

The Dissolution Kinetics Of Chalcopyrite Concentrate In Aqueous Chlorination Solutions Of Chalcopyrite Concentrate

Ahmet Yartaşı

Hakan Temur

M. Muhtar Kocakerim

Atatürk University, Engineering Faculty
Department of Chemical Engineering
Erzurum TURKEY
yartasi@atauni.edu.tr

Abstract: In this study, the dissolution kinetics of chalcopyrite concentrate was investigated by using the solutions obtained with dissolution of chalcopyrite concentrate in water saturated with chlorine. Reaction temperature, solid-to-liquid ratio, stirring speed, $[Fe^{3+}]$, $[Cu^{2+}]$ and $[H^+]$ were chosen as parameters. It was determined that the dissolution rate of chalcopyrite concentrate increased with increasing reaction temperature, $[Fe^{3+}]$ and $[H^+]$, and decreasing solid-to-liquid ratio, but was not affected importantly by $[Cu^{2+}]$ and stirring speed. A mathematical expression representing the process was established by using experimental data and a package program, as follows, $1-(1-X)^{1/3} = \{0.803.(S/L)-0.32.(SS)^{0.17}.[Fe^{3+}]^{0.38} .[Cu^{2+}]^{0.19} .[H^+]^{1.19} .\exp(-31.78/RT)\}.t$ Also, it was found that the dissolution rate was controlled by chemical reaction step with an activation energy of 31.78 kJ.mol⁻¹ in the reaction temperature range 50-88 °C.

Keywords: Chalcopyrite, copper, chlorination, dissolution kinetics.

Introduction

Chalcopyrite, being one of the most abundant copper ores in the world is the most important ore used in production of the copper by pyrometallurgical methods. It contains minerals such as FeS_2 , ZnS , PbS in addition to $CuFeS_2$ in nature. On the other hand, the SO_2 gas emitted to atmosphere during the production of copper by pyrometallurgical methods is an important pollutant. Nowadays, the governments force the firms producing metals from sulphide minerals to use less harmful technologies because of its threatening properties for environment. This situation brings along the necessity of developing of new environmentalist technologies. As an alternative to the pyrometallurgical processes, hydrometallurgical metal recovery is getting importance in this area. Furthermore, the problem of evaluating the chlorine gas being a by-product in production of $NaOH$ needed in enormous amounts in industry is waiting a solution because of impossibility of its emission to the atmosphere.

There are many studies on the dissolution, dissolution kinetics and mechanism of copper ores in various aqueous media. Havlik et al.(1995) examining the leaching of chalcopyrite concentrate with ferric chloride solutions found that the rate of leaching increased with concentration of ferric ions up to the 0.5 M concentrations of ferric chloride and the activation energy of this process was 55 ± 5 kJ.mol⁻¹. Havlik and Kammel(1995) investigated leaching of chalcopyrite in acidified $FeCl_3$ and acidified $FeCl_3 + CCl_4$ solutions. They found that the leaching in the absence of CCl_4 was a chemically controlled reaction with activation energy of 68.9 kJ.mol⁻¹ in the temperature range 45–80 °C and in the presence of CCl_4 was a diffusion controlled process with activation energy of 31.2 kJ.mol⁻¹ in the same temperature range.

The high reactivity of gaseous chlorine as an oxidizing agent in leaching processes have been caused a number of studies on the extraction of metal sulphides by chlorine leaching. Bayrakçeken et al.(1990) studied the kinetics of the chlorination of pyrite in aqueous suspensions and found that the rate controlling step was the chemical reaction between chlorine and pyrite for the temperature range 13–35 °C, and the diffusion of chlorine through the fluid film for the temperature range 40–60 °C with the activation energies respectively 36.7 kJ.mol⁻¹ and 3.7 kJ.mol⁻¹, respectively. Çolak et al.(1987) examined the kinetics of dissolution of chalcopyrite in aqueous solutions saturated by chlorine gas and determined that the diffusion of the reactants through product layer was the rate controlling step with an activation energy of 9.81 kJ.mol⁻¹.

Reactions of copper sulfide minerals with chlorine in an aqueous media were studied by Groves and Smith(1973) and determined that when the dissolution process was complete, the reaction products(copper, iron and sulfur) were in their highest oxidation states and stoichiometric amount of chlorine was consumed.

In an study carried out by Ekmekyapar et. al.(1988), it was investigated the dissolution kinetics of an oxidized copper ore in water saturated by chlorine, and found that the dissolution process proceeded in two stages and was controlled by diffusion through the ash layer in each stage. The authors determined that the activation energies for the first and second stages were 27.15 and 20.21 kJ.mol⁻¹, respectively.

Chalcopyrite can be dissolved with various leaching agents such as hydrochloric acid (Habashi and Toor, 1979), chloride/hypo chloride media (Puvvada and Murthy, 2000), ferric chloride (Dutrizac, 1990; Maurice and Hawk,1999), acidic Cl⁻ solutions(Lu et al., 2000), CCl₄ saturated with chlorine(Saraç et al., 1994) and H₂SO₄-NaCl-O₂ (Padilla et al., 2003). In addition to these, oxide and sulphide ores of base metal minerals were examined by using various chlorinating agents such as Cl₂, HCl, Cl₂-O₂, FeCl₂ and O₂ and CuCl₂ (Mukherjee and Gupta, 1983).

In this study, the dissolution kinetics of concentrate chalcopyrite in the chlorination solution (solution obtained by dissolution of chalcopyrite concentrate in water saturated with chlorine was investigated and effects of the parameters, such as reaction temperature, solid-to-liquid ratio, stirring speed, [Fe³⁺], [Cu²⁺] and [H⁺] on the dissolution rate were determined.

Methods And Materials

The chalcopyrite concentrate used in this study was provided from Çayeli, Rize in Turkey and sieved by using a 75 µm ASTM standard sieve. Chemical analysis of concentrate gave a composition of 24.02 % Cu, 29.36 % Fe, 36.55 % S, 2.19 % Zn, 0.19 % Pb, 0.1 % Al₂O₃, 0.9 % moisture and 6.69 % other components. X-ray diffractogram obtained by a Rigaku DMAX 2000 Series X-ray diffractometer and given in Figure 1 shows that the concentrate contains CuFeS₂, FeS₂, ZnS, Cu₂S, CuS and very small amount of Al₂O₃ and SiO₂. Also, SEM photogram of the concentrate is seen in Figure 2.

250mL- a jacketed glass reactor was used for dissolution experiments under atmospheric pressure. The reactor contents were mixed by a mechanical stirrer with tachometer and its temperature was controlled by a constant temperature circulator. The reactor was fitted with a cooler to prevent the volume reduction of the solution by the evaporation. The parameters used in the experiments and their ranges are given in Table 1.

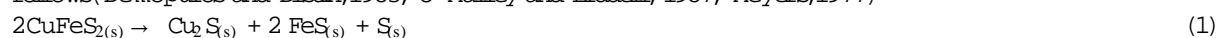
Dissolution experiments were carried out using the chlorination solutions. In order to obtain this solution an enough amount of chalcopyrite concentrate was dissolved in enough amount of chlorine saturated water under predetermined optimum conditions(45° C for reaction temperature, 0.05gmL⁻¹ for solid to liquid ratio, 0.2 molL⁻¹ for [Fe³⁺], 0.025 molL⁻¹ for [Cu²⁺] and 120 min for reaction time), and then, the suspension was filtered and the filtrate stocked. The obtained solution was containing species such as Fe³⁺, Cu²⁺, H⁺, SO₄²⁻ and Cl⁻. Concentrations of these species were 14.6, 4.0, 4.46, 2.2 and 124.3 gmL⁻¹, respectively. Various concentrations of Fe³⁺, Cu²⁺ and H⁺ were prepared by adding Fe³⁺, Cu²⁺ or H⁺ to this solution or by diluting the solutions. After 250 mL of the chlorination solution was placed into reaction vessel it was heated to the reaction temperature. And then, a certain amount of the concentrate was added to the reaction vessel, and the vessel content was stirred at a certain stirring speed for a desired period. At the end of dissolution period, reaction mixture was filtered, and the amounts of Cu²⁺ passing to the solution was determined by the volumetric method(Gülensoy, 1984).

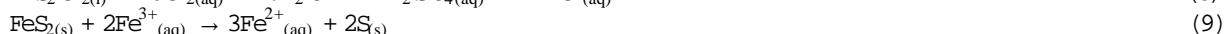
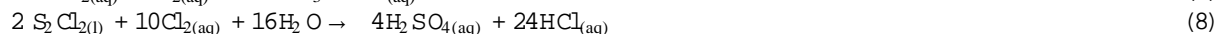
In the experiments, while the effect of one parameter was examining, the values of other parameters were kept constant. The data obtained were plotted in the form of conversion fraction, described as X = [the amount of Cu passing to the solution from chalcopyrite concentrate / the amount of Cu in chalcopyrite concentrate] versus time.

Results And Discussion

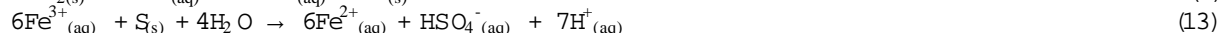
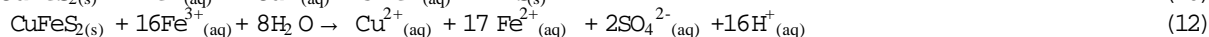
Dissolution Reactions

In aqueous medium, the reactions between chalcopyrite concentrate and chlorine gas are as follows(Demopoulos and Distin,1983, O' Malley and Liddell, 1987, Meyers,1977)





When chalcopryrite concentrate is added into the chlorination solution, the reactions taking place in the medium can be written as follows;



After dissolving the concentrate at reaction temperature of 75 °C, particle size of 75 µm, stirring speed of 450 min⁻¹, solid-to-liquid ratio of 0,02 g.mL⁻¹, Cu²⁺ ion concentration of 4.03 g.L⁻¹, Fe³⁺ ion concentration of 13.90 g.L⁻¹ and H⁺ ion concentration of 4.46 g.L⁻¹ and the mixture was filtered. After the solid part was extracted with 100 mL of carbon sulphide in a reaction vessel equipped with a condenser and the extraction mixture was filtered, the filtrate was evaporated and it was seen that the residue was elemental sulphur.

The effects of parameters

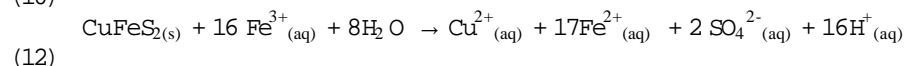
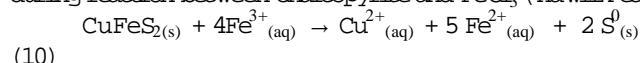
The effect of reaction temperature on the dissolution rate was studied using four reaction temperatures (50, 65, 75 and 88 °C) at particle size of 75 µm, stirring speed of 450 min⁻¹, solid-to-liquid ratio of 0,02 g.mL⁻¹, [Cu²⁺] of 4.03 g.L⁻¹, [Fe³⁺] of 13.90 g.L⁻¹ and [H⁺] of 4.46 g.L⁻¹. As seen in Figure 4, the dissolution rate of chalcopryrite concentrate increases with increasing reaction temperature.

The effect of stirring speed on the dissolution rate was studied by using three stirring speeds (300, 450 and 600 min⁻¹) at particle size of 75 µm, reaction temperature of 75 °C, solid-to-liquid ratio of 0.02 g.mL⁻¹, [Cu²⁺] of 4.03 g.L⁻¹, [Fe³⁺] of 13.90 g.L⁻¹ and [H⁺] of 4.46 g.L⁻¹. The experimental results seen in Figure 5 show evidently that the dissolution rate is not affect importantly of stirring speed.

To investigate the effect of solid-to-liquid ratio on the dissolution rate, the experiments were carried out by using three solid-to-liquid ratios (0.01, 0.02 and 0.04 g.mL⁻¹) at particle size of 75 µm, reaction temperature of 75 °C, stirring speed of 450 min⁻¹, [Cu²⁺] of 4.03 g.L⁻¹, [Fe³⁺] of 13.90 g.L⁻¹ and [H⁺] of 4.46 g.L⁻¹. Data for various solid-to-liquid ratios is seen in Figure 6. This figure shows that decreasing solid-to-liquid ratio increases the dissolution rate, which can be explained by the decrease in the amount of solid per amount of solution in the reaction mixture.

To determine the effect of [Cu²⁺] on the dissolution rate, the experiments were carried out by using three [Cu²⁺] values (4.03, 6.03 and 8.05 g.L⁻¹) at particle size of 75 µm, reaction temperature of 75 °C, solid-to-liquid ratio 0.02 g.mL⁻¹, stirring speed of 450 min⁻¹, [Fe³⁺] of 13.90 g.L⁻¹ and [H⁺] of 4.46 g.L⁻¹. As can be seen in Figure 7, which the experimental results are given, the effect of [Cu²⁺] on the dissolution rate is not important. This case can be explained by the fact that when the large amount of Fe³⁺ ions are present in reaction medium, Cu²⁺ ions can not have an oxidizing effect.

The effect of [Fe³⁺] on the dissolution rate was investigated by using three [Fe³⁺] values (13.90, 20.89 and 27.85 g.L⁻¹) at particle size of 75µm, reaction temperature of 75 °C, solid-to-liquid ratio 0.02 g.mL⁻¹, stirring speed of 450 min⁻¹, [Cu²⁺] of 4.02 g.L⁻¹ and [H⁺] of 4.46 g.L⁻¹. Experimental results plotted in Figure 8 show that the dissolution rate increase with increasing [Fe³⁺]. It has been stated that the following reactions occur during reaction between chalcopryrite and FeCl₃ (Hawlik et al. 1995; Çolak et al., 1987);



Due to above reactions (1 and 2), the dissolution rate increases with increasing [Fe³⁺].

The effect of [H⁺] on the dissolution rate was investigated by using three [H⁺] values (4.46, 2.23 and 1.12 g.L⁻¹) at particle size of 75µm, reaction temperature of 75 °C, solid-to-liquid ratio 0.02 g.mL⁻¹, stirring speed of 450 min⁻¹, [Cu²⁺] of 4.03 g.L⁻¹ and [Fe³⁺] of 13.90 g.L⁻¹. The experimental results plotted in Figure 9 show that dissolution rate increase with increasing [H⁺].

Kinetics Analysis

The kinetics of a noncatalytic reaction between a solid and a liquid, represented by $A_{(fluid)} + bB_{(solid)} \rightarrow$ Products, can be represented by one of two ideal model: Progressive-conversion model and shrinking core

model (Levenspiel, 1999).

In progressive-conversion model, it is visualized that reactant liquid enters to particle and reacts throughout the particle at all times. At this case, the reaction rate can be defined by pseudo-homogenous models and in the shrinking core model it is derived integrated rate equations to show the reaction rate. In such a case, the particle size may unchanged or shrink. If it unchanged, the derived integrated rate equations are

$$t/t^* = X, \text{ (for diffusion control through liquid film)}$$

$$t/t^* = 1-3(1-X)^{2/3} + 2(1-X), \text{ (for diffusion control through ash or product layer)}$$

$$t/t^* = 1-(1-X)^{1/3}, \text{ (for surface chemical reaction control)}$$

If it shrinks during the reaction, the diffusion through ash or product layer is absent and the integrated rate equation are

$$t/t^* = 1-(1-X)^{2/3}, \text{ (the diffusion control through liquid film for small particles)}$$

$$t/t^* = 1-(1-X)^{1/2}, \text{ (the diffusion control through liquid film for large particles)}$$

$$t/t^* = 1-(1-X)^{1/3}, \text{ (for surface chemical reaction control)}$$

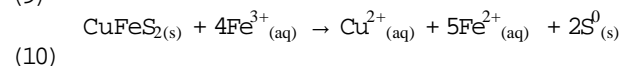
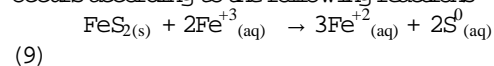
In the presented study, it was determined by statistical and graphical methods that which of above models fits with experimental data and was observed that the most appropriate model was surface chemical reaction control.

As shown in Figure 10, graphs of $[1-(1-X)^{1/3}]$ versus t for various reaction temperatures (50, 65, 75 and 88 °C) gave straight lines. The similar straight lines were obtained for other parameters, also.

The regression coefficients of these lines were higher than those obtained for other models. This result stated that the dissolution rate is controlled by chemical reaction. The activation energy of this dissolution process was found to be 32.96 kJ.mol⁻¹ from the slope of the straight line of $\ln k$ versus $1/T$ in Figure 11.

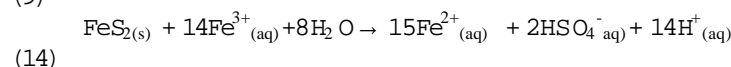
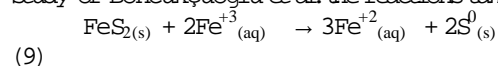
When the activation energy result of the present work is compared the results from the literature for chalcopryrite leaching (Dutrizac 1978, Jermilow et al. 1969, Dutrizac 1978, Dutrizac 1982 and Hirato et al. 1986), it is seen that the results of this work is lower than those in the literature (Table 2). To find the reason of this case, the initial rate values, r_0 were determined from Figure 4, and accepting that the kinetic equation is in the form of $r_0 = k_0 [\exp(-E_a/RT)]$, another activation energy value of 47.59 kJ.mol⁻¹ was calculated from the graph of $\ln r_0$ versus $1/T$ shown in Figure 12. This value is in a good agreement with the literature values given in Table 2, and can be considered as true value of the activation energy.

The difference between the observed activation energy and the one calculated from initial rate values can be explained by the formation of elemental sulphur covering the surface of the particle. When the reactions between the active species in the leaching solution and chalcopryrite and/or pyrite proceeds, elemental sulphur occurs according to the following reactions



Elemental sulphur precipitating on the particle surface can cover the surface, forming a product layer. Due to this film, the activation energy reduces from the true value of 47.59 to 32.96 kJ.mol⁻¹ as the reaction proceeds.

Similar observations have been recorded by Boncukçuoğlu et al. (1994) and Erşahan et al. (1995). In the study of Boncukçuoğlu et al. the reactions taking place in the leaching system were



Because reaction 9 is very fast compared to reaction 14 and high acidity gains speed this reaction (Boncukçuoğlu et al., 1994; Erşahan et al., 1995, Meyers, 1977) and, in similar way, it may say that reaction 10 is faster than reaction 12, also, sulphur obtained by reactions 9 and 10 forms a sulphur layer increasing on particle surface and the dissolution reaction becomes slow.

As a results, taking into account the values of the activation energies, $1-(1-X)^{1/3}$ versus t graphs and their regression coefficients, ineffectiveness of stirring speed on the dissolution rate, it can be concluded that the dissolution process was controlled by chemical reaction.

To drive a mathematical expression including the effects of the parameters, the experimental data were treated using a statistical program and the following equation was developed

$$1-(1-X)^{1/3} = \{0.803.(S/L)^{0.32} .(SS)^{0.17} .[\text{Fe}^{3+}]^{0.38} .[\text{Cu}^{2+}]^{0.19} .[\text{H}^{+}]^{1.19} .\exp(-31.78/RT)\} .t \quad (15)$$

This method gave an activation energy of 31.78 kJ.mol⁻¹ which is slightly lower than the value of 32.96 kJ.mol⁻¹ calculated from $\ln k - 1/T$ graph.

To test the agreement between the experimental conversion values and the values calculated from mathematical expression, the plot of X_{exp} versus X_{theo} was drawn. As seen in Figure 13, the agreement between the experimental and calculated values is very good.

Conclusions

In the presented study, the dissolution kinetics of concentrate chalcopyrite in a solution obtained by dissolution of chalcopyrite concentrate in water saturated with chlorine have been investigated using reaction temperature, solid-to-liquid ratio, stirring speed, $[\text{Fe}^{3+}]$, $[\text{Cu}^{2+}]$ and $[\text{H}^+]$ as parameters. It was determined that the dissolution rate of chalcopyrite concentrate increased with increasing reaction temperature, $[\text{Fe}^{3+}]$ and $[\text{H}^+]$, and decreasing solid-to-liquid ratio, but was not affected importantly by $[\text{Cu}^{2+}]$ and stirring speed. For this dissolution process, a mathematical model was obtained as follows,

$$1-(1-X)^{1/3} = \{0.803.(S/L)^{-0.32} .(SS)^{0.17} .[\text{Fe}^{3+}]^{0.38} .[\text{Cu}^{2+}]^{0.19} .[\text{H}^+]^{1.19} .\exp(-31.78/RT)\} .t \quad (15)$$

It has found that the dissolution rate is controlled by chemical reaction step with an activation energy as much as $31.78 \text{ kJ.mol}^{-1}$ in the reaction temperature range $50-88^\circ\text{C}$.

List Of Symbols

X	fractional conversion
t	time (min)
t*	time for complete conversion of a single solid particle(min)
b	stochiometric coefficient of B (solid) reacting with each mole of A (fluid)
D	particle size (μm)
T	reaction temperature (K)
S/L	solid-to-liquid ratio (g.mL^{-1})
SS	stirring speed(min^{-1})
$[\text{H}^+]$	H^+ ion concentration (g.L^{-1})
$[\text{Fe}^{3+}]$	Fe^{3+} ion concentration (g.L^{-1})
$[\text{Cu}^{2+}]$	Cu^{2+} ion concentration (g.L^{-1})

References

- Bayrakçeken, S., Yaşar, Y. and Çolak, C., (1990). *Kinetics of the chlorination of pyrite in aqueous suspension*. Hydrometallurgy. 25, 27-36.
- Boncukcuoğlu, R., Kocakerim, M. M. and Erşahan, H., (1994). *Kinetics of desulphurization of Nevşehir-Dadağı coal with ferric chloride solutions*, *Fuel Processing Technol.* 38, 31-44
- Çolak, S., Alkan, M. and Kocakerim, M.M., (1987). *Dissolution kinetics of chalcopyrite containing pyrite in water saturated with chlorine*. Hydrometallurgy. 18, 183-193.
- Demopoulos, G.P. and Distin, P.A., (1983). *Ferric Chloride Leaching of Sulphidized Chalcopyrite*. Hydrometallurgy, 10, 111-122.
- Dutrizac, J.E., (1978). *The kinetics of dissolution of chalcopyrite in ferric ion media*. Metallurgical Transactions B. 12B, 431-438.
- Dutrizac, J.E., (1982). *Ferric ion leaching of chalcopyrite from different localities*. Metallurgical Transactions B. 13B: 303-309.
- Dutrizac, J.E., (1990). *Elemental Sulphur Formation During The Ferric Chloride Leaching Of Chalcopyrite*. Hydrometallurgy. 23, 153-176.
- Erşahan, H., Boncukcuoğlu, R. and Kocakerim, M.M., (1995). *Elemental Sulfur Formation In The Meyers Coal Desulphurization Process*, *Fuel*. Vol 74, No:11, 1682-1686
- Ekmekyapar, A., Çolak, S., Alkan, M. and Kayadeniz, İ., (1988). *Dissolution Kinetics Of An Oxidized Copper Ore In Water Saturated By Chlorine*. Chem.Tech. Biotechn. 43, 195-204.
- Groves R. D. and Smith, P.B., (1973). *Reactions Of Copper Sulphide Minerals With Chlorine In An Aqueous System*. United States Bureau of Mines, Report of Investigation 7801.
- Gülensoy, H., (1984). *Kompleksometrinin Esasları ve Kompleksometrik Titrasyonlar*. Fatih Yayınevi Matbaası, 259 s, İstanbul.

Habashi, F. and Toor, T., (1979). *Aqueous Oxidation Of Chalcopyrite In Hydrochloric Acid*. Metallurgical Transactions B. 10B, 49-56.

Havlik, T. and Kammel, R., (1995). *Leaching Of Chalcopyrite With Acidified Ferric Chloride And Carbontetrachloride Addition*. Minerals Engineering, 8 (10), 1125-1134.

Havlik, T., Skrobjan, M., Balaz, P. and Kammel, R., (1995). *Leaching Of Chalcopyrite Concentrate With Ferric Chloride*. Int., J., Miner. Process. 43, 61-72.

Hirato, T., Kinoshita M, and Awakura, Y, (1986). *The Leaching Of Chalcopyrite With Ferric Chlorides*. Metallurgical Transactions B. 17B, 19-28.

Küçük, Ö., Kocakerim, M.M., Yartaşı, A. and Çopur, M., (2002). *Dissolution of Kestelek's colemanite containing clay minerals in water saturated with sulphur dioxide*. Ind. Eng.Chem. Res. 41, 2853-2857.

Levenspiel, O., (1999). Chemical Reaction Engineering, 2nd ed., John Wiley and Sons, New York, pp. 566-586.

Lu, Z.Y., Jeffrey, M.I. and F. Lawson, (2000). *The effect of chloride ions on the dissolution of chalcopyrite in acidic solutions*. Hydrometallurgy. 56 (2), 189-202.

Maurice, D. and Hawk, J.A., (1999). *Simultaneous autogenous milling and ferric chloride leaching of chalcopyrite*. Hydrometallurgy. 51, 371-377.

Meyers, R.A., (1977), Coal Desulphurization, Dekker, New York.

Mukherjee, T.K. and Gupta, C.K., (1983). *Base metal resource processing by chlorination*. Mineral Processing Technology Review. 1, 111-153.

O'Malley and Liddell, K.C., *Leaching of CuFeS₂ by aqueous FeCl₃, HCl and NaCl: Effects of solution composition and limited oxidant*. Metallurgical Transaction B, 18B,505-510.

Padilla, R., Zambrano, P. and Ruiz, M.C., (2002). *Leaching of sulfidized chalcopyrite with H₂SO₄-NaCl-O₂*, Metallurgical and Materials Transactions B. 34B, 153-159.

Puvvada, G.V.K. and Murthy, D.S.R., (2000). *Selective precious metals leaching from a chalcopyrite concentrate using chloride/hypochlorite media*. Hydrometallurgy. 58, 185-191.

Saraç, H., Kocakerim, M.M. and Çolak, S., (1994). *Dissolution kinetics of chalcopyrite containing pyrite in carbon tetrachloride saturated with chlorine*. Chimica Acta Turcica. 22 (3), 259-370.

Parameters	Values			
Reaction temperature (°C)	50	65	75	88
Solid-to-liquid ratio(g. mL ⁻¹)	0.01	0.02	0.04	
Stirring speed(min ⁻¹)	300	450	600	
[Fe ³⁺] (g.L ⁻¹)	13.90	20.89	27.85	
[Cu ²⁺] (g.L ⁻¹)	4.03	6.03	8.05	
[H ⁺] (g.L ⁻¹)	4.46	2.13	1.12	

Table 1.Parameters used in the experiments and their ranges

Temperature range (°C)	Ea (kJ. mol ⁻¹)	Literature
50-100	46 ± 4	Dutrizac (1978)
30-100	42 ± 4	Dutrizac (1978)
40-100	63 ± 8	Dutrizac (1982)
58-85	59.5	Hirato et al. (1986)

Table 2. Apparent activation energy values Ea of chalcopyrite leaching with ferric chloride

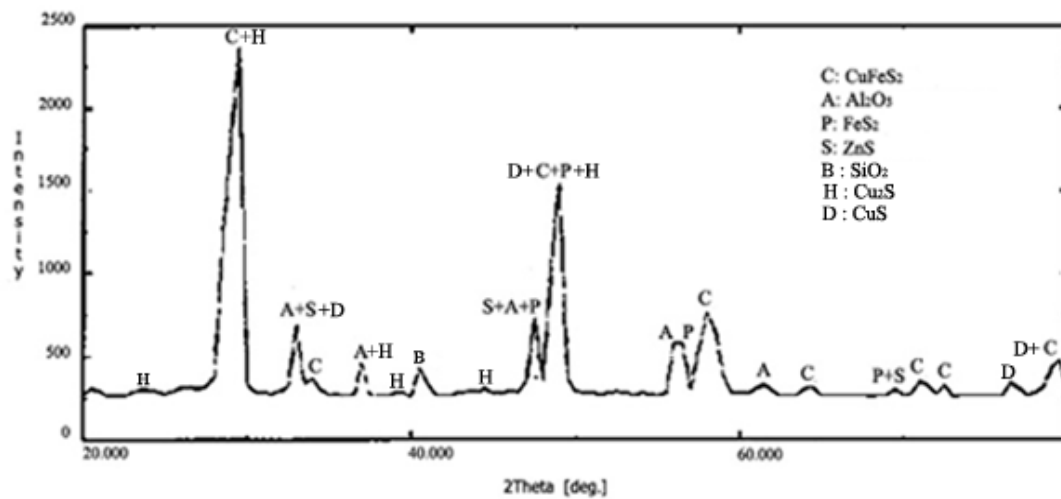


Figure 1. X-Ray diffractogram of the chalcopyrite concentrate



Figure 2. SEM photograph of the chalcopyrite concentrate

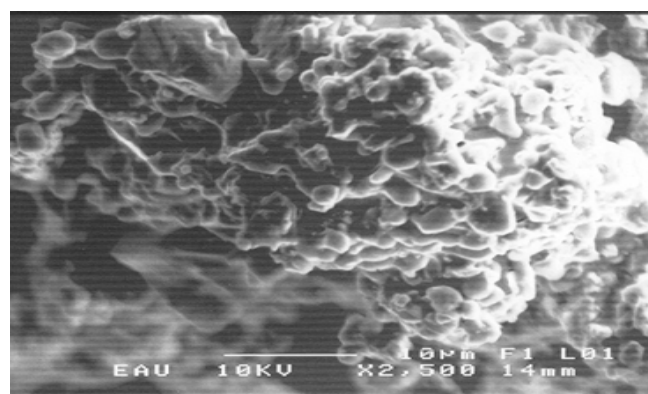


Figure 3. SEM photograph of undissolved solid portion during the reaction

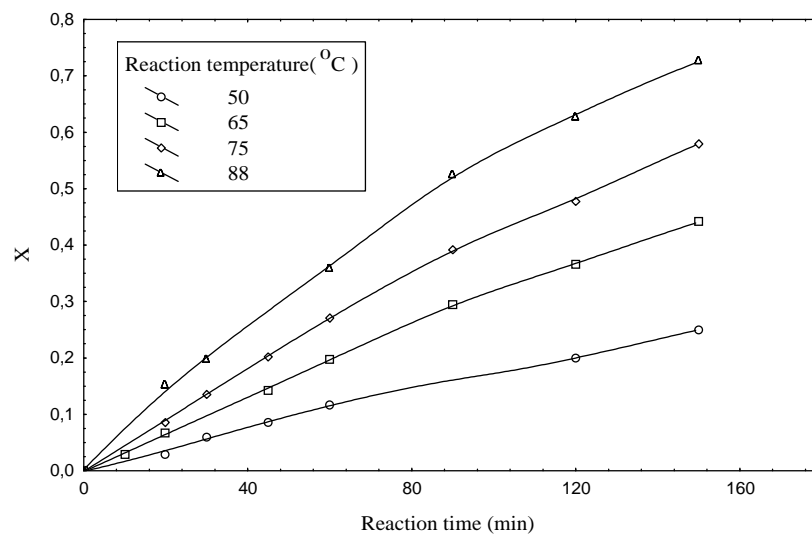


Figure 4. Effect of reaction temperature on dissolution of chalcopyrite concentrate

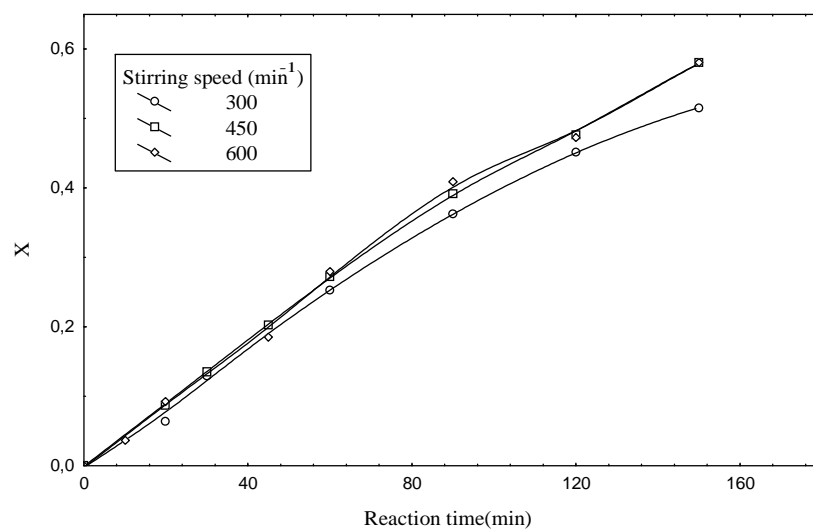


Figure 5. Effect of stirring speed on dissolution of chalcopyrite concentrate

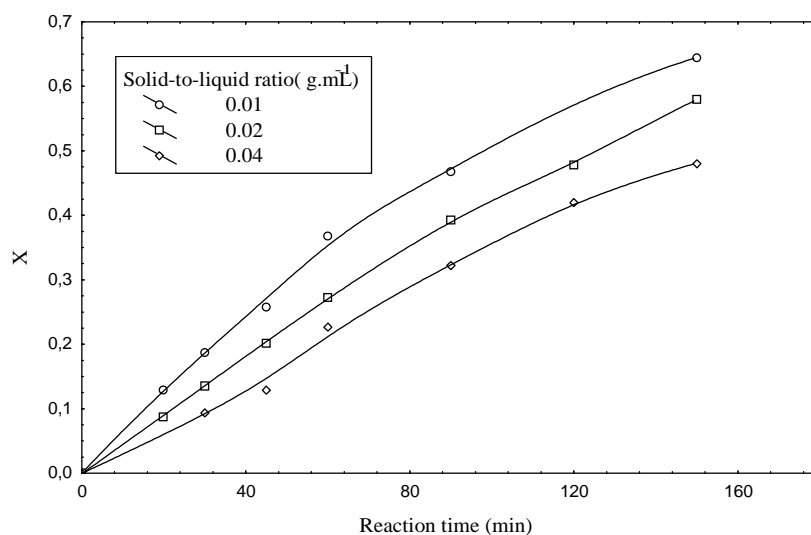


Figure 6. Effect of solid-to-liquid ratio on dissolution of chalcopyrite concentrate

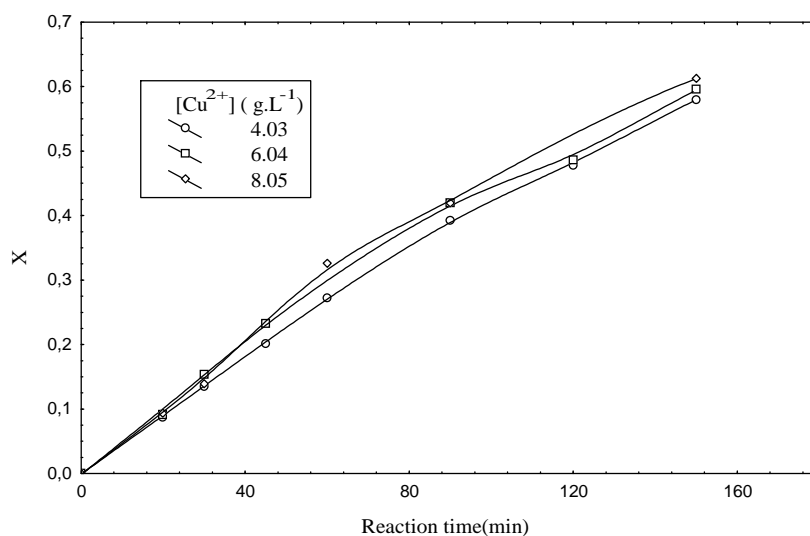


Figure 7. Effect of $[Cu^{2+}]$ on dissolution of chalcopyrite concentrate

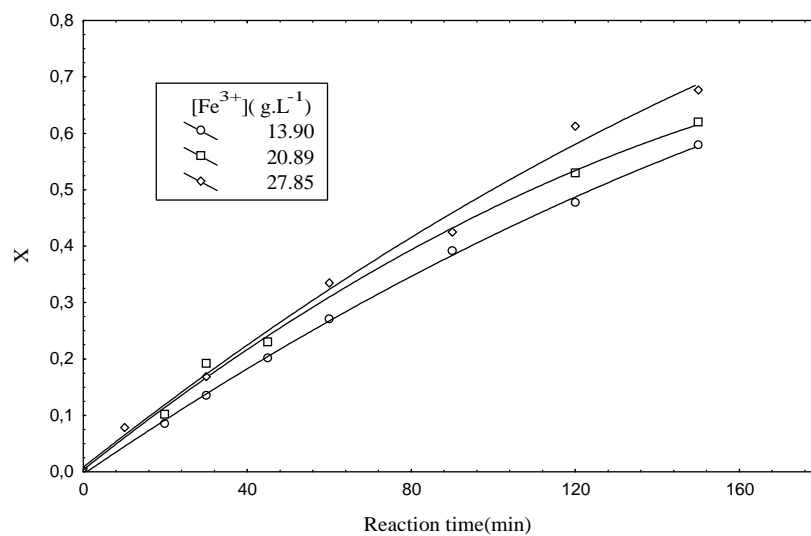


Figure 8. Effect of $[Fe^{3+}]$ on dissolution of chalcopyrite concentrate

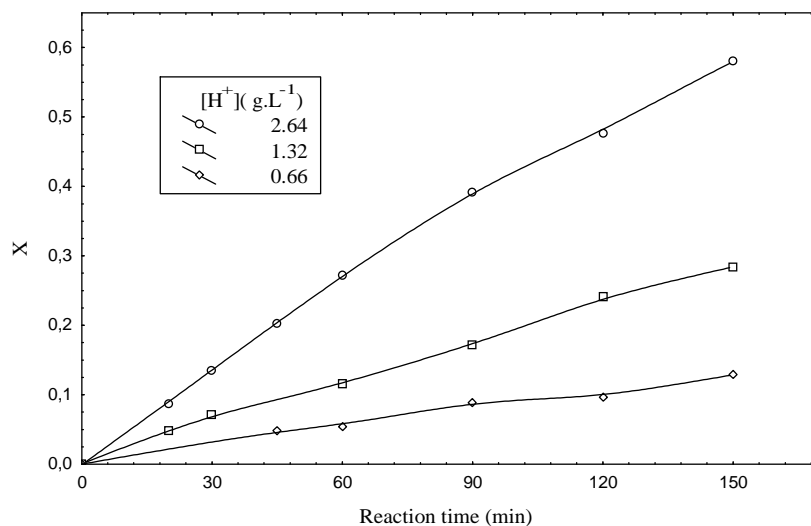


Figure 9. Effect of $[H^+]$ on dissolution of chalcopyrite concentrate

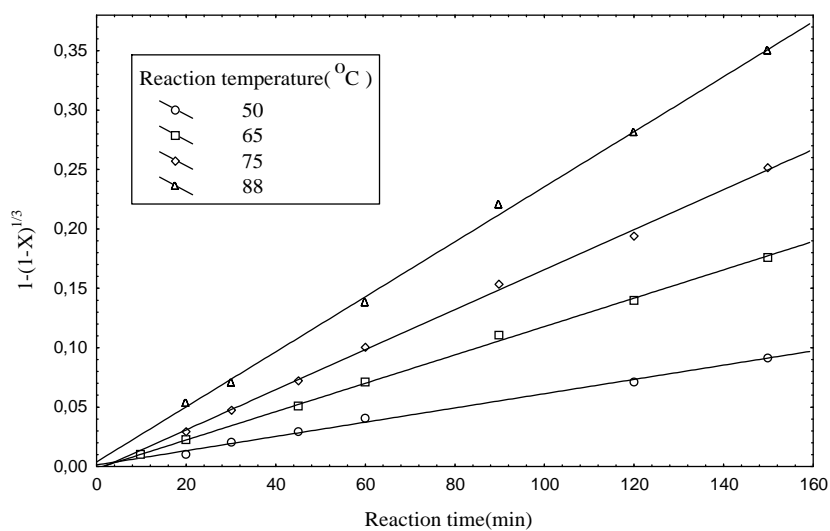


Figure 10. Plot of $1-(1-X)^{1/3}$ against reaction time for various reaction temperature

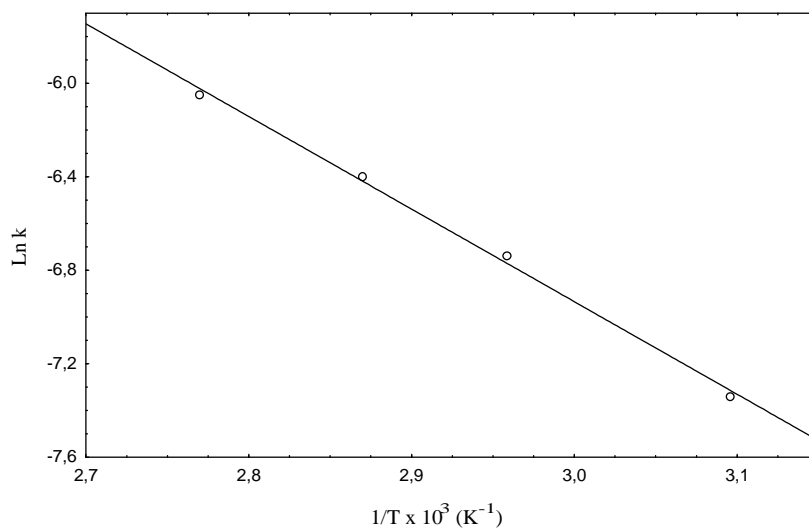


Figure 11. Graph of $\ln k$ versus $1/T$ for dissolution process in the reaction temperature range 50-88 °C.

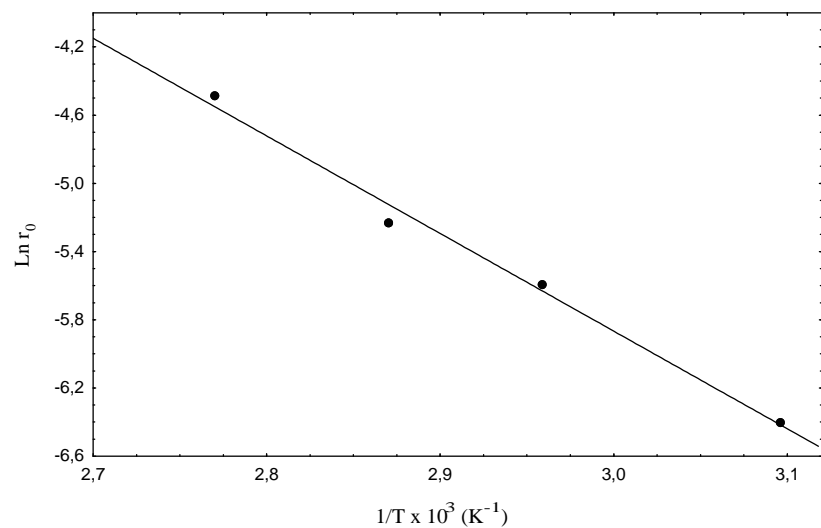


Figure 12. Graph of $\text{Ln } r_0$ versus $1/T$ for initial reaction rate

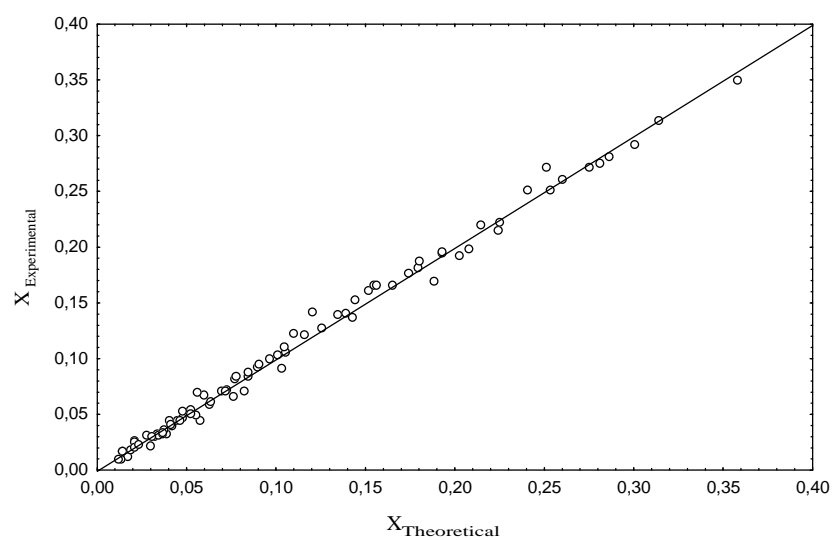


Figure 13. Comparison of experimental and theoretical conversion values from mathematical expression in Eq. 15