THERMODYNAMIC AND KINETICS ANALYSIS OF THE SULFUR-FIXED ROASTING OF ANTIMONY SULFIDE USING ZnO AS SULFUR-FIXING AGENT


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Abstract

Currently, the commercial antimony metallurgy is mainly based on pyrometallurgical processes and oxidative volatilization of Sb2S3 is an essential step. This step includes the problems of high energy consumption and low concentration of SO2 pollution. Aiming at these problems, we present a new method of sulfur-fixing roasting of antimony sulfide. This method uses ZnO as a sulfur-fixing agent, and roasting with Sb2S3 was carried out at 673 K~1073 K to produce Sb2O3 and ZnS. By calculating the thermodynamics of the reactions, we can conclude that the Gibbs Free Energy Change (ΔGθ) of roasting reaction is below -60 kJ/mol and the predominance areas of Sb2O3 and ZnS are wide and right shifting with the temperature increase, which all indicates that this method is theoretically feasible. The reacted products between Sb2S3 and ZnO indicated that the reaction began at 773 K and finished approximately at 973K. We used the Ozawa-Flynn-Wall, Kissinger and Coats-Redfern method to calculate the kinetics of the roasting reaction. The conclusion is as follows: The average values of apparent activation energy (E) and natural logarithmic frequency factor (lnA) calculated by Ozawa-Flynn-Wall, Kissinger and Coats-Redfern were 189.72 kJ·mol-1 and 35.29 s-1, respectively. The mechanism of this reaction was phase boundary reaction model. The kinetic equation is shown as follow, where αrepresents reaction fraction:

1-(1-α)θ = 2.12×10^5 × \exp \left( \frac{1.90×10^4}{RT} \right) t

Keywords: Antimony sulfide; Zinc oxide; Sulfur-fixing; Kinetics; Roasting.

1. Introduction

Antimony is mainly used in the production of flame retardants and the manufacture of battery materials, sliding bearings ammunition and solders [1]. Most of the resources of antimony known in the world are distributed in China, accounting for 80% [1-2]. At present, the main mineral for producing antimony is stibnite (Sb2S3) and jamesonite (Pb,FeSb,S3) [3-5]. The traditional method for the production of antimony is volatilization smelting followed by reduction smelting [6-7], which consists of two steps: oxidative volatilization of Sb2S3 and reducing smelting of Sb2O3 [8-9]. The reduction smelting is relatively mature and the main equipment is reverberatory furnace with soda addition. However, the oxidative volatilization of Sb2S3 is the key process and a large numbers of studies were carried out. At present, the main equipment is blast furnace in practice using air or oxygen-enriched air to oxidize Sb2S3 and then generate Sb2O3 and SO2. The characteristics of this method are thin material layer, high coke rate, and high temperature of furnace roof (>1273K). The disadvantages are high energy consumption and low concentration SO2 smoke pollution (<6%). Meanwhile, arsenic, a drug substance associated with Sb2S3 ore, is also volatile at high temperature causing environment hazardous.

Hydrometallurgical process, including the acidity and alkaline methods and consisting of a two steps of leaching and electrodereposition, can be used for both simple and complex antimony ore. In practice, NaOH-Na2S [10] and FeCl3/SbCl5-HCl [11] were the main leaching reagents, direct electrowinning, membrane electrowinning and slurry electrolysis method were the subsequent process of Sb extraction. Samuel a. Awe [12-13] investigated recovering metallic antimony from the copper and sulfur concentrate containing antimony by selective leaching in alkaline sulphide solution. Yang [14] investigated separation and recovery of Sb from stibnite using SbCl3-HCl as a leaching reagent and it was regenerated by electrowinning. These methods eliminate the atmospheric pollution caused by SO2. However, the shortcomings are the discharge of a large amount of wastewater, equipment corrosion and low current efficiency. Only a few plants applied it to produce antimony white products.
In the area of pyrometallurgy, Liu [15] investigated the bath smelting process of stibnite by using bottom blow furnace and fuming furnace. The advantages are a high volatilization rate of Sb and the elimination of the briquetting process. Hua [16] studied the selective oxidation of antimony sulphide by water vapor. The maximum direct recovery rate of lead and antimony were 97% and 85%. These new methods have improved the traditional process and strengthened the environmental protection. However, the main shortcomings are flue bonding by antimony oxide and valuable metal dispersion at high temperature (>1373K). Generally, these methods have enhanced antimony metallurgy, but there are all far away from industrial manufacture.

Aiming at the problems of SO2 pollution and the difficulty of Sb2O3 production at high temperature, R. Padilla [17] adopted the direct reduction of metal sulfides in the presence of lime. In this method, lime and carbon were used as the sulfur-fixing agent and reductant, respectively, and metallic Sb and CaS were the final products. This method solved the problem of SO2 pollution and realized the direct produce of Sb. However, this method consumed a large amount of lime and generated large amounts of calcium sulfide slag, which is not easy to be separated and utilized again. Our team [18] once proposed a one-step process to extract antimony from low-grade stibnite in Na2CO3-NaCl binary molten salt at a low temperature (873-1173K). However, the regeneration of molten salt was difficult.

In view of the above issues, we proposed a sulfur-fixing and low temperature roasting process to produce Sb2O3 using a reproducible and available sulfur-fixing agent to replace lime, and Sb2O3 can be volatilized for separation from roasted products, or the sulfide can be separated by flotation. Then the Sb2O3 can be engaged in the reducing process by the current reverberatory furnace process. Meanwhile, a large amount of zinc oxide (ZnO) ash was produced in lead and zinc smelter [19-20], and its main component was ZnO (>70%) while contained fluorine (>0.2%) and chlorine (>0.3%). If it is directly returned to the lead and zinc smelter [19-20], and its main component large amount of zinc oxide (ZnO) ash was produced in the current reverberatory furnace process. Meanwhile, a large amount of zinc oxide (ZnO, Sinopharm Co. Ltd. PRC) and antimony sulfide (Sb2S3. WengJiang Reagent Co. Ltd. PRC) used for roasting experiments are all analytical grade. The roasting reactions were conducted in a tubular furnace (SGM, T60/12A, Sigma Furnace Co. Ltd. PRC). The thermogravimetric and differential scanning calorimetry instrument (TG-DSC, Universal V4.0C TA Instrument, USA) was used for the detection of thermal effects and weight changes between the reaction of ZnO and Sb2S3. The uniform mixture of ZnO Sb2S3 was prepared by solution dispersion using an ultrasonic machine (KQ5200DA, KunShan Ultrasonic Instrument Co. Ltd. PRC). The phase and morphology of the products were detected by X ray diffractometer (XRD, Rigaku D/max 2550VB + 18 kW) and scanning electron microscopy (JSM-6490LV, JEOL).

2. Experimental

2.1. Experimental agents and instruments

The raw materials included zinc oxide (ZnO, Sinopharm Co. Ltd. PRC) and antimony sulfide (Sb2S3, WengJiang Reagent Co. Ltd. PRC) used for roasting experiments are all analytical grade. The roasting reactions were conducted in a tubular furnace (SGM, T60/12A, Sigma Furnace Co. Ltd. PRC). The thermogravimetric and differential scanning calorimetry instrument (TG-DSC, Universal V4.0C TA Instrument, USA) was used for the detection of thermal effects and weight changes between the reaction of ZnO and Sb2S3. The uniform mixture of ZnO Sb2S3 was prepared by solution dispersion using an ultrasonic machine (KQ5200DA, KunShan Ultrasonic Instrument Co. Ltd. PRC). The phase and morphology of the products were detected by X ray diffractometer (XRD, Rigaku D/max 2550VB + 18 kW) and scanning electron microscopy (JSM-6490LV, JEOL).

2.2. The experimental procedure

The uniform mixture of Sb2S3 and ZnO was prepared by the following steps: (i) A total of 35 g of antimony sulfide and zinc oxide powder, both with the particle of 250~300 mesh, were weighed according to the mole ratio of equation (1); (ii) The mixture powder was pulpified by 75ml of alcohol with a mechanical mixer for 30min in the ultrasonic machine; (iii) The seriflux was dried in the blast oven at 323K, and the final drying mixture was sealed and kept in a dryer and used as a raw material for all experiments. In the roasting experiments, each 5g of the sample was pressed to a block cylinder (Ø1cm) at 12 MPa, and then it was charged in a crucible and located in the hot zone of the tube furnace in the temperature range of 673K to 1173K at argon atmosphere. After the predetermined reaction time, the crucible was quickly pushed out of the hot zone and quenched to room temperature at argon. The reactions that might occur during the roasting process are as follows [23-24]:

\[
\begin{align*}
Sb_S\cdot + 3ZnO &= Sb_2O_3 + 3ZnS \\
Sb_S\cdot + 2Sb + 3/2S_2(g) &= Sb_2O_3 \\
Sb_S\cdot + 2Sb + 3/2S_2(g) &= Sb_2O_3 + 3ZnS \\
ZnO + S_2(g) &= ZnO + SO_2(g)
\end{align*}
\]

After cooling sufficiently, the roasting products...
were grounded to fine particles for XRD and SEM detection. TG-DSC experiments, used for kinetics calculations, were carried out in nitrogen atmosphere at a flow of 100 mL/min with different heating rate of 5 K/min to 20 K/min. The kinetics equations were calculated by Ozawa-Flynn-Wall, Kissinger and Coats-Redfern methods by the following formulas [25-26]:

Mass action law: 
\[ \frac{dx}{dt} = k_f(\alpha) \]  

Arrhenius formula: 
\[ k = A \exp\left(\frac{-E}{RT}\right) \]  

Ozawa-Flynn-Wall method:
\[ \log\beta = \log\left(\frac{AE}{Rf(\alpha)}\right) - 2.315 - 0.4567 \frac{E}{RT} \]  

Kissinger method: 
\[ \ln\frac{\beta}{T_p^2} = \ln\frac{A}{E} - \frac{1}{R} \ln\frac{E}{T_p} \]  

Coats-Redfern method: 
\[ \ln\frac{G(\alpha)}{T_p} = \ln\frac{A}{E} - \frac{E}{RT} \]  

where \( \alpha \) is reaction fraction, \( \% \); \( t \) is reaction time, s; \( k \) is reaction rate constant, s\(^{-1}\); \( A \) is frequency factor, s\(^{-1}\); \( E \) is active energy, kJ/mol; \( R \) is gas constant 8.314, \( T \) is temperature, K; \( \beta \) the heating rate, K/min; \( n \) is reaction order number; \( T_p \) the peak temperature, K; \( f(\alpha) \) and \( G(\alpha) \) are integral expressions depended on the particular decomposition mechanism of solid reaction listed in Table 1 [27-29].

### Table 1. Reaction models and the corresponding functions of the solid reaction

<table>
<thead>
<tr>
<th>Symbol of reaction models</th>
<th>Reaction models</th>
<th>( G(\alpha) )</th>
<th>( f(\alpha) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_2 )</td>
<td>Power law</td>
<td>( \alpha^{1/2} )</td>
<td>( 2\alpha^{1/2} )</td>
</tr>
<tr>
<td>( P_3 )</td>
<td>Power law</td>
<td>( \alpha^{1/3} )</td>
<td>( 3\alpha^{2/3} )</td>
</tr>
<tr>
<td>( P_4 )</td>
<td>Power law</td>
<td>( \alpha^{1/4} )</td>
<td>( \alpha^{3/4} )</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>Phase boundary reaction</td>
<td>( \alpha )</td>
<td>( 1 )</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>Phase boundary reaction</td>
<td>( 1-(1-\alpha)^{1/2} )</td>
<td>( 2(1-\alpha)^{1/2} )</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>Phase boundary reaction</td>
<td>( 1-(1-\alpha)^{1/3} )</td>
<td>( 3(1-\alpha)^{2/3} )</td>
</tr>
<tr>
<td>( D_1 )</td>
<td>One-dimensional diffusion</td>
<td>( \alpha^2 )</td>
<td>( \alpha^{1/2} )</td>
</tr>
<tr>
<td>( D_2 )</td>
<td>Two-dimensional diffusion</td>
<td>( \alpha(1-\ln(1-\alpha)) )</td>
<td>( [-\ln(1-\alpha)]^{-1} )</td>
</tr>
<tr>
<td>( A_n )</td>
<td>Avrami-Erofeev ((n=1,2,3,4))</td>
<td>( [-\ln(1-\alpha)]^{1/n} )</td>
<td>( n(1-\alpha)[-\ln(1-\alpha)]^{1/(n-1)} )</td>
</tr>
</tbody>
</table>

### 3. Results and Discussion

#### 3.1. Thermodynamics Analysis

To investigate the feasibility of the roasting reactions, HSC software was used to calculate the predominance area and thermodynamic equilibrium of the Sb\(_2\)S\(_3\) - ZnO system, the results are shown in Fig.1. It can be seen from the Fig.1(a) that the objective areas of predominance were in equilibrium with the vapor phase at 773 K, 973 K and 1173 K, and the stable regions of Sb\(_2\)O\(_3\) and ZnS were presented with a wide concentration range of O\(_2\) partial pressure \( (P_{O_2}) \) \( 10^{-12} \) to \( 10^{-18} \) and sulfur partial pressure \( (P_{S_2}) \) \( 10^{-1.5} \) to \( 10^{-8.3} \) in the gas phase. Meanwhile, the equilibrium area of antimony oxide and zinc sulfide was gradually moving to the upper and right axis with the temperature increase. It shows that the \( P_{O_2} \) and \( P_{S_2} \) increased, so the equilibrium required conditions are easier to achieve. However, if the reaction equilibrium was conducted at a high partial pressure of gaseous sulfur, oxygen and temperature, then antimony sulfate would be yield and it was adverse for Sb\(_2\)O\(_3\) generation and reducing. Therefore, a relative oxygen-free or reducing atmosphere was needed, as well as a low roasting temperature. Fig. 1(b) shows...
that the ΔG° of the reaction (1) is negative in the
temperature range of 373 K to 1273 K, which
indicated that the interaction between zinc oxide and
antimony sulfide is a feasibility in thermodynamics.
For reaction (2) and reaction (3), the ΔG° values are
both positive between 373 K and 1273 K, so they are
not spontaneous in theory. But the ΔG° value of
equation (3) decreased quickly with the temperature
increase and it might occur at high temperatures.

3.2. Procedure analysis

The TG-DSC curves of the reaction between
Sb2S3 and ZnO with a heating rate of 10 K·min−1 is
presented in Fig.2(a). As shown in DSC curve, there
was an exothermic peak at 782.47 K and an
endothermic peak at 901.63 K. According to the TG
curve, we can see that the reaction has two stages of
weight losses. The losses rate of the weight for the
first stage is 2.36%, which was caused by the
volatilization of the raw mixture at the exothermic
peak of 782.47 K. In the second stage, the weight
losses rate was 15.78% might cause by the
volatilization of Sb2O3 and Sb2S3 at 901.63 K, which
is close to the melting-point of antimony oxide of
929.15 K. Meanwhile, R. Padilla once investigated
the volatilization of antimony sulfide and verified
that it would thoroughly volatilize at the
temperature ranges of 873 K to 1073 K [4], so this
20% weight loss of mixture is impossible by
volatilization of Sb2S3. In order to find out the phase
composition of the product in two weightlessness
stages, the XRD patterns of the samples obtained at
different temperatures are shown in Fig.2(b).

The roasted products at 673 K were basically
antimony sulfide and zinc oxide, which showed that
no reaction occurred. When temperature increased
to 773 K, the peaks of Sb2S3 and ZnO still existed
while the peaks of Sb2O3 and ZnS appeared. It
showed that the roasting reactions proceeded, but
not completely. With the temperature further
increased to 873 K, the peaks of Sb2S3 and ZnO
gradually disappeared, and only ZnS and Sb2O3 left.
However, the peak intensity of Sb2O3 was gradually
decreased. It is found that the vapor pressure of
Sb2O3 is 2.72 kPa and 6.13 kPa at 973 K and 1073
K, and increases quickly with the temperature
increase [30]. So, rapid weight at the second stages
in TG curves are caused by the volatilization of
Sb2O3. Based on the XRD results, it can be
supported that the first exothermic peak at 782.47 K
can be attributed to the interaction between Sb2S3
and ZnO, and the second endothermic peak was the
fusion of Sb2O3.

As shown in Fig.3, images and EDX spectra of
the roasting products obtained at 873 K and 1073 K
were also studied. It can be seen from the Fig.3 that
antimony oxide and zinc sulfide appeared in the
sample at 873 K and 1073 K, and it can be inferred
that the reaction was more sufficient for a simple
images composition at 1073 K. The ZnS was
random distributed in Sb2O3 particle, and the shape
of zinc sulfide is regular polygon. In addition, with
increasing the temperature, the Sb2O3 particles were
getting bigger because it melted at 1073 K and
gathered together. However, Fig.3(b) also indicated
that little metallic Sb was generated at 1073 K,
combined with the thermodynamic calculation, it
can be explained by the fact of interaction between
Sb2O3 and Sb2S3. Reaction smelting, which is the
cross reaction between Sb2S3 and Sb2O3, was once
application in practice for the Sb production
according to the reaction (3).
3.3. Kinetics analysis

The kinetics of roasting reactions was studied by DSC to obtain kinetic equation including the activation energy and reaction order. In general, three methods including Ozawa-Flynn-Wall, Kissinger and Coats-Redfern method are used for calculating the kinetics parameters. The results of DSC curves of the reaction between Sb$_2$S$_3$ and ZnO at different heating rate are shown in Fig.4. From this figure, it can be seen that all four DSC curves have the similar tendency and shape at the heating rates of 10 K/min, 15 K/min, and 20 K/min. However, the thermal effect at 5 K/min was gentle and the peak height was smaller. With the increase in temperature, the position of the peak gradually shifts to right. Based on the above issues, the first peak is the reaction peak of Sb$_2$S$_3$ and ZnO, and the second is the melting peak of Sb$_2$O$_3$. The relationship between the conversion rate and the heating temperature can be obtained by integrating the first peak, as shown in Fig.5. According to Fig.5, the reaction kinetics of Sb$_2$S$_3$ and Sb$_2$O$_3$ can be calculated.

Figure 3. The SEM images of the reaction products at 873K (a) and 1073K (b) and Energy spectrum diagrams of different region

Figure 4. DSC curves of Sb$_2$S$_3$-ZnO mixture reacted at different heating rates (a - 5 K/min, b - 10 K/min, c - 15 K/min, d - 20 K/min)
ZnO were calculated by Ozawa-Flynn-Wall method, Kissinger method and Coats-Redfern method.

As shown in Fig. 6, the relationships between \( \lg \beta \) and \( 1/T \) were calculated by Ozawa-Flynn-Wall method. The data of the slopes, activation energy, correlation coefficients (\( R^2 \)) and residual standard deviation (\( S \)) calculated from Fig.6 are exhibited in Table 2. It is apparent that when \( \alpha \) increased from 10\% to 100\%, the \( E \) was corresponding changed from 287.7 kJ\( \cdot \)mol\(^{-1} \) to 310.1 kJ\( \cdot \)mol\(^{-1} \). The average of the \( E \) is 297.0 kJ\( \cdot \)mol\(^{-1} \).

The relationships between \( \ln(\beta T_p^{-2}) \) and \( 1/T_p \) were also calculated by the Kissinger method, and the results are shown in Fig.7. The corresponding kinetics parameters were exhibited in Table 3. It can be seen that the \( E \) and \( S \) of the roasting reaction are 296.87 kJ\( \cdot \)mol\(^{-1} \) and 38.97 s\(^{-1} \). Compared with the calculating results by Ozawa-Flynn-Wall method listed in Table 3, it can be found that the calculation results obtained by these two methods were very close.

Table 2. The data of the slopes, \( E \), \( S \) and \( R^2 \) calculated by Ozawa-Flynn-Wall method

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>Slope</th>
<th>( E ) (kJ( \cdot )mol(^{-1} ))</th>
<th>( S )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-16.03</td>
<td>287.7</td>
<td>4.65\times10^{-7}</td>
<td>0.996</td>
</tr>
<tr>
<td>20</td>
<td>-15.82</td>
<td>288</td>
<td>3.58\times10^{-6}</td>
<td>0.977</td>
</tr>
<tr>
<td>30</td>
<td>-16.37</td>
<td>297.9</td>
<td>2.14\times10^{-6}</td>
<td>0.997</td>
</tr>
<tr>
<td>40</td>
<td>-16.42</td>
<td>298.9</td>
<td>1.79\times10^{-6}</td>
<td>0.997</td>
</tr>
<tr>
<td>50</td>
<td>-17.04</td>
<td>310.1</td>
<td>1.26\times10^{-6}</td>
<td>0.998</td>
</tr>
<tr>
<td>60</td>
<td>-16.72</td>
<td>304.4</td>
<td>1.63\times10^{-6}</td>
<td>0.997</td>
</tr>
<tr>
<td>70</td>
<td>-16.26</td>
<td>296</td>
<td>4.41\times10^{-6}</td>
<td>0.994</td>
</tr>
<tr>
<td>80</td>
<td>-16.03</td>
<td>291.7</td>
<td>4.55\times10^{-6}</td>
<td>0.994</td>
</tr>
<tr>
<td>90</td>
<td>-16.42</td>
<td>298.9</td>
<td>3.75\times10^{-6}</td>
<td>0.995</td>
</tr>
<tr>
<td>100</td>
<td>-16.05</td>
<td>292.2</td>
<td>4.75\times10^{-6}</td>
<td>0.994</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>297</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The values of the frequency factor and the activation energy were obtained by the Ozawa-Flynn-Wall and Kissinger methods. In order to obtain the more accurate and reliable date, the Coats-Redfern method was used to calculate the reaction model and its results were shown in Table 4. Based on the data in Table 4 and the results of Ozawa-Flynn-Wall and
Kissinger methods, it can be inferred that the possible reaction model of the interaction reaction between Sb$_2$S$_3$ and ZnO was inferred as R$_3$. The corresponding values of the active energy and lnA are 275.3 kJ mol$^{-1}$ and 31.6 s$^{-1}$.

**Table 4.** Calculated results of kinetic parameters by Coats-Redfern method at heating rate of 10 K min$^{-1}$

<table>
<thead>
<tr>
<th>No.</th>
<th>E (kJ mol$^{-1}$)</th>
<th>lnA (s$^{-1}$)</th>
<th>S</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$_1$</td>
<td>411.8</td>
<td>53.3</td>
<td>10.37</td>
<td>0.783</td>
</tr>
<tr>
<td>D$_2$</td>
<td>582.6</td>
<td>80</td>
<td>4.33</td>
<td>0.919</td>
</tr>
<tr>
<td>D$_3$</td>
<td>563.6</td>
<td>75.7</td>
<td>7.07</td>
<td>0.909</td>
</tr>
<tr>
<td>A$_{1.5}$</td>
<td>238.6</td>
<td>27.1</td>
<td>0.248</td>
<td>0.971</td>
</tr>
<tr>
<td>A$_2$</td>
<td>175.8</td>
<td>17.2</td>
<td>0.14</td>
<td>0.97</td>
</tr>
<tr>
<td>A$_3$</td>
<td>112.9</td>
<td>6.9</td>
<td>0.062</td>
<td>0.967</td>
</tr>
<tr>
<td>A$_4$</td>
<td>81.48</td>
<td>1.7</td>
<td>0.035</td>
<td>0.965</td>
</tr>
<tr>
<td>R$_1$</td>
<td>199.5</td>
<td>20.2</td>
<td>2.6</td>
<td>0.772</td>
</tr>
<tr>
<td>R$_2$</td>
<td>250.3</td>
<td>27.9</td>
<td>2.173</td>
<td>0.864</td>
</tr>
<tr>
<td>R$_3$</td>
<td>275.3</td>
<td>31.6</td>
<td>1.771</td>
<td>0.904</td>
</tr>
<tr>
<td>P$_2$</td>
<td>93.3</td>
<td>3.3</td>
<td>0.652</td>
<td>0.747</td>
</tr>
<tr>
<td>P$_3$</td>
<td>57.9</td>
<td>-2.6</td>
<td>0.29</td>
<td>0.718</td>
</tr>
<tr>
<td>P$_4$</td>
<td>40.2</td>
<td>-5.6</td>
<td>0.164</td>
<td>0.685</td>
</tr>
</tbody>
</table>

Summary: the kinetic parameters of the roasting reactions between Sb$_2$S$_3$ and ZnO were calculated by three different methods, and the average values of activation energy and the frequency factor by each method were showed in Table 5, and the average of these two parameters were also calculated in the table as 189.72 kJ mol$^{-1}$ and 35.29 s$^{-1}$ respectively. According to the values of E and lnA, the kinetic equation of the roasting reaction can be obtained as shown in Eqs. (9).

**Table 5.** Average activation energy and frequency factor

<table>
<thead>
<tr>
<th>Methods</th>
<th>E (kJ mol$^{-1}$)</th>
<th>lnA (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozawa-Flynn-Wall</td>
<td>297</td>
<td></td>
</tr>
<tr>
<td>Kissinger</td>
<td>296.87</td>
<td>38.97</td>
</tr>
<tr>
<td>Coats-Redfern</td>
<td>275.3</td>
<td>31.6</td>
</tr>
<tr>
<td>Average</td>
<td>189.72</td>
<td>35.29</td>
</tr>
</tbody>
</table>

1 - (1-α)$^{n} = 2.12 \times 10^{5} \exp \left( \frac{1.90 \times 10^{4}}{RT} \right)$  \quad (9)

**4. Conclusions**

A new sulfur-fixed roasting method of Sb$_2$S$_3$ by using ZnO as sulfur-fixed agent for stibnite extraction was proposed. The thermodynamics calculation and equilibrium dominance analysis indicated that the reaction process is completely feasible and easier to achieve with the temperature increase. The TG-DSC and XRD analyses showed that roasting reaction took place after 773 K and was basically completed at 873K. By using the method of TG-DSC, the non-isothermal kinetics of the roasting reaction between Sb$_2$S$_3$ and ZnO was conducted to obtain the kinetics parameters. The average of activation energy and frequency factor calculated by Ozawa-Flynn-Wall, Kissinger and Coats-Redfern were 189.72 kJ mol$^{-1}$ and 35.29 s$^{-1}$ respectively. In addition, the results obtained by Ozawa-Flynn-Wall method showed that the mechanism of this reaction is phase boundary model (R$_n$). The new method is expected to solve the shortcomings of low-concentration sulfur oxide emission and high energy consumption in the smelting of Sb$_2$S$_3$ as well as the comprehensive utilization of secondary ZnO material, and it also has a potential application in the extraction metallurgy of the congeneric sulfide ore.

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**Reference**

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TERMODINAMIČKA I KINETIČKA ANALIZA PRŽENJA SULFIDA ANTIMONA KORIŠĆENJEM ZnO KAO AGENSA ZA FIKSIRANJE SUMPORA

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Apstrakt
Komercijalna metalurgija antimona je trenutno zasnovana na pirometalurškim procesima, i oksidativno isparavanje Sb2S3 je neophodan korak koji sa sobom nosi probleme velike potrošnje energije i niske koncentracije SO2 zagađenja. U cilju rešenja ovih problema predstavljen je novi metod prženja sulfida antimona gde se fiksira sumpor. Ovaj metod koristi ZnO kao agens za fiksiranje sumpora, i prženje sa Sb2S3 je izvedeno na temperaturi od 673 K~1073 K da bi se dobio Sb2O3 i ZnS. Termodinamičkom analizom reakcija možemo zaključiti da je promena Gibsove slobodne energije(ΔGθ) reakcije prženja ispod -60 kJ/mol, a da su predominantne oblasti Sb2O3 i ZnS široke i da se sa porastom temperature pomeraju udruženo, što sve ukazuje na to da je ovaj metod teoretski izvodljiv. Produkti reakcije između Sb2S3 i ZnO ukazuju na to da je reakcija počela na 773 K i završila se približno na 973K. Koristili smo Ozawa-Flynn-Wall, Kissinger i Coats-Redfern metode za izračunavanje kinetike reakcije prženja. Zaključak je sledeći: prosečne vrednosti aktivacione energije (E) i prirodnog logaritamskog faktora frekvencije (lnA) izračunate uz pomoć Ozawa-Flynn-Wall, Kissinger i Coats-Redfern metoda bile su 189.72 kJ·mol-1 i 35.29 s-1. Mehanizam ove reakcije je bio model reakcije granične faze. Kinetički model je prikazan jednačinom:

\[ 1 - (1 - \alpha)^{3/2} = 2.12 \times 10^{14} \exp \left( \frac{1.9 \times 10^8}{RT} \right) t \]

gde \( \alpha \) predstavlja stepen izreagovanosti.

Ključne reči: Sulfid antimona; Cink oksid; Fiksiranje sumpora; Kinetika; Prženje