolizing the process, can be used to describe the

kinetic equation. The model can provide a more accurate description of the chloridization mechanism and the real reaction process through experimental validation.

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