THE KINETICS OF INDONESIAN GALENA CONCENTRATE LEACHING IN FLUOROSILICIC ACID AND HYDROGEN PEROXIDE AS ITS OXIDANTS

KINETIKA PELINDIAN KONSENTRAT GALENA INDONESIA DALAM LARUTAN ASAM FLUOROSILIKAT DAN HIDROGEN PEROKSIDA SEBAGAI OXIDATOR

REZKY I. ANUGRAH¹ and M. ZAKI MUBAROK²
¹ Research and Development Centre for Oil and Gas Technology "LEMIGAS"
Jalan Ciledug Raya Kaveling 109, Cipulir, Kebayoran Lama,
South Jakarta 12230, Indonesia
e-mail: rezkyia.2407@gmail.com
² Department of Metallurgical Engineering, Faculty of Mining and Petroleum Engineering,
Bandung Institute of Technology
Jalan Ganesha, 10, Bandung, 40132, West Java, Indonesia

ABSTRACT

Lead smelting is known as a lead extraction technique which has negative impact to environment because it produces emissions of dust, SO₂ gas and lead. The leaching is conducted to reduce the smelting’s weaknesses by extracting the lead without damaging the environment. This technique, often called hydrometallurgical lead extraction, uses liquid media to extract the lead and separate it from the elemental sulphur (S⁰) by filtration. Particle size, slurry density (solid percentage) and acid concentration affect the dissolution of Indonesian galena concentrate with fluorosilicic acid and hydrogen peroxide as oxidants. By means of these reagents, it is expected that the Pb extraction process from galena concentrate resulted from flotation of sulfide ore can be carried out at low temperatures and lead recovery can be accomplished from the leach solution by electrowinning. Studying galena leaching kinetics is required to perform galena leaching with high Pb extraction percentages. Two kinetics models are commonly used to study leaching kinetics, namely shrinking core model (SCM) and shrinking particle model (SPM). These models are used to determine the mechanism which controls leach reaction and reaction rate constant or diffusion constant of the reacting species. Total plotting of sulfide fraction dissolved with time adjusted to the existing mathematical model, and fitting the curve from the dummy model to the experimental data, are two techniques that are utilized to obtain the best kinetics model which is important in controlling the leaching reaction rate. Applying the Arrhenius equation, the relation between the reaction rate constant or the diffusion constant and the temperature is determined to calculate the leaching activation energy. The result from kinetics analysis showed that the leaching of Indonesian galena concentrate in fluorosilicic acid with hydrogen peroxide as oxidants followed the shrinking core model with diffusion through porous solid product layer as the reaction controller with activation energy of 45.81 kJ/mol or 10.91 kcal/mol.

Keywords: galena concentrate, leaching, fluorosilicic acid, kinetics, activation energy.

ABSTRAK

Peleburan timah dikenal sebagai teknik ekstraksi timah yang memiliki dampak negatif terhadap lingkungan karena menghasilkan emisi debu, gas SO₂ dan timah. Pelindian hadir untuk mengurangi sejumlah kelemahan peleburan, dengan mengekstraksi timbal tanpa merusak lingkungan. Teknik ini, yang sering disebut ekstraksi timbal secara hidrometalurgi, menggunakan media cair untuk mengekstraksi timbal dan memisahkananya dari unsur sulfur (S⁰) melalui penyaringan. Ukuran partikel, berat jenis bubur (persentase padatan) dan konsentrasi asam mempengaruhi keleratan konsentrat galena Indonesia dalam asam fluorosilikat dan hidrogen peroksida sebagai oksidator. Dengan menggunakan reagen-reagen...
Lead smelting is believed to have a number of impacts on the environment because it produces emissions of dust, \( \text{SO}_2 \) gas and lead. To overcome such smelting’s weaknesses, leaching is a promising process to extract lead without damaging the environment.

In hydrometallurgical lead extraction, sulphur is separated from the Pb as the elemental sulphur (\( S^\text{\textdegree} \)) and removed by filtration. The produced elemental sulfur is a porous solid and does not inhibit the dissolution of galena and becomes a sell-able by-product (Aydoğan et al., 2007). The dissolution of Indonesian galena concentrate in fluorosilicic acid and hydrogen peroxide as oxidants is affected by its particle size, slurry density (solid percentage) and acid concentration (Anugrah, Mubarok and Amalia, 2018). With fluorosilicic acid and hydrogen peroxide as oxidants it is expected that the Pb extraction process from galena concentrate resulting from flotation of sulfide ore can be carried out at low temperatures, and lead recovery can be carried out from the leach solution by electrowinning. To perform galena leaching with high Pb extraction percentages, it is necessary to study its kinetics. Leaching kinetics were studied using a shrinking core model (SCM) and a shrinking particle model (SPM) as determinant mechanism which controls leach reaction and the reaction rate constant or diffusion constant of the reacting species. In this research, through the Arrhenius equation, the relation of the reaction rate constant or the diffusion constant is determined by temperature to calculate the leaching activation energy.

**INTRODUCTION**

Reaction kinetics provides information about the reaction rate until equilibrium is reached. Dissolution of Pb from galena with \( \text{H}_2\text{SiF}_6 \) in the presence of \( \text{H}_2\text{O}_2 \) may be performed through Eq.(1) while parts of sphalerite and pyrite in the concentrate will be also dissolved through Eq. (2) and (3) (Anugrah, Mubarok and Amalia, 2017).

\[
PbS(S) + \text{H}_2\text{SiF}_6(aq) + \text{H}_2\text{O}_2(aq) \rightarrow \text{PbSiF}_6(aq) + \text{SO}^+ + 2\text{H}_2\text{O}(aq) \tag{1}
\]

\[
\text{ZnS}(s) + \text{H}_2\text{SiF}_6(aq) + \text{H}_2\text{O}_2(aq) \rightarrow \text{ZnSiF}_6(aq) + \text{SO} + 2\text{H}_2\text{O}(aq) \tag{2}
\]

\[
\text{FeS}_2(s) + \text{H}_2\text{SiF}_6(aq) \rightarrow \text{FeSiF}_6(aq) + 2\text{SO} + 2\text{H}_2\text{O}(aq) \tag{3}
\]

The chemical stability of hydrogen peroxide is very sensitive to temperature (Pecina et al., 2008) therefore the oxidant should be poured into the reactor in a short time interval. According to Pecina et al. (2008), the leaching of sulfide minerals in an acidic atmosphere follows the shrinking core model (SCM) which assume the particle size does not change and the particles are spherical.

Mathematical models for each type of reaction rate controller that follows the SCM are formulated as follows (Levenspiel, 1999).
1. Diffusion through a fluid film on a mineral surface
\[ \frac{\tau}{t} = 1 - (1 - X_T) = X_T \] \hspace{1cm} (4)
\[ \tau = \frac{\rho T R}{3b_k C} \] \hspace{1cm} (5)

2. Diffusion through layer of the porous solid product (ash)
\[ \frac{\tau}{t} = 1 - 3 (1 - X_T)^3 + 2 (1 - X_T) \] \hspace{1cm} (6)
\[ \tau = \frac{\rho T R^2}{6b D_e C H_2 SiF_6} \] \hspace{1cm} (7)

3. Interface reaction
\[ \frac{\tau}{t} = 1 - (1 - X_T)^\frac{1}{3} \] \hspace{1cm} (8)
\[ \tau = \frac{\rho T R^2}{b k'' C} \] \hspace{1cm} (9)

Meanwhile the mathematical models of the controller following the SPM are formulated as follows (Levenspiel, 1999).

1. Diffusion through a fluid film on a mineral surface
\[ \frac{\tau}{t} = 1 - (1 - X_T)^\frac{2}{3} \] \hspace{1cm} (10)
\[ \tau = \frac{\rho T R^2}{2b D_e C} \] \hspace{1cm} (11)

2. Interface reaction
\[ \frac{\tau}{t} = 1 - (1 - X_T)^\frac{2}{3} \] \hspace{1cm} (12)

\[ \tau = \frac{\rho T R}{b k C} \] \hspace{1cm} (13)

where \( t \) is the leaching time, \( \tau \) is the residence time of leaching until the metal sulfides in the galena concentrate has totally dissolved and \( X_T \) is the total sulfides fraction that dissolves at the time \( t \). For leaching of galena concentrate, it is assumed that the core is shrinking due to the dissolution of PbS, ZnS and FeS\(_2\) and leaving sulfur behind so that \( X_T \) is calculated from the total of the moles metallic sulfides dissolved and then it is divided by the moles of the metallic sulfides in the feed (galena concentrate), where \( R \) is the average of particles radius, \( \rho T \) are the specific molar of the ore, \( b \) is the ratio of the stoichiometric coefficient to the acid. \( C_{H_2 SiF_6} \) is a concentration of the fluorosilicic acid reagent, \( k_l \) is the diffusion coefficient in the diffusion film, \( D_e \) is the coefficient in the porous solid (ash) layer and \( k'' \) is the reaction rate constant.

The experiments were performed for 150 minutes with a feed weight of 10.66 g, stirrer speed of 300 rpm, \( H_2 SiF_6 \) volume of 295.38 ml and \( H_2 O_2 \) volume of 103.88 ml.

The procedure for conducting a kinetics study of leaching galena concentrate can be seen in the following flow chart (Figure 1).
RESULTS AND DISCUSSIONS

According to the previous research, Anugrah, Mubarok and Amalia (2018) has determined the chemical composition of the galena concentrate as the Table 1 shows.

Table 1. Chemical composition of the galena concentrate sample (as-received sample) (Anugrah, Amalia and Mubarok, 2018)

| Element | Content (%) |
|---------|-------------|
| Pb      | 66.6        |
| Zn      | 7.38        |
| Cu      | 0.84        |
| Fe      | 2.79        |
| S       | 17.62       |
| Sb      | <0.001      |
| Mo      | 0.12        |
| Co      | <0.001      |

It is assumed that the dissolved metallic sulfide minerals are PbS (galena), ZnS ( sphalerite) and pyrite (FeS₂). By inputting the data of the Pb, Zn and Fe metals dissolved in fluorosillicic acid and those of the Table 1, then the mole of the metallic sulfides dissolved and Xᵣ can be calculated as shown by Table 2.

According to Astuti et al. (2016), the kinetics of the leaching reaction were examined over a specific temperature range. Leaching kinetics analysis was carried out from leaching experiment data at 50, 65, 85 and 97°C. Profiles of the fraction of the total mole of the converted sulfide (Xᵣ) against time (t) for each leaching temperature are presented in Figures 1 to 4.

Table 2. Calculation of Pb, Zn and Fe sulfides dissolved mole and the fraction of the total dissolved sulfides (Xᵣ)

| Temp. (°C) | Minutes | Hours | Metals dissolved (g/L) | Mole of the dissolved metals | Mole of the metallic sulfides dissolved | Xᵣ |
|------------|---------|-------|------------------------|-----------------------------|----------------------------------------|-----|
| 50         | 0.00    | 0.00  | 0.00                   | 0.00                        | 0.00                                   | 0.00 |
|            | 5.00    | 0.05  | 1.87                   | 0.05                        | 0.06                                   | 0.06 |
|            | 15.25   | 0.11  | 2.89                   | 0.13                        | 0.0056                                 | 0.0056 |
|            | 25.42   | 0.15  | 3.79                   | 0.30                        | 0.0073                                 | 0.0073 |
|            | 35.58   | 0.18  | 4.71                   | 0.33                        | 0.0091                                 | 0.0091 |
|            | 75.125  | 0.26  | 7.33                   | 0.58                        | 0.0141                                 | 0.0141 |
|            | 125.225 | 0.30  | 7.58                   | 0.70                        | 0.0146                                 | 0.0146 |
|            | 150.50  | 0.30  | 7.94                   | 0.72                        | 0.0153                                 | 0.0153 |
| 65         | 0.00    | 0.00  | 0.00                   | 0.00                        | 0.00                                   | 0.00 |
|            | 5.00    | 0.05  | 7.26                   | 0.63                        | 0.0140                                 | 0.0140 |
|            | 15.25   | 0.20  | 7.83                   | 0.64                        | 0.0151                                 | 0.0151 |
|            | 25.42   | 0.23  | 10.15                  | 0.64                        | 0.0196                                 | 0.0196 |
|            | 35.58   | 0.26  | 10.64                  | 0.67                        | 0.0203                                 | 0.0203 |
|            | 75.125  | 0.30  | 11.19                  | 0.75                        | 0.0216                                 | 0.0216 |
|            | 125.225 | 0.30  | 11.38                  | 0.85                        | 0.0219                                 | 0.0219 |
|            | 150.50  | 0.30  | 11.35                  | 0.88                        | 0.0219                                 | 0.0219 |
| 85         | 0.00    | 0.00  | 0.00                   | 0.00                        | 0.00                                   | 0.00 |
|            | 5.00    | 0.05  | 12.40                  | 0.50                        | 0.0239                                 | 0.0239 |
|            | 15.25   | 0.18  | 10.40                  | 0.74                        | 0.0200                                 | 0.0200 |
|            | 25.42   | 0.23  | 15.37                  | 0.79                        | 0.0296                                 | 0.0296 |
|            | 35.58   | 0.26  | 14.75                  | 0.84                        | 0.0284                                 | 0.0284 |
|            | 75.125  | 0.30  | 14.35                  | 1.02                        | 0.0277                                 | 0.0277 |
|            | 125.225 | 0.30  | 13.04                  | 1.52                        | 0.0251                                 | 0.0251 |
|            | 150.50  | 0.30  | 14.96                  | 1.77                        | 0.0288                                 | 0.0288 |
| 97         | 0.00    | 0.00  | 0.00                   | 0.00                        | 0.00                                   | 0.00 |
|            | 5.00    | 0.05  | 11.54                  | 1.18                        | 0.0222                                 | 0.0222 |
|            | 15.25   | 0.22  | 12.56                  | 1.22                        | 0.0242                                 | 0.0242 |
|            | 25.42   | 0.29  | 13.93                  | 1.28                        | 0.0261                                 | 0.0261 |
|            | 35.58   | 0.30  | 15.62                  | 0.96                        | 0.0301                                 | 0.0301 |
|            | 75.125  | 0.31  | 16.41                  | 0.93                        | 0.0316                                 | 0.0316 |
|            | 125.225 | 0.31  | 16.20                  | 1.50                        | 0.0312                                 | 0.0312 |
|            | 150.50  | 0.31  | 17.08                  | 2.67                        | 0.0329                                 | 0.0329 |
Figure 1 shows the total mole of the converted sulfide increased as the leaching times increased. Figure 2 to 4 show the similar tendency compared to Figure 1 but after 15 minutes of leaching, the $X_T$ slightly declined then rose following the increase in temperature. The $X_T$ declined at minutes of 15 because there was a probably porous solid product formation which will be examined in the next stage.

Based on the SCM, the reaction kinetics will be controlled by (Şahin and Erdem, 2015):
1. Diffusion through fluid film if the plot of $X_T$ and $t$ was linear
2. Diffusion through the porous solid product (ash) layer if plot of $1-3(1-X_T)^{2/3}+ 2(1-X_T)$ and $t$ was linear
3. Interface reaction if the plot of $1-(1-X_T)^{1/3}$ and $t$ was linear.

Meanwhile, based on the SPM, the reaction kinetics will be controlled by:
1. Diffusion through fluid film if the plot of $1-(1-X_T)^{2/3}$ and $t$ was linear
2. Chemical reaction on the interface if the plot of $1-(1-X_T)^{1/3}$ and $t$ was linear.

All of those plots, both SCM and SPM are presented at these following Figures 5 to 9:
A summary of $R^2$ values which was obtained from the linear regression equations of experimental data with all the kinetic models was used for each leach temperature and presented in Table 3.

Based on Table 3, the value of $R^2$ which close to 1 was obtained from the experimental data of the linear regression of SCM for porous solid layer diffusion. It concludes that the most suitable model for analyzing the leaching kinetics of galena concentrate in fluorosilicic acid solution was a SCM model with diffusion of porous solid product layer as chemical reaction controller.

The selection of reaction rate controller was also done by a method which is fitting the curve from the dummy model to the experimental data. For this purpose, the value of $\tau$ (time needed for all minerals to react completely when $X_T = 1$) needs to be calculated first. The value of $\tau$ was determined from the slopes of all linear equations following the SCM for porous solid layer diffusion as reaction controller since its $R^2$ was closer to 1 than other types have. $\tau = 1/slope$ was determined from linear regression of $1-3(1-X_T)2/3 + 2(1-X_T)$ to $t$. Table 4 presents the values of $\tau$ from leaching at 50, 65, 85 and 97°C.

From the values of $\tau$, dummy curve was constructed that was fitting to the experimental data by plotting the values of $X_T$ orderly from 0 to 1 and determined the time that was suitable for the simulated $X_T$. This
The Kinetics of Indonesian Galena Concentrate Leaching … Rezky I. Anugrah and M. Zaki Mubarok

The procedure was conducted for all the leaching temperatures. The result for fitting the dummy curve to the experimental data is presented at Figures 10 to 13.

Table 3. Summary of $R^2$ values which is obtained from the linear regression equations of experimental data with all the kinetic models used for each leach temperature

| Temperature (°C) | R$^2$ for each kinetics models of reaction rate controller |  |
|------------------|----------------------------------------------------------|--|
|                  | SCM                                                      | SPM                                      |
|                  | Fluid film diffusion                                     | Porous layer diffusion                   | Interface reaction | Fluid film diffusion | Interface reaction |
| 50               | 0.628                                                    | 0.944                                    | 0.716              | 0.674              | 0.716              |
| 65               | -1.88                                                    | 0.041                                    | -1.67              | -1.78              | -1.67              |
| 85               | -1.02                                                    | 0.445                                    | -0.28              | -0.66              | -0.28              |
| 97               | -1.01                                                    | 0.635                                    | 0.177              | -0.42              | 0.177              |

Table 4. The determination of $\tau$ from the line equations of the diffusion through porous solid layer

| Temperature (°C) | Equation       | Slope  | $\tau$ (minutes) | $\tau$ (hours) |
|------------------|----------------|--------|------------------|----------------|
| 50               | $y=0.0005x$    | 0.0005 | 2000.00          | 33.33          |
| 65               | $y=0.001x$     | 0.001  | 1000.00          | 16.67          |
| 85               | $y=0.003x$     | 0.003  | 333.33           | 5.56           |
| 97               | $y=0.004x$     | 0.004  | 250.00           | 4.17           |

Figure 10. Fitting dummy curve model to experimental data at 50°C leaching temperature

Figure 11. Fitting dummy curve model to experimental data at 65°C leaching temperature

Figure 12. Fitting dummy curve model to experimental data at 85°C leaching temperature

Figure 13. Fitting dummy curve model to experimental data at 97°C leaching temperature
From all the graphs in the dummy models to the experimental data fitting curves, it shows that the dummy curve of the SCM kinetics model was controlled by diffusion through a porous solid layer which was the closest to the experimental data. This curve fitting result convinces the previous conclusion which used kinetics analysis with linear regression. Again, the reaction rate of the galena concentrate leaching in fluorosilicic acid was controlled by the diffusion through the porous solid products (ash) layer.

Activation energy ($E_a$) is determined from the Arrhenius equation for diffusion controller through the porous solid products (ash) layer (Levenspiel, 1999):

$$D_e = D_0 \exp \left(\frac{-E_a}{RT}\right) \quad \ldots \ldots \ldots \ldots (14)$$

or

$$\ln D_e = \frac{-E_a}{RT} + \ln D_0 \quad \ldots \ldots \ldots \ldots (15)$$

By plotting $1-3\left(1-X_T\right)^{2/3}+2\left(1-X_T\right)$ to $t$ (time), the gradient or slope ($m$) was determined and thus $D_e$ was also calculated by using the following formula.

$$D_e = m \frac{\rho_TR^2}{6bCH_2SiF_6} \quad \ldots \ldots \ldots \ldots (16)$$

Where $\rho_T$ is total sulfide molar density, $R$ is particle radius, $CH_2SiF_6$ is fluorosilicic acid concentration and $b$ is stoichiometric ratio of feed to fluorosilicic acid. The concentration of the fluorosilicic acid was 3.44 M or $CH_2SiF_6 = 3.44$ mol/litre = 3,440 mol/m$^3$. Total sulfide molar density was calculated by the following formula:

$$\rho_T = \frac{\text{total sulfide mol}}{\text{total volume}} \quad \ldots \ldots \ldots \ldots (17)$$

The galena specific density was 6.04 g/cm$^3$ (6,040 kg/m$^3$). The kinetics experiment was performed by using 10.66 g feed so that the total sulfide mol of PbS, ZnS and FeS$_2$ dissolved was 0.0516 mol. These data was put into equation (17)

$$\rho_T = \frac{0.0516 \text{ mol x 6,040 kg/m}^3}{10.66 \text{ gram}}$$

$$\rho_T = 29,236.77 \text{ mol/m}^3$$

The feed particle size ($P_{80}$) was -100+150 mesh, therefore the average diameter of the particles was

$$D = \frac{(100+150)\text{mesh}}{2} = 125 \text{ mm}$$

or the particles radius ($R$) was

$$R = \frac{D}{2} = \frac{0.1245 \text{ mm}}{2} = 0.0622 \text{ mm}$$

$$R = 0.0622 \times 10^{-3} \text{ m}$$

Based on the previous experiment (Anugrah, Mubarok and Amalia, 2018), the values and the $b$ of the converted mole fractions from the dissolution of galena concentrate’s mineral sulfides, are presented in Table 5.

The next step was calculating $D_e$ based on equation (16) from the gradient of the line equation for porous solid layer diffusion at different leaching temperatures. Then $1/T$ and $\ln D_e$ were also calculated according to Table 6.

Table 5. The calculation of the sulfide minerals converted fraction and the value of b

| Sulfides | Content | Feed weight (g) | Weight (g) | Mole | Mole fraction (X) | b  | bX   |
|----------|---------|----------------|------------|------|------------------|----|------|
| PbS      | Pb      | 66.60%         | Pb 7.0996  | PbS  | 0.0343           | 0.6638 | 1   |
| ZnS      | Zn      | 7.38%          | Zn 0.7867  | ZnS  | 0.0120           | 0.2331 | 1   |
| FeS$_2$  | Fe      | 2.79%          | Fe 0.2974  | FeS$_2$ | 0.0053         | 0.1032 | 1   |
| **Total**|         |                |            |      | **0.0516**       | 1.0000 | **1.0000** |
Table 6. ln $D_e$ and 1/T calculation

| Temperature °C | K  | Slope (m) | $D_e$ (m/s) | 1/T   | ln $D_e$ |
|---------------|----|-----------|-------------|-------|---------|
| 50            | 323| 0.0005    | 2.74013E-12| 0.003096| -26.6230|
| 65            | 338| 0.0010    | 5.48025E-12| 0.002959| -25.9299|
| 85            | 358| 0.0030    | 1.64408E-11| 0.002793| -24.8313|
| 97            | 370| 0.0040    | 2.1921E-11  | 0.002703| -24.5436|

Plotting ln $D_e$ to 1/T results in a graph at Figure 14.

According to Figure 14, plotting ln $D_e$ to 1/T resulted in a linear line equation ($R^2 = 0.99$) with a gradient of -5,510. The activation energy was then calculated by the following calculation.

Activation energy ($E_a$) = gradient x R

= 5,510 K x 8.3143 J/K/mol
= 45,811.79 J/mol
= 45.81 kJ/mol
= 10.91 kcal/mol

Activation energy of 45.81 kJ/mol for diffusion-controlled reactions through porous solid layer can be categorized as high. According to Randhawa, Gharami and Kumar (2016), for the reaction that was controlled by diffusion mechanism, $E_a$ ranged between 1 to 3 kcal/mol and higher if it was controlled by chemical reaction. The high activation energy is was probably affected by Pb existence which undissolved because it reacted with $SO_4^{2-}$ ion forming PbSO$_4$ precipitate (Zárate-Gutiérrez, Lapidus and Morales, 2012). It can also be affected by a mineral existence which has low solubility in fluorosilicic acid such as chalcopyrite (CuFeS$_2$) (Zárate-Gutiérrez, Lapidus and Morales, 2010).

CONCLUSION

Leaching Indonesian galena concentrate in fluorosilicic acid and hydrogen peroxide as oxidants followed the shrinking core model with diffusion through porous solid product layer as the reaction controller with activation energy of 45.81 kJ/mol or 10.91 kcal/mol.

ACKNOWLEDGEMENT

The authors would like to express gratitude to the R & D Center for Mineral and Coal Technology for funding this research. The authors would also acknowledge the role of Indonesian Mining Journal editors for their assistance and direction to improve the quality of this paper.

REFERENCES

Anugrah, R. I., Mubarok, M. Z. and Amalia, D. (2017) ‘Study on the leaching behavior of galena concentrate in fluosilicic acid solution using hydrogen peroxide as oxidant’, in Proceedings of the 1st International Process Metallurgy Conference (IPMC 2016). Bandung: American Institute of Physics, pp. 030006-1-030006-7. doi: 10.1063/1.4974417.

Anugrah, R. I., Mubarok, M. Z. and Amalia, D. (2018) ‘Parameters that affect the dissolution of Indonesian galena concentrate in fluorosilicic acid and hydrogen peroxide’, Indonesian Mining Journal, 21(2), pp. 89–97. doi: 10.30556/imj.Vol21.No2.2018.677.

Astuti, W., Hirajima, T., Sasaki, K. and Okibe, N. (2016) ‘Comparison of atmospheric citric acid leaching kinetics of nickel from different Indonesian saprolitic ores’, Hydrometallurgy, 161, pp. 138–151. doi: 10.1016/j.hydromet.2015.12.015.
Aydoğan, S., Erdemoğlu, M., Uçar, G. and Aras, A. (2007) ‘Kinetics of galena dissolution in nitric acid solutions with hydrogen peroxide’, *Hydrometallurgy*, 88(1–4), pp. 52–57. doi: 10.1016/j.hydromet.2007.03.005.

Levenspiel, O. (1999) ‘Chemical reaction engineering’, *Industrial & Engineering Chemistry Research*, 38(11), pp. 4140–4143. doi: 10.1021/ie990488g.

Pecina, T., Franco, T., Castillo, P. and Orrantia, E. (2008) ‘Leaching of a zinc concentrate in H2SO4 solutions containing H2O2 and complexing agents’, *Minerals Engineering*, 21(1), pp. 23–30. doi: 10.1016/j.mineng.2007.07.006.

Randhawa, N. S., Gharami, K. and Kumar, M. (2016) ‘Leaching kinetics of spent nickel–cadmium battery in sulphuric acid’, *Hydrometallurgy*, 165, pp. 191–198. doi: 10.1016/j.hydromet.2015.09.011.

Şahin, M. and Erdem, M. (2015) ‘Cleaning of high lead-bearing zinc leaching residue by recovery of lead with alkaline leaching’, *Hydrometallurgy*, 153, pp. 170–178. doi: 10.1016/j.hydromet.2015.03.003.

Zárate-Gutiérrez, R., Lapidus, G. T. and Morales, R. D. (2010) ‘Pressure leaching of a lead–zinc–silver concentrate with nitric acid at moderate temperatures between 130 and 170°C’, *Hydrometallurgy*, 104(1), pp. 8–13. doi: 10.1016/j.hydromet.2010.04.001.

Zárate-Gutiérrez, R., Lapidus, G. T. and Morales, R. D. (2012) ‘Aqueous oxidation of galena and pyrite with nitric acid at moderate temperatures’, *Hydrometallurgy*, 115–116, pp. 57–63. doi: 10.1016/j.hydromet.2011.12.010.