

# Leaching Kinetics of Chalcopyrite Concentrate by Ionic Liquids

Y. Moazzami<sup>1</sup>, S. Z. Shafaei Tonkaboni<sup>1</sup>, M. Gharabaghi<sup>1,\*</sup>

\* gharabaghi@ut.ac.ir

<sup>1</sup> School of Mining engineering, College of Engineering, University of Tehran, Tehran

Received: April 2022

Revised: November 2022

Accepted: December 2022

DOI: 10.22068/ijmse.2812

**Abstract:** Ionic liquids as green solvents with high thermal stability, recyclability, low flash point, and low vapor pressure, have been considered as a viable alternative in hydrometallurgical processes. In this study the leaching kinetics of chalcopyrite concentrate was investigated using 1-Butyl-3-methylimidazolium hydrogen sulfate (BmimHSO<sub>4</sub>) as an acidic ionic liquid. The Effect of operational parameters, including temperature, BmimHSO<sub>4</sub> concentration, H<sub>2</sub>O<sub>2</sub> concentration, stirring speed, solid-to-liquid ratio, and particle size on the rate of copper dissolution of CuFeS<sub>2</sub> were examined systematically. The highest Cu efficiency (ca. 97%) was achieved using 40% (w/v) BmimHSO<sub>4</sub>, 30 %v/v H<sub>2</sub>O<sub>2</sub>, and 10 g.L<sup>-1</sup> solid to liquid ratio for particle sizes less than 37 μm at 300 rpm and 45°C after 180 min leaching time. Kinetics study using Shrinking Core Model (SCM) revealed that CuFeS<sub>2</sub> leaching process using BmimHSO<sub>4</sub> follows chemical reaction-controlled process. Under these circumstances, the calculated activation energy was 46.66 KJ/mol. Moreover, the orders of reaction with respect to BmimHSO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> concentration, solid to liquid ratio and particle size were estimated to be 0.539, 0.933, -0.676 and -1.101 respectively. The obtained Arrhenius constant was found to be  $0.26 \times 10^6$ . The calculation of apparent activation energy using "time given to a fraction method" revealed that the leaching mechanism remains the same over the course of time.

**Keywords:** Cu extraction, Chalcopyrite, Leaching, BmimHSO<sub>4</sub>, Ionic liquid, Kinetic.

## 1. INTRODUCTION

Chalcopyrite, with the chemical formula of CuFeS<sub>2</sub>, is the most important and the most common copper mineral found on the Earth [1]. This mineral which comprises 70% of the world's copper resources [2-4], is highly resistant to dissolution mainly due to its chemical structure, variations on the surface of mineral, and formation of passive layer with substantial porosity on its surface [5, 6]. Accordingly, more than 80 to 85% of the world's copper is produced by pyrometallurgy [7]. However, there are problematic issues regarding pyrometallurgy such as environmental pollution as a result of SO<sub>2</sub> emission, high investment and operational costs, decrease in purity of produced mineral over the course of time, and low efficiency of small particles processing. These issues have led to the application of hydrometallurgy methods in copper industry in recent years [7-10]. Therefore, there have been numerous studies on leaching of copper from CuFeS<sub>2</sub>. Due to low dissolution rate of this mineral, several processes including chloride leaching [11], ammonia leaching [12], bio-leaching [13], and pressure sulfate leaching [14, 15], have been developed for Cu extraction from CuFeS<sub>2</sub>. However, due to the issues

regarding solvent extraction from the product, incomplete extraction, safety, toxicity, environmental pollution, and high expenses for solvent management, there are some controversies about the applicability of solvent-based leaching of Cu from CuFeS<sub>2</sub> [16, 17]. Therefore, novel hydrometallurgical processes are necessary for the green and sustainable development of metallurgy industry for efficient Cu production with low energy consumption, minimal acid requirement, and less pollution under ambient conditions. As a result, ionic liquids have been considered as a viable alternative in metallurgic processes, due to their higher solubility in organic/inorganic compounds, non-volatile nature, and thermal stability [18].

Ionic liquids can be considered as a new branch of chemical compounds with extraordinary properties, creating green chemical environments for chemical processes. These compounds are considered as a suitable alternative to organic/inorganic solvents which provide a non-aqueous organic liquid environment for conduction of numerous chemical reactions. Nowadays, ionic liquids are considered as organic compounds with melting point below 100°C [19-22].

Recently, ionic liquids have been used in

hydrometallurgy in which they are applied for leaching of gold and silver [17, 23, 24], precious metals [25, 26], and metal oxides [22, 27-29]. The promising ability of ionic liquids for dissolution of metal and metal oxides has been demonstrated in several publications. They also can be used for processing and enrichment of metals via ionometallurgical method [18, 27].

In recent years, several studies on leaching of Cu from  $\text{CuFeS}_2$  with ionic liquids as solvent have been conducted successfully. Early studies on the dissolution of chalcopyrite concentrate were conducted by McCloskey et al. [30] using 1-Butyl-3-methylimidazolium tetrafluoroborate ( $[\text{Bmim}]\text{BF}_4$ ) and iron tetrafluoroborate hexahydrate ( $\text{Fe}(\text{BF}_4)_3$ ) as oxidative agent. Their results revealed that more than 90% Cu extraction is achievable at  $100^\circ\text{C}$  for 8 h. Moreover, in another study, Cu extraction from chalcopyrite concentrate comprised of 20% Cu and 34% Fe was reported using 1-Butyl-3-methylimidazolium hydrogen sulfate ( $\text{BmimHSO}_4$ ) and Fe (III) as oxidative agent [17]. Results demonstrated that increasing the  $\text{BmimHSO}_4$  concentration from 10 to 100% leads to the increase of Cu extraction from 55 to 87% at  $70^\circ\text{C}$ . In addition, Fe extraction was 8%. Dong et al. [31] conducted studies on dissolution of  $\text{CuFeS}_2$  using  $\text{BmimHSO}_4$  and  $\text{O}_2$  gas as oxidative agent. It was found that the copper dissolution increases from 52 to 88% after 24 h at  $70^\circ\text{C}$  by increasing the concentration of  $\text{BmimHSO}_4$  from 10 to 100%. Moreover, the mechanism of chalcopyrite concentrate dissolution using  $\text{BmimHSO}_4$  and oxygen is controlled by surface electrochemistry due to the high activation energy (ca. 69.4 KJ/mol). Carlesi et al. [18] investigated chalcopyrite leaching from sulfidic ore using  $\text{BmimHSO}_4$  and 1-h-3-methylimidazolium hydrogen sulfate ( $\text{HmimHSO}_4$ ). Similar to the previous studies [17, 31], results demonstrated that copper extraction increases by increasing the ionic liquid concentration and temperature. Moreover,  $\text{HmimHSO}_4$  is superior to  $\text{BmimHSO}_4$ , and in combination with sulfuric acid, chalcopyrite dissolution yield increases to 70% after 20 h. Aguirre et al. [32] studied chalcopyrite leaching using  $\text{BmimHSO}_4$ , sulfuric acid, and chloride as oxidative agents. The investigated sample contained 96.6%  $\text{CuFeS}_2$ . Results revealed that Cu extraction efficiency at  $90^\circ\text{C}$  for 24 h using 20% (v/v)  $\text{BmimHSO}_4$  and  $100 \text{ g.L}^{-1}$  chlorine ion

reached 80%. In addition, they concluded that increasing the chlorine concentration and temperature leads to an increase in Cu extraction from chalcopyrite. Kinetic mechanism of chalcopyrite dissolution was also investigated. According to the results, chalcopyrite dissolution with  $\text{BmimHSO}_4$  and chlorine ion follows chemical reaction with activation energy of 60.4 KJ/mol. 1-ethyl-3-methylimidazolium hydrogen sulfate ( $\text{EmimHSO}_4$ ) and potassium dichromate as oxidative agent were used by Hu et al. [33] for Cu extraction from chalcopyrite. They concluded that  $\text{EmimHSO}_4$  concentration, oxidant concentration, temperature, and particle size have significant effect on Cu extraction, so that 90.2% Cu extraction was achieved after 90 min. Investigation of dissolution kinetic mechanism revealed that chalcopyrite dissolution follows diffusion through a protect layer of elemental sulfur and pyrite mechanism with activation energy of 36.26 KJ/mol.

All of the work done in this field reveals the significant effect of ionic liquids during chalcopyrite leaching. In addition, achievement of considerable efficiency using ionic liquid requires utilization of oxidative agent. The main oxidative agents are  $\text{KNO}_3$ ,  $\text{NaClO}_3$ ,  $(\text{NH}_4)_2\text{S}_2\text{O}_8$ ,  $\text{K}_2\text{Cr}_2\text{O}_7$ ,  $\text{H}_2\text{O}_2$ , and  $\text{Fe}^{3+}$  which have been used in  $\text{CuFeS}_2$  leaching [33]. Among them,  $\text{H}_2\text{O}_2$  is known to be a strong oxidant and has been frequently used for the leaching of chalcopyrite [34-36], molybdenite [37] and other minerals [38]. Therefore, in this study,  $\text{H}_2\text{O}_2$  was chosen as oxidant.

The literature review shows there are few studies on the utilization of main models such as shrinking core model (SCM), to describe the kinetic of chalcopyrite dissolution with  $\text{BmimHSO}_4$ . Also, no study has been reported on the effect of leaching parameters on the dissolution kinetics of chalcopyrite using  $\text{BmimHSO}_4$ . Therefore, in the current study, kinetics of chalcopyrite concentrate leaching using  $\text{BmimHSO}_4$  at low temperature in the presence of  $\text{H}_2\text{O}_2$  was investigated using SCM. The effect of operational parameters such as temperature,  $\text{BmimHSO}_4$  and  $\text{H}_2\text{O}_2$  concentration, stirring speed, solid-to-liquid ratio, and particle size on the kinetic of chalcopyrite dissolution has been also investigated. In addition, the changes of activation energy during leaching were investigated using the "time given to a fraction method".

## 2. EXPERIMENTAL PROCEDURES

### 2.1. Materials

CuFeS<sub>2</sub> concentrate was supplied from the flotation unit of Taknar Copper Mines Complex (Razavi Khorasan, Iran). X-ray diffraction (XRD) analysis (D8-Advance, Bruker axs, USA) was carried out in order to identify the minerals (Figure 1). Accordingly, the main mineral in the sample was CuFeS<sub>2</sub> along with trace amounts of Pyrite. Microscopic mineralogy revealed less than 5% Cu with trace amounts of Cu oxide minerals, chalcocite, and bornite which were not detectable by XRD analysis.

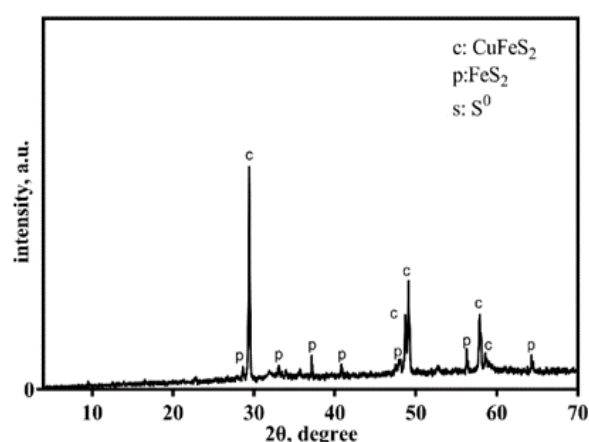


Fig. 1. XRD pattern of CuFeS<sub>2</sub> concentrate as leaching feed.

The sample was divided into four size fractions, i.e. <37, 37-53, 53-74, and 74-88 μm, using wet sieving method. The results of X-ray fluorescence (PW1410, Philips, Netherlands) analysis are shown in Table 1.

Table 1. Chemical composition of different size fractions of feed CuFeS<sub>2</sub> concentrate

Particle size (μm)	Content (%)		
	Fe	S	Cu
-37	27.58	32.63	30.66
(-53, +37)	30.20	32.49	29.13
(-74, +53)	30.74	31.51	27.84
(-88, +74)	28.48	30.60	29.04

BmimHSO<sub>4</sub> (≥94.5% purity) was used as ionic liquid due to its satisfactory performance, water solubility, low price, and availability (Sigma Aldrich, Germany). H<sub>2</sub>O<sub>2</sub> (30 wt%) was acquired from Sigma Aldrich (Germany). De-ionized water was used throughout the experiments.

### 2.2. Procedure

The leaching solution was prepared in a 50 ml Erlenmeyer flask using digital magnetic stirrer-hot plate at 0, 100, 200, 300, 400, and 500 rpm. For this purpose, calculated amounts of BmimHSO<sub>4</sub> (10, 20, 30, and 40 % w/v) and H<sub>2</sub>O<sub>2</sub> (7.5, 15, 22.5, and 30 %v/v) were placed in flask and heated up to the operation temperature (i.e. 30, 35, 40, and 45°C). After achieving the desired temperature, specific amounts of the CuFeS<sub>2</sub> particles (10, 20, 30, and 40 g.L<sup>-1</sup>) with the aforementioned size fractions were added to the solution. Aliquot samples from solution were drawn and filtered at certain times from start of each experiment. The amount of leached Cu was analyzed using Atomic Absorption Spectrophotometer (Varian, AA240, USA). In order to compensate the errors resulted from sampling, Equation 1 was used for the calculation of Cu extraction [39].

$$X_i = \frac{(V_0 - \sum_{i=1}^{i-1} v_i) C_i + \sum_{i=1}^{i-1} v_i C_i}{M(C_M/100)} \quad (1)$$

where  $X_i$  is the Cu extraction percent from  $i^{\text{th}}$  sample,  $V_0$  is the volume of leaching solution in Erlenmeyer (mL),  $v_i$  is the volume of  $i^{\text{th}}$  sample drawn from the solution (mL),  $C_i$  is the Cu concentration in  $i^{\text{th}}$  sample (g mL<sup>-1</sup>),  $M$  is the weight of CuFeS<sub>2</sub> in leaching solution (g), and  $C_M$  is the Cu concentration in CuFeS<sub>2</sub> concentrate.

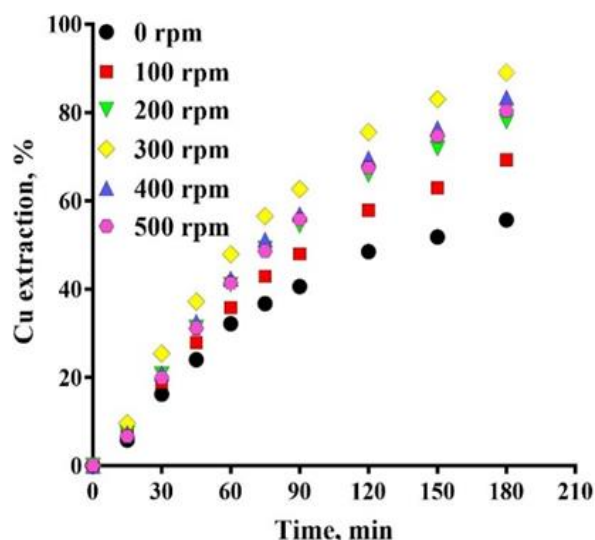
## 3. RESULTS AND DISCUSSION

### 3.1. Effect of Stirring Speed

Effect of stirring speed on leaching efficiency was studied under the following operational conditions: 40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, 40°C, 10 g.L<sup>-1</sup> solid to liquid ratio, particle size of less than 37 μm, and leaching time of 180 min. The results are presented in Figure 2.

By increasing the stirring speed to 300 rpm, the dissolution of CuFeS<sub>2</sub> increased to 89.1%. However, further increase in stirring speed led to a slight decrease in CuFeS<sub>2</sub> dissolution (80.4% Cu extraction at 500 rpm). The same result was obtained by other researchers during chalcopyrite leaching with hydrogen peroxide [36]. The reason for this phenomenon is that the increase of steering speed presumably accelerates the decomposition of the hydrogen peroxide and interferes with the adsorption of hydrogen peroxide on the surface of chalcopyrite and sulfur,

resulting in significant decrease in the dissolution rate [40]. Sokić et al [34], also observed an increased in the  $\text{H}_2\text{O}_2$  decomposition at higher stirring speeds leading to the absorption of more generated  $\text{O}_2$  molecules onto the  $\text{CuFeS}_2$  surface. Therefore, the optimal stirring speed of 300 rpm was used in the subsequent experiments.



**Fig. 2.** Effect of stirring speed on leaching efficiency (40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, 40°C, 10 g.L<sup>-1</sup> solid to liquid ratio, particle size of less than 37  $\mu\text{m}$ , and leaching time of 180 min).

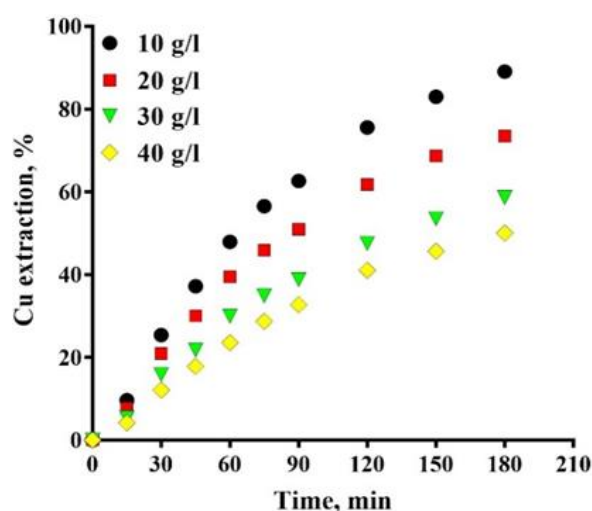
### 3.2. Effect of Solid to Liquid Ratio

Effect of solid to liquid ratio was investigated under the following operational conditions: 40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, particle size of less than 37  $\mu\text{m}$ , stirring speed of 300 rpm, 40°C, and leaching time of 180 min. The results are displayed in Figure 3. It can be seen that, by increasing the solid to liquid ratio, Cu extraction decreased; after 180 min, increasing the ratio from 10 to 40 g.L<sup>-1</sup> led to the decrease in Cu extraction from 89.1 to 50%. From the results, it can be concluded that increasing the solid-to-liquid ratio cannot increase the leaching efficiency.

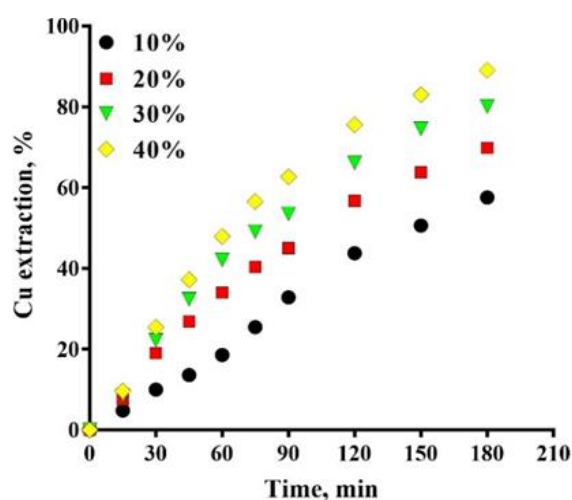
This may be related to the presence of less leaching solution available per unit mass of solids [41, 42], and increase in mass transfer resistance due to increased viscosity[43]. Hence, the optimum solid-to-liquid ratio for leaching reaction in the subsequent experiments was 10 g.L<sup>-1</sup>.

### 3.3. Effect of BmimHSO<sub>4</sub> Concentration

Effect of BmimHSO<sub>4</sub> concentration on CuFeS<sub>2</sub> dissolution during leaching process was investigated under the following operational conditions: 30% H<sub>2</sub>O<sub>2</sub>, 40°C, 10 g.L<sup>-1</sup> solid to liquid ratio, particle size of less than 37  $\mu\text{m}$ , stirring speed of 300 rpm, and leaching time of 180 min. As can be seen in Figure 4, by increasing the BmimHSO<sub>4</sub> concentration from 10 to 40% w/v, Cu extraction increases from 57.6 to 89.1% after 3 h of leaching which is in accordance with the results of previous studies [17, 18, 31].



**Fig. 3.** Effect of solid to liquid ratio on leaching efficiency (40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, particle size of less than 37  $\mu\text{m}$ , stirring speed of 300 rpm, 40°C, and leaching time of 180 min).



**Fig. 4.** Effect of BmimHSO<sub>4</sub> concentration on leaching efficiency (30% H<sub>2</sub>O<sub>2</sub>, 40°C, 10 g.L<sup>-1</sup> solid to liquid ratio, particle size of less than 37  $\mu\text{m}$ , stirring speed of 300 rpm, and leaching time of 180 min).

This may be related to the higher acidity of the



solution and higher concentration of dissolved oxygen in the presence of higher concentration of BmimHSO<sub>4</sub>. In addition, the reason for insignificant increase in dissolution of CuFeS<sub>2</sub> by further increasing the concentration of BmimHSO<sub>4</sub> could be the increased solution viscosity which eventually restricts the diffusion phenomenon [17, 31]. As a result the optimal concentration of 40 % w/v BmimHSO<sub>4</sub> was used in the subsequent experiments.

### 3.4. Effect of H<sub>2</sub>O<sub>2</sub> Concentration

Effect of H<sub>2</sub>O<sub>2</sub> concentration on CuFeS<sub>2</sub> dissolution was investigated under the following operational conditions: 40% BmimHSO<sub>4</sub>, 40°C, 10 g.L<sup>-1</sup> solid to liquid ratio, stirring speed of 300 rpm, particle size of less than 37 µm, and leaching time of 180 min. Ganbari et al [37] observed with increasing the amount of H<sub>2</sub>O<sub>2</sub> in the solution, the rate of dissolution is increased. As can be seen in Figure 5, increasing H<sub>2</sub>O<sub>2</sub> concentration led to significant change in dissolution rate of CuFeS<sub>2</sub>. So that, after leaching for 3 h, increasing the H<sub>2</sub>O<sub>2</sub> concentration from 7.5 to 30% led to an increase in Cu extraction from 37 to 89.1%. The increase in dissolution rate could be related to the increased solubility of oxygen and/or the high oxidation potential of hydrogen peroxide [44].



**Fig. 5.** Effect of H<sub>2</sub>O<sub>2</sub> concentration on leaching efficiency (40% BmimHSO<sub>4</sub>, 40°C, 10 g.L<sup>-1</sup> solid to liquid ratio, stirring speed of 300 rpm, particle size of less than 37 µm, and leaching time of 180 min).

Also, according to Figure 5, it can be seen that the improvement of CuFeS<sub>2</sub> dissolution by increasing H<sub>2</sub>O<sub>2</sub> concentration in the range of 7.5 to 15% was more significant than that in the range of 15 to 30%. This may be due to the direct

relationship between H<sub>2</sub>O<sub>2</sub> decomposition and its concentration; higher H<sub>2</sub>O<sub>2</sub> concentration leads to higher H<sub>2</sub>O<sub>2</sub> decomposition rate [34-36]. Therefore, the optimal H<sub>2</sub>O<sub>2</sub> concentration of 30% was used in the subsequent experiments.

### 3.5. Effect of Particle size

Since economic efficiency is highly dependent on the grinding costs, the feed particle size required for leaching process is considered as an effective parameter. In general, smaller particle size leads to more surface area available for leaching, enhancing the leaching rate [45]. Effect of particle size was evaluated under the following operational conditions: 40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, 10 g.L<sup>-1</sup> solid to liquid ratio, stirring speed of 300 rpm, 40°C, and leaching time of 180 min. As can be seen in Figure 6, the Cu extraction efficiency increased from 45.8 to 89.1% by decreasing the particle size from 74-88 µm to less than 37 µm.



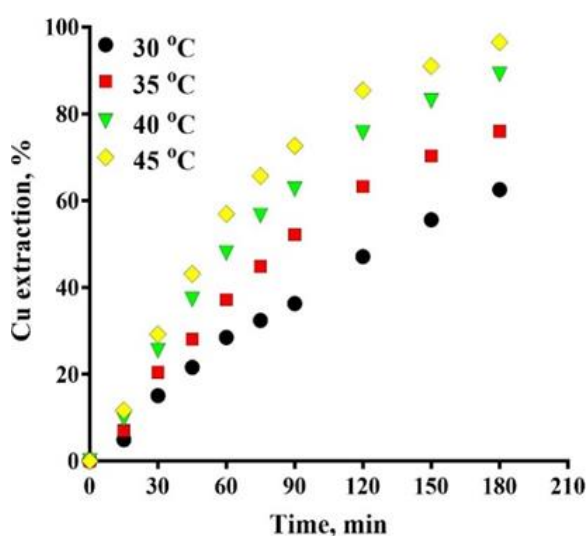
**Fig. 6.** Effect of particle size on leaching efficiency (40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, 10 g.L<sup>-1</sup> solid to liquid ratio, stirring speed of 300 rpm, 40°C, and leaching time of 180 min).

This is due to the increase in contact area between the particles and the leaching solution. In addition, porosities and natural cracks on the surface of smaller CuFeS<sub>2</sub> particles further increase the dissolution rate [46-48]. Hence, the optimum particle size less than 37 µm was used in the subsequent experiments.

### 3.6. Effect of Temperature

Temperature is one of the main factors that significantly affects on the leaching rate of

chalcopryrite. More precisely, at low temperatures the dissolution rate of chalcopryrite is very slow [49]. Effect of temperature on  $\text{CuFeS}_2$  dissolution was studied under the following operational conditions: 40%  $\text{BmimHSO}_4$ , 30%  $\text{H}_2\text{O}_2$ , 10  $\text{g.L}^{-1}$  solid to liquid ratio, stirring speed of 300 rpm, particle size of less than 37  $\mu\text{m}$ , and leaching time of 180 min. In general, the dissolution rate of  $\text{CuFeS}_2$  improved by increasing the temperature. As can be seen in Figure 7, by increasing the temperature from 30 to 45°C,  $\text{CuFeS}_2$  dissolution rate increased from 62.5 to 96.5%. This revealed the significant temperature dependence of Cu dissolution which is in good accordance with the previous studies [17, 18, 31, 32].



**Fig. 7.** Effect of temperature on leaching efficiency (40%  $\text{BmimHSO}_4$ , 30%  $\text{H}_2\text{O}_2$ , 10  $\text{g.L}^{-1}$  solid to liquid ratio, stirring speed of 300 rpm, particle size of less than 37  $\mu\text{m}$ , and leaching time of 180 min).

Also, according to Figure 7, it can be seen that the improvement of  $\text{CuFeS}_2$  dissolution by increasing the temperature in the range of 30 to 40°C was more significant than that in the range of 40 to 45°C because, as confirmed by other researchers, at temperatures above 40°C, the dissolution rate of chalcopryrite slows down, due to the decrease in the amount of  $\text{H}_2\text{O}_2$  in the solution [40, 50].

### 3.7. Kinetic Analysis

#### 3.7.1. Kinetics Model of $\text{CuFeS}_2$ Leaching

The reaction that occurs between chalcopryrite concentrate particles and  $\text{BmimHSO}_4$  solution during the leaching process is a typical example of liquid and solid heterogeneous reaction. For

this reaction system, depending on the nature of the solid materials and the type of the products, the reaction rate is usually controlled by one of the following steps [51-54]:

Diffusion through the liquid film, diffusion through the ash/product layer, chemical reaction at the surface of the solid particles or a mixed state of diffusion and chemical reaction. The shrinking core model (SCM) determines which of these steps controls the leaching process [29, 53, 54].

In order to determine the kinetic parameters and rate controlling step of leaching process, the data obtained in the leaching experiments were analyzed based on shrinking core model. Equations describing different rate-limiting steps of SCM are defined in Table 2 [51, 54]. Coefficient of determination ( $R^2$ ) for each equation is also presented in this. The step with the greatest resistance toward reaction is considered as the rate-limiting step [51, 54].

According to Table 2 Eq. T5 resulted in higher  $R^2$  values in the studied temperature range in comparison with the other equations, which shows the leaching is mainly controlled by chemical reaction. As a result, the experimental data of the  $\text{CuFeS}_2$  dissolution can be well described by equation related to this mechanism.

#### 3.7.2. Determination of Activation Energies

The temperature dependence of the rate constant for most chemical reactions is defined by the Arrhenius equation (Equations 2 and 3) [54].

$$K_p = A \exp\left(\frac{-E_a}{RT}\right) \quad (2)$$

$$\ln K_p = \ln A - \left(\frac{-E_a}{RT}\right) \quad (3)$$

Where  $k_p$  is the rate constant,  $A$  is the frequency factor,  $E_a$  is the activation energy (KJ/mol),  $R$  is the universal gas constant, and  $T$  is the absolute temperature (K).

To obtain rate constant ( $k_p$ ) for each temperature,  $1-(1-x)^{1/3}$  was plotted vs. reaction time according to data collected in the leaching experiments (Figure 8a). The slope of the fitted straight lines was considered as the rate constant.

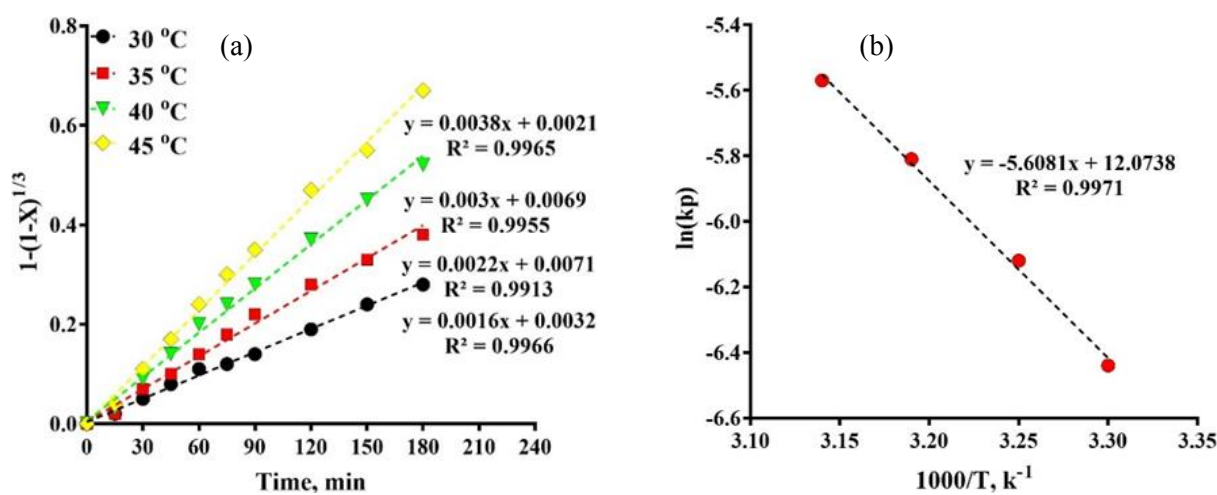
Using the apparent rate constants derived from Equation 3 along with the Arrhenius plot ( $\ln(k_p)$  vs.  $1/T$ ) (Figure 8b), the value of  $E_a$  was calculated to be 46.63 KJ/mol.

Large activation energy values (>40 KJ/mol) imply that chemical reaction is the limiting step.

**Table 2.** Coefficient of determination ( $R^2$ ) for different SCM equations

Eq. NO.	Limiting Step	Equation	$R^2$			
			30°C	35°C	40°C	45°C
T1	Diffusion through the product layer (sp)	$1 - 3(1 - x)^{\frac{2}{3}} + 2(1 - x) = kt$	0.9485	0.9725	0.9743	0.9776
T2	Diffusion through the product layer (cp)	$x + (1 - x)\ln(1 - x) = kt$	0.9432	0.9738	0.9827	0.986
T3	Diffusion through the liquid film (sp and cp)	$x = kt$	0.9787	0.9545	0.9325	0.9069
T4	Surface chemical reactions (cp)	$1 - (1 - x)^{\frac{1}{2}} = kt$	0.9907	0.9764	0.9733	0.9642
T5	Surface chemical reactions (sp)	$1 - (1 - x)^{\frac{1}{3}} = kt$	0.9966	0.9913	0.9955	0.9965

sp—spherical particles, cp—cylinder particles, k—a chemical constant, X—the degree of copper recovery into the solution, and t—the leaching time



**Fig. 8.** (a) Plot of  $1 - (1 - x)^{\frac{1}{3}} = kt$  vs. time for dissolution of  $\text{CuFeS}_2$  at different temperatures, (b) Arrhenius plot obtained for chalcopyrite dissolution.

Meanwhile, small activation energy values (<40 KJ/mol) are related to the case where diffusion is rate-limiting step [47]. However, different values, 12-26 KJ/mol [55], are reported for activation energy required for diffusion step. Moreover, different values (40-80 KJ/mol) are reported for activation energy where chemical reaction is the controlling factor [56]. According to the results, the activation energy values higher than 40 KJ/mol, and also values reported in the literature, it can be concluded that  $\text{CuFeS}_2$  leaching using  $\text{BmimHSO}_4$  does not follow diffusion-controlled kinetics. Instead it is well presented by kinetics controlled by chemical reaction. Although, Arrhenius equation is used for determination of activation energy as well as analysis of mechanism during chemical reactions, this method has two main drawbacks. First, the calculated value of rate constant depends highly

on experimental selection of rate equation. For a given reaction, various rate equations present good fit with experimental data. So, several rate constants and subsequently various activation energies might be calculated. Second, activation energy is calculated on average basis. In most chemical reactions, however, especially complex fluid-solid reactions, rate constant and activation energy vary as reaction progresses due to the changes in the reaction mechanism. In order to overcome this problem, “time to a given fraction method” is suggested [57]. Various researchers have used this method in their reports [58-60]. This method is based on the relation of fractional conversion ( $x$ ) with time ( $t$ ) according to Equation 4. In this method, time is considered as a dependent variable (Equation 5). Continuity between initial, mean, and final fractional conversions is evaluated using Equation 6-8.

$$\frac{dx}{xI} = k_c \cdot f(x) \quad (4)$$

$$dt = k_c^{-1} \cdot f^{-1}(x) dx \quad (5)$$

$$t_x = k_c^{-1} \int_{x=0}^{x=x_1} f^{-1}(x) dx \quad (6)$$

$$t_x \propto A^{-1} \exp\left(\frac{E_a}{RT}\right) \text{ if } t_x \propto k_c^{-1} \quad (7)$$

$$\ln t_x = \text{const} - \ln A + \frac{E_a}{R} \left(\frac{1}{T}\right) \quad (8)$$

Where  $E_a$  is the apparent activation energy required for the progress of certain reaction in specific time. According to Equation 8 the slope of  $\ln(t_x)$  plot vs.  $1/T$  is  $E_a/R$ . When multiplied by  $R$ , the value of activation energy is obtained for a given fractional conversion. Calculation of  $E_a$  for different fractional conversions provides full monitoring of possible changes in reaction mechanism. Graphical representation of the calculated activation energy for specific fractional extraction efficiency of Cu is shown in Figure 9.

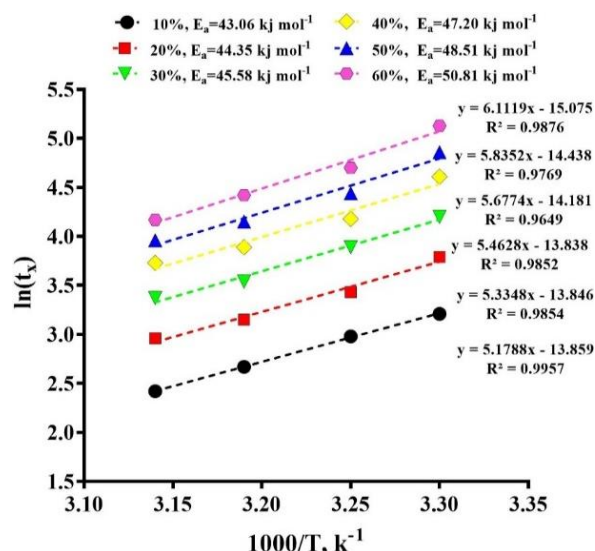


Fig. 9. Plot of  $\ln(t_x)$  vs.  $1/T$  for different Cu extraction fractions.

The activation energy calculated using time given to a fraction method for Cu extraction of 10 to 60% varies in the range of 43.1-50.8 KJ/mol. These values are in accordance with those obtained by SCM and Arrhenius equation. Therefore, it can be concluded that the mechanism of leaching is remained unchanged overtime. According to Figure 9, the increasing trend for activation energy may be related to the reaction with elemental sulfur (Figure 10), which may warp CuFeS<sub>2</sub> particles and prevent the complete leaching of Cu. Value of Gibbs free energy is calculated using the values of  $\Delta S^{++}$  and  $\Delta H^{++}$  according to Equation 9.

$$\Delta G^{++} = \Delta H^{++} - T\Delta S^{++} \quad (9)$$

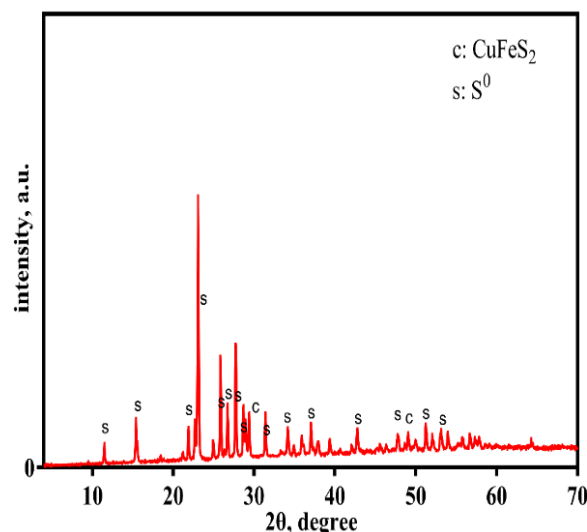


Fig. 10. XRD pattern of leached sample (40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, 10 g.L<sup>-1</sup> solid to liquid ratio, stirring speed of 300 rpm, 45°C, particle size of under 37µm, and leaching time of 180 min).

According to Equation 10, by plotting  $T \times \ln \frac{k_p}{T}$  vs.  $T$ , activation parameters, namely enthalpy and entropy, are calculated to be 48.98 KJ/mol and -153.40 J mol<sup>-1</sup> K<sup>-1</sup>, respectively. In addition, according to Equation 11, the slight difference in enthalpy and activation energy at room temperature is acceptable.

$$E_a = \Delta H^{++} + RT \quad (10)$$

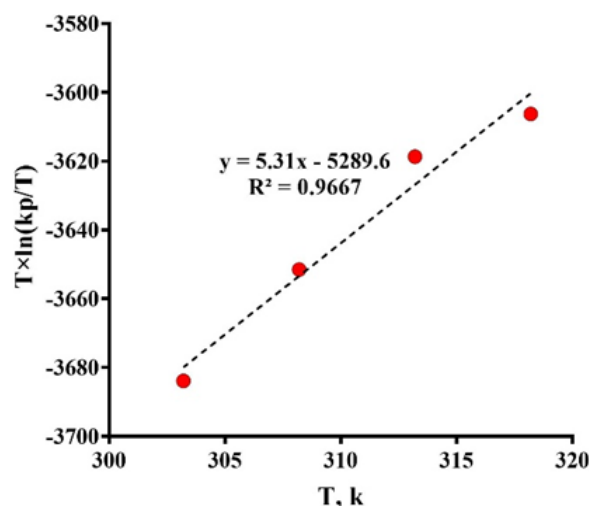


Fig. 11. Eyring equation for CuFeS<sub>2</sub> dissolution using experimental data.

### 3.7.3. Effect of Operational Parameters on the Kinetics of Leaching



In order to further evaluate the leaching kinetics, the effect of experimental parameters (i.e., BmimHSO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> concentration, solid to liquid ratio and particle size (R<sub>o</sub>)) and the role of each of these parameters on the leaching kinetics was investigated. The effect of these parameters is expressed according to Equation 11.

$$k_p = k_0 [\text{BmimHSO}_4]^a [\text{H}_2\text{O}_2]^b \left[ \frac{s}{l} \right]^c [R_o]^d \times \exp\left(\frac{-E_a}{RT}\right) \quad (11)$$

Where  $k_0$  is the Arrhenius constant. Constants  $a$ ,  $b$ ,  $c$ , and  $d$  are the order of reaction according with BmimHSO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> concentration, solid to liquid ratio, and particle size, respectively. In order to determine the order of reaction of each parameter,  $1-(1-x)^{1/3}$  was plotted versus time at different levels of each operational parameter to obtain the corresponding  $k_p$  for each parameter (Table 3). Then,  $\ln(k_p)$  was plotted versus  $\ln(\text{variable value})$  (Figure 12).

The slope of the straight line ( $k_c$ ) indicates the “calculated” order of reaction for each parameter. Which was 0.5386, 0.933, -0.676 and -1.1078 for BmimHSO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> concentration, solid to liquid ratio and particle size, respectively.

Negative values of  $k_c$  for each parameter reveal that the dissolution rate decreases with increasing the parameter value. Substituting Equation 11 and the values for the order of reaction into  $1-(1-x)^{1/3}$  gives Equation 12 for leaching of CuFeS<sub>2</sub> using BmimHSO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> as oxidative agent.

$$1-(1-x)^{1/3} = k_0 [\text{BmimHSO}_4]^{0.54} [\text{H}_2\text{O}_2]^{0.93} \times \left[ \frac{s}{l} \right]^{-0.68} [R_o]^{-1.11} \exp\left(\frac{-46625.74}{RT}\right) t \quad (12)$$

By plotting left side versus the right side expressions of Equation 12, a line is obtained (Figure 13), the slope of which is the Arrhenius constant ( $k_0 = 0.2595 \times 10^6$ ).

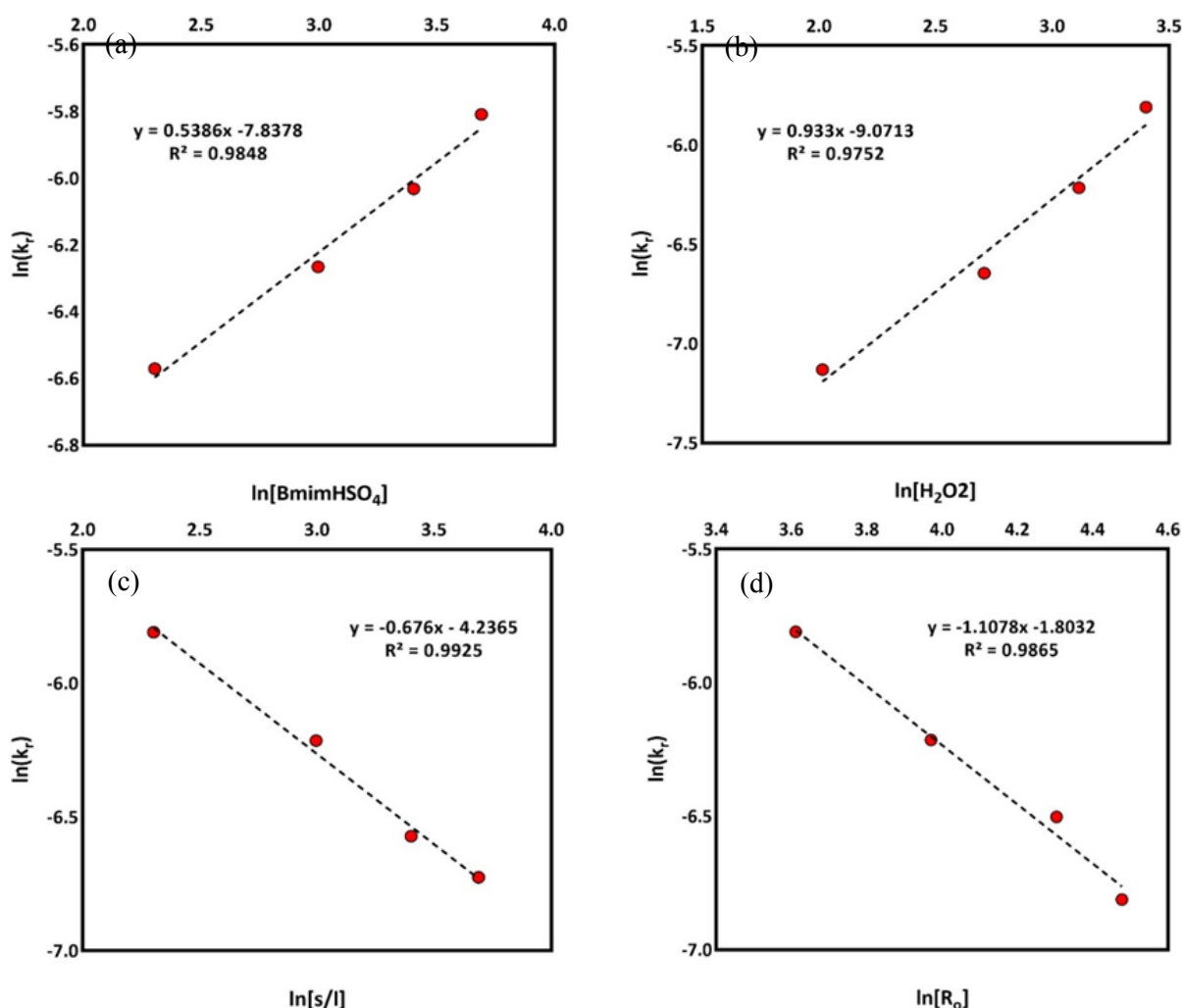


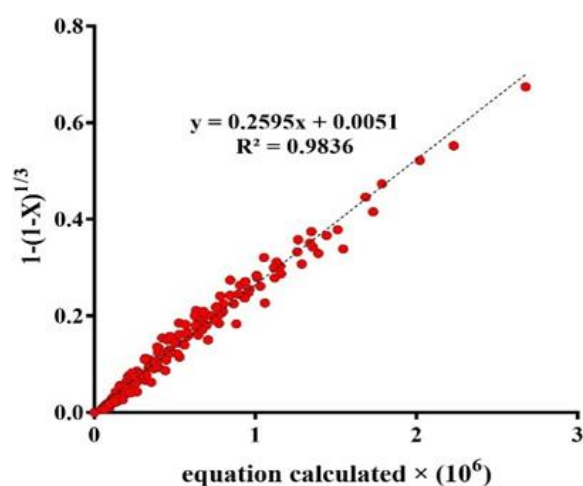
Fig. 12. Plot of  $\ln k_d$  vs: (a)  $\ln[\text{BmimHSO}_4]$ , (b)  $\ln[\text{H}_2\text{O}_2]$ , (c)  $\ln[S/L]$  and (d)  $\ln[R_o]$

**Table 3.** Results of order of reaction calculation relative to each operational parameter

parameter	$K_p$ ( $h^{-1}$ )	$R^2$	$\ln(k_p)$
BmimHSO <sub>4</sub> (%w/v)			
10	0.0014	0.993	-6.57
20	0.0019	0.993	-6.27
30	0.0024	0.993	-6.03
40	0.0030	0.996	-5.81
H <sub>2</sub> O <sub>2</sub> (%v/v)			
7.5	0.0008	0.988	-7.13
15	0.0013	0.995	-6.65
22.5	0.0020	0.981	-6.21
30	0.0030	0.996	-5.81
Particle size ( $\mu m$ )			
37	0.0030	0.996	-5.81
53	0.0020	0.981	-6.21
74	0.0015	0.989	-6.50
88	0.0011	0.998	-6.81
s/l (g/l)			
10	0.0030	0.996	-5.81
20	0.0020	0.984	-6.21
30	0.0014	0.982	-6.57
40	0.0012	0.983	-6.73

Moreover,  $R^2$  value is 0.9836 which confirms the acceptable agreement with the experimental data. Finally, the kinetic model for CuFeS<sub>2</sub> leaching using BmimHSO<sub>4</sub> in the presence of H<sub>2</sub>O<sub>2</sub> oxidative agent is obtained as Equation 13

$$1-(1-x)^{\frac{1}{3}} = 0.26 \times 10^6 [BmimHSO_4]^{0.54} \times [H_2O_2]^{0.93} \left[ \frac{s}{l} \right]^{-0.68} [R_o]^{-1.11} \exp\left(\frac{-46625.74}{RT}\right) t \quad (13)$$

**Fig. 13.** Plot of Arrhenius constant ( $k_0$ ).

#### 4. CONCLUSIONS

The effect of leaching operational parameters, i.e. BmimHSO<sub>4</sub> concentration, H<sub>2</sub>O<sub>2</sub> concentration, solid to liquid ratio, stirring speed, temperature,

and particle size on leaching of CuFeS<sub>2</sub> concentrate was investigated. The results are summarized as follows:

- The highest Cu extraction was achieved using 40% BmimHSO<sub>4</sub>, 30% H<sub>2</sub>O<sub>2</sub>, and 10 g.L<sup>-1</sup> solid to liquid ratio for particle sizes less than 37  $\mu m$  at 300 rpm and 45°C for leaching time of 180 min. It was found that the increase in BmimHSO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> concentration, and temperature, as well as the decrease in solid to liquid ratio and particle size, contributed to the dissolution of chalcopyrite.
- Investigation of kinetic models showed that dissolution of CuFeS<sub>2</sub> using BmimHSO<sub>4</sub> can be well described by SCM, which demonstrated that the leaching process using BmimHSO<sub>4</sub> does not follow the diffusion-controlled reaction and the results better fit with chemical reaction-controlled mechanism.
- The calculated activation energy was 46.63 KJ/mol and calculation of apparent activation energy using time given to a fraction method revealed that the leaching mechanism remains unchanged overtime.
- The orders of reaction with respect to BmimHSO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> concentration, solid to liquid ratio and particle size were estimated to be 0.539, 0.933, -0.676 and -1.108, respectively. Under these circumstances, the

calculated Arrhenius constant was  $0.2596 \times 10^6$ .

## ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Taknar Copper Mines Complex (Razavi Khorasan, Iran) and its research laboratory cooperation. Our sincere thanks also go to geochemistry laboratory, mineral processing laboratory, X-ray laboratory, and the library of the University of Tehran.

## REFERENCES

- [1] Li, Y., Wang, B., Xiao, Q., Lartey, C. and Zhang, Q., "The mechanisms of improved chalcopryrite leaching due to mechanical activation". *Hydrometallurgy*. 2017, 173, 149-155.
- [2] Zhao, H., Wang, J., Gan, X., Hu, M., Tao, L., Qin, W. and Qiu, G., "Role of pyrite in sulfuric acid leaching of chalcopryrite: An elimination of polysulfide by controlling redox potential". *Hydrometallurgy*. 2016, 164, 159-165.
- [3] Olvera, O., Rebolledo, M. and Asselin, E., "Atmospheric ferric sulfate leaching of chalcopryrite: Thermodynamics, kinetics and electrochemistry". *Hydrometallurgy*. 2016, 165, 148-158.
- [4] Veloso, T. C., Peixoto, J. J., Pereira, M. S. and Leao, V. A., "Kinetics of chalcopryrite leaching in either ferric sulphate or cupric sulphate media in the presence of NaCl". *International Journal of Mineral Processing*. 2016, 148, 147-154.
- [5] Nazari, G. and Asselin, E., "Morphology of chalcopryrite leaching in acidic ferric sulfate media". *Hydrometallurgy*. 2009, 96, 183-188.
- [6] Córdoba, E., Muñoz, J., Blázquez, M., González, F. and Ballester, A., "Passivation of chalcopryrite during its chemical leaching with ferric ion at 68 °C". *Minerals Engineering*. 2009, 22, 229-235.
- [7] Faris, N., Ram, R., Chen, M., Tardio, J., Pownceby, M. I., Jones, L. A., McMaster, S., Webster, N. A. and Bhargava, S., "The effect of thermal pre-treatment on the dissolution of chalcopryrite ( $\text{CuFeS}_2$ ) in sulfuric acid media". *Hydrometallurgy*. 2017, 169, 68-78.
- [8] Li, Y., Kawashima, N., Li, J., Chandra, A. and Gerson, A. R., "A review of the structure, and fundamental mechanisms and kinetics of the leaching of chalcopryrite". *Advances in colloid and interface science*. 2013, 197, 1-32.
- [9] Baba, A. A., Ayinla, K. I., Adekola, F. A., Ghosh, M. K., Ayanda, O. S., Bale, R. B., Sheik, A. R. and Pradhan, S. R., "A review on novel techniques for chalcopryrite ore processing". *International journal of mining engineering and mineral processing*. 2012. 94, 95-104.
- [10] Pradhan, N., Nathsarma, K., Rao, K. S., Sukla, L. and Mishra, B., "Heap bioleaching of chalcopryrite: a review". *Minerals Engineering*. 2008, 21, 355-365.
- [11] Watling, H., "Chalcopryrite hydrometallurgy at atmospheric pressure: 2. Review of acidic chloride process options". *Hydrometallurgy*. 2014, 146, 96-110.
- [12] Radmehr, V., Koleini, S. M. J., Khalesi, M. R. and Mohammadi, M. R. T., "Ammonia Leaching: A new approach of copper industry in hydrometallurgical processes". *Journal of The Institution of Engineers (India): Series D*. 2013, 94, 95-104.
- [13] Panda, S., Akcil, A., Pradhan, N. and Deveci, H., "Current scenario of chalcopryrite bioleaching: a review on the recent advances to its heap-leach technology". *Bioresource technology*. 2015, 196, 694-706.
- [14] Padilla, R., Vega, D. and Ruiz, M., "Pressure leaching of sulfidized chalcopryrite in sulfuric acid-oxygen media". *Hydrometallurgy*. 2007, 86, 80-88.
- [15] McDonald, R. and Muir, D., "Pressure oxidation leaching of chalcopryrite. Part I. Comparison of high and low temperature reaction kinetics and products". *Hydrometallurgy*. 2007, 86, 191-205.
- [16] Anderson, C., Dahlgren, E., Huang, H., Miranda, P., Stacey, D., Jeffrey, M. and Chandra, I. Fundamentals and applications of alkaline sulfide leaching and recovery of gold. in *CIM Gold Symposium*, Calgary, Alberta. 2005.
- [17] Whitehead, J., Zhang, J., Pereira, N., McCluskey, A. and Lawrance, G., "Application of 1-alkyl-3-methylimidazolium ionic liquids in the oxidative

- leaching of sulphidic copper, gold and silver ores". *Hydrometallurgy*. 2007, 88, 109-120.
- [18] Carlesi, C., Cortes, E., Dibernardi, G., Morales, J. and Muñoz, E., "Ionic liquids as additives for acid leaching of copper from sulfidic ores". *Hydrometallurgy*. 2016, 161, 29-33.
- [19] Singh, G. and Kumar, A., "Ionic liquids: Physico-chemical, solvent properties and their applications in chemical processes". 2008. 197, 1-32.
- [20] Blasucci, V. M., Hart, R., Pollet, P., Liotta, C. L. and Eckert, C. A., "Reversible ionic liquids designed for facile separations". *Fluid Phase Equilibria*. 2010, 294, 1-6.
- [21] Greaves, T. L. and Drummond, C. J., "Protic ionic liquids: properties and applications". *Chemical reviews*. 2008, 108, 206-237.
- [22] Park, J., Jung, Y., Kusumah, P., Lee, J., Kwon, K. and Lee, C. K., "Application of ionic liquids in hydrometallurgy". *International journal of molecular sciences*. 2014, 15, 15320-15343.
- [23] Whitehead, J., Zhang, J., McCluskey, A. and Lawrance, G., "Comparative leaching of a sulfidic gold ore in ionic liquid and aqueous acid with thiourea and halides using Fe (III) or  $\text{HSO}_5^-$  oxidant". *Hydrometallurgy*. 2009, 3, 276-280.
- [24] Whitehead, J. A., Lawrance, G. A. and McCluskey, A., "'Green' leaching: recyclable and selective leaching of gold-bearing ore in an ionic liquid". *Green Chemistry*. 2004, 6, 313-315.
- [25] Davris, P., Balomenos, E., Pantias, D. and Paspaliaris, I., "Selective leaching of rare earth elements from bauxite residue (red mud), using a functionalized hydrophobic ionic liquid". *Hydrometallurgy*. 2016, 164, 125-135.
- [26] Davris, P., Balomenos, E., Pantias, D. and Paspaliaris, I. Leaching of rare earths from bauxite residues using imidazolium based ionic liquids. in *ERES2014: 1st European Rare Earth Resources Conference*, Milos, Greece. 2014.
- [27] Abbott, A. P. and Frisch, G., "Ionometallurgy: Processing of Metals using Ionic Liquids". *Element Recovery and Sustainability*. 2013, 22, 59.
- [28] Abbott, A. P., Frisch, G., Hartley, J. and Ryder, K. S., "Processing of metals and metal oxides using ionic liquids". *Green Chemistry*. 2011, 13, 471-481.
- [29] Tian, G.-C., Jian, L. and Hua, Y.-X., "Application of ionic liquids in hydrometallurgy of nonferrous metals". *Transactions of Nonferrous Metals Society of China*. 2010, 20, 513-520.
- [30] McCluskey, A., Lawrance, G. A., Leitch, S. K., Owen, M. P. and Hamilton, I. C., "Ionic liquids and metal ions: from green chemistry to ore refining". 2002. 94, 48-53.
- [31] Dong, T., Hua, Y., Zhang, Q. and Zhou, D., "Leaching of chalcopryrite with Brønsted acidic ionic liquid". *Hydrometallurgy*. 2009, 99, 33-38.
- [32] Aguirre, C. L., Toro, N., Carvajal, N., Watling, H. and Aguirre, C., "Leaching of chalcopryrite ( $\text{CuFeS}_2$ ) with an imidazolium-based ionic liquid in the presence of chloride". *Minerals Engineering*. 2016, 99, 60-66.
- [33] Hu, J., Zi, F. and Tian, G., "Extraction of copper from chalcopryrite with potassium dichromate in 1-ethyl-3-methylimidazolium hydrogen sulfate ionic liquid aqueous solution". *Minerals Engineering*. 2021, 172, 107179.
- [34] Sokić, M., Marković, B., Stanković, S., Kamberović, Ž., Štrbac, N., Manojlović, V. and Petronijević, N., "Kinetics of chalcopryrite leaching by hydrogen peroxide in sulfuric acid". *Metals*. 2019, 9, 1173.
- [35] Wu, J., Ahn, J. and Lee, J., "Kinetic and mechanism studies using shrinking core model for copper leaching from chalcopryrite in methanesulfonic acid with hydrogen peroxide". *Mineral Processing and Extractive Metallurgy Review*. 2021, 42, 38-45.
- [36] Petrović, S. J., Bogdanović, G. D. and Antonijević, M. M., "Leaching of chalcopryrite with hydrogen peroxide in hydrochloric acid solution". *Transactions of Nonferrous Metals Society of China*. 2018, 28, 1444-1455.
- [37] Ganbari Arbat, A., Asghari Fesaghandis, E., Taghizadeh Tabrizi, A. and Aghajani, H., "Comparison of the effect of  $\text{NaClO}_3$  and  $\text{H}_2\text{O}_2$  on the molybdenum leaching



- from molybdenite concentrate". Transactions of the Indian Institute of Metals. 2020, 73, 2355-2360.
- [38] Nicol, M. J., "The role and use of hydrogen peroxide as an oxidant in the leaching of minerals. 1. acid solutions". Hydrometallurgy. 2020, 193, 105328.
- [39] Georgiou, D. and Papangelakis, V., "Sulphuric acid pressure leaching of a limonitic laterite: chemistry and kinetics". Hydrometallurgy. 1998, 49, 23-46.
- [40] Antonijević, M., Dimitrijević, M. and Janković, Z., "Leaching of pyrite with hydrogen peroxide in sulphuric acid". Hydrometallurgy. 1997, 46, 71-83.
- [41] Copur, M., Kizilca, M. and Kocakerim, M. M., "Determination of the optimum conditions for copper leaching from chalcopyrite concentrate ore using taguchi method". Chemical Engineering Communications. 2015, 202, 927-935.
- [42] Bayrak, B., Laçin, O. and Saraç, H., "Kinetic study on the leaching of calcined magnesite in gluconic acid solutions". Journal of Industrial and Engineering Chemistry. 2010, 16, 479-484.
- [43] Kim, C.-J., Yoon, H.-S., Chung, K. W., Lee, J.-Y., Kim, S.-D., Shin, S. M., Lee, S.-J., Joe, A.-R., Lee, S.-I. and Yoo, S.-J., "Leaching kinetics of lanthanum in sulfuric acid from rare earth element (REE) slag". Hydrometallurgy. 2014, 146, 133-137.
- [44] Olubambi, P. and Potgieter, J., "Investigations on the mechanisms of sulfuric acid leaching of chalcopyrite in the presence of hydrogen peroxide". Mineral Processing & Extractive Metallurgy Review. 2009, 30, 327-345.
- [45] Dreisinger, D. and Abed, N., "A fundamental study of the reductive leaching of chalcopyrite using metallic iron part I: kinetic analysis". Hydrometallurgy. 2002, 66, 37-57.
- [46] Watling, H., "The bioleaching of sulphide minerals with emphasis on copper sulphides—a review". Hydrometallurgy. 2006, 84, 81-108.
- [47] Habashi, F., Principles of extractive metallurgy. Vol. 1. CRC Press. 1969, 35-126.
- [48] Ruan, Z., Li, M., Gao, K., Zhang, D., Huang, L., Xu, W. and Liu, X., "Effect of Particle Size Refinement on the Leaching Behavior of Mixed Rare-Earth Concentrate Using Hydrochloric Acid". ACS omega. 2019, 4, 9813-9822.
- [49] Córdoba, E., Muñoz, J., Blázquez, M., González, F. and Ballester, A., "Leaching of chalcopyrite with ferric ion. Part II: Effect of redox potential". Hydrometallurgy. 2008, 93, 88-96.
- [50] Mahajan, V., Misra, M., Zhong, K. and Fuerstenau, M., "Enhanced leaching of copper from chalcopyrite in hydrogen peroxide-glycol system". Minerals Engineering. 2007, 20, 670-674.
- [51] Faraji, F., Alizadeh, A., Rashchi, F. and Mostoufi, N., "Kinetics of leaching: a review". Reviews in Chemical Engineering. 2020, 1.
- [52] Gharabaghi, M., Irannajad, M. and Noaparast, M., "A review of the beneficiation of calcareous phosphate ores using organic acid leaching". Hydrometallurgy. 2010, 103, 96-107.
- [53] Gharabaghi, M., Irannajad, M. and Azadmehr, A. R., "Leaching kinetics of nickel extraction from hazardous waste by sulphuric acid and optimization dissolution conditions". Chemical Engineering Research and Design. 2013, 91, 325-331.
- [54] Levenspiel, O., Chemical reaction engineering. John Wiley & Sons. 1999.
- [55] Harvey, T., Yen, W. T. and Paterson, J., "A kinetic investigation into the pressure oxidation of sphalerite from a complex concentrate". Minerals engineering. 1993, 6, 949-967.
- [56] Romankiw, L. T., "Kinetics of dissolution of zinc sulfide in aqueous sulfuric acid". Massachusetts Institute of Technology. 1962, 146, 133-137.
- [57] Putnis, A., An introduction to mineral sciences. Cambridge University Press. 1992, 215-286.
- [58] Hidalgo, T., Kuhar, L., Beinlich, A. and Putnis, A., "Kinetic study of chalcopyrite dissolution with iron (III) chloride in methanesulfonic acid". Minerals Engineering. 2018, 125, 66-74.
- [59] Karimov, K. A., Rogozhnikov, D. A., Kuzas, E. A. and Shoppert, A. A., "Leaching kinetics of arsenic sulfide-containing materials by copper sulfate

- solution”. *Metals*. 2020, 10, 7.
- [60] Hidalgo, T., Kuhar, L., Beinlich, A. and Putnis, A., “Kinetics and mineralogical analysis of copper dissolution from a bornite/chalcopyrite composite sample in ferric-chloride and methanesulfonic-acid solutions”. *Hydrometallurgy*. 2019, 188, 140-156.