Selection of reductants for extracting selenium and tellurium from degoldized solution of copper anode slimes

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Abstract: This paper focused on investigating high-efficient reductants of recovering selenium and tellurium from degoldized solution of copper anode slimes. Firstly, the effect of various reductants on recovery rates of Se and Te was investigated based on thermodynamic analysis of various metallic ions in degoldized solution. Secondly, the single factor experiments were made to investigate the effect of the process parameters on recovering Se and Te with hydrazine hydrate. Finally, the hydroxylamine hydrochloride was added to intensify the extraction efficiencies of Se and Te. The results indicated that hydrazine hydrate was the most suitable reductant, and the recovery rates of Se and Te are 71.23% and 76.50%, respectively; the recovery rates of Se and Te were 92.07% and 97.81%, respectively, under the optimal process conditions of hydrazine hydrate dosage of 0.2133 mol/L, H+ concentration of 4.305 mol/L, reaction temperature of 85 °C and reaction time of 5 h; the recovery rate of Se was 97.59%, and that Te reached up to 100% when hydroxylamine hydrochloride dosage was 1.5116 mol/L.

Key words: degoldized solution; hydrazine hydrate; hydroxylamine hydrochloride; selenium; tellurium; recovery rate

1 Introduction

Copper anode slimes are valuable by-products generated in copper electrolytic refining process, which account for 0.2%−1.0% (mass fraction) of anode copper [1−5]. Approximately 90% of selenium (Se) and tellurium (Te) are obtained from copper anode slimes, which are also one of the most important materials for extracting gold and silver [6−11]. Generally, the conventional process of treatment of copper anode slime includes the following steps [12−15]. Copper anode slimes are firstly pretreated with different methods to remove copper which is harmful for the subsequent procedure. Then, the decopperization residue is used to recover gold and silver by either hydrometallurgy or pyrometallurgy process. During the process, gold is sometimes separated from the leached residue by chlorination followed by precipitating gold. The obtained products are gold dust with high purity and degoldized solution, which still contains large amount of selenium, tellurium and certain amount of gold and platinum group metals.

So far, several techniques have been developed for recovering valuable metals from the degoldized solution, and the most popular ones are zinc dust replacement process [16,17] and sulfur dioxide reduction process [18,19]. The zinc dust replacement process is usually designed with the purpose to recover precious metals, especially gold and platinum group metals with low recovery rates on selenium and tellurium. Meanwhile, zinc dust tends to react with H+ in degoldized solution to generate H2, which is the potential security danger for production. The sulfur dioxide reduction process can not only efficiently capture gold and platinum group metals, but also recover Se and Te in colloidal state. However, sulfur dioxide tends to escape from strong acidic solution, which pollutes the environment.

With the increasing demand of valuable metals and more strict requirements of environmental protection, it is necessary to explore suitable reductant with high extraction efficiencies for Se and Te from degoldized solution. The aim of this work is to investigate the novel
reduction system for efficiently extracting both Se and Te from degoldized solution. Firstly, the effect of various reductants on recovery rates of Se and Te was investigated to determine suitable reductant for extracting Se and Te. Then, the process parameters in hydrazine hydrate reduction system were studied in a systematic manner. Finally, the combined system of hydrazine hydrate and hydroxylamine hydrochloride was used to intensify the extraction efficiencies of Se and Te.

2 Experimental

2.1 Materials

A sample of copper anode slimes was provided by one of the copper smelters in China. Copper anode slimes were firstly decopperized by high pressure leaching process, and then followed by chlorination process to separate Au and Ag. In subsequent steps, Au was precipitated from the gold-bearing solution with sodium sulfite and the obtained degoldized solution was used as the raw materials in all experiments, wherein \([H^+]=3.75\text{ mol/L}\). Chemical analysis of the solutions was carried out by inductively coupled plasma-atomic emission spectroscopy (Intrepid II XSP, Thermo Electron, USA), and the results are given in Table 1.

| Table 1 Main chemical composition of degoldized solution (mmol/L) |
|-----------------|-----------|--------|----|-----|-----|----|
| Se | Te | Au | Pt | Pd | Cu | Fe | Cl |
| 3.92 | 23.60 | 0.18 | 0.0095 | 0.11 | 8.95 | 2.34 | 6536 |

It can be seen from Table 1 that the degoldized solution was rich in Se (3.92 mmol/L) and Te (23.60 mmol/L), while a negligible amount of precious metals (0.18 mmol/L Au, 0.0095 mmol/L Pt and 0.11 mmol/L Pd) was dissolved in degoldized solution.

2.2 Methods

Accurate amount of degoldized solution was added to the flask, a measured amount of reductant was charged to the flask and heated to a specific temperature under magnetically stirring and the reaction initiated. Two reflux condensers were installed at the top of the flask to minimize the loss of solution due to evaporation. After the required time, the slurries were separated by vacuum filtration immediately. The residues were washed with distilled water and then dried in air oven at 105 °C for weighing. The recovery rates of valuable metals were estimated on the basis of materials balance. AR-grade chemical reagents were used in all experiments.

Chemical compositions of the reduction products were analyzed by X-ray fluorescence analysis (ARL Perform’X, Thermo Electron, USA). The crystalline lattice and the micro morphology of the reduction products were analyzed by X-ray diffraction (D/max-TTR III, Rigaku, Japan) and scanning electron microscope (JSM-6300, JEOL, Japan).

3 Thermodynamic analysis

In copper anode slimes, Se and Te occur as silver and copper selenides and tellurides, while in degoldized solution Se mainly exists as \(\text{SeO}_3^{2-}\), \(\text{HSeO}_3^-\), \(\text{H}_2\text{SeO}_3\), and Te mainly exists as \(\text{TeO}_3^{2-}\), \(\text{HTeO}_3\), \(\text{H}_2\text{TeO}_3\), \(\text{H}_3\text{SeO}_3\) [18–21]. The dissociation equations of selenides and tellurides are presented as follows:

\[
\begin{align*}
\text{H}_2\text{SeO}_3 &= \text{HSeO}_3^- + \text{H}^+, \quad K_{a1}=2.40 \times 10^{-3} \\
\text{HSeO}_3^- &= \text{SeO}_3^{2-} + \text{H}^+, \quad K_{a2}=5.01 \times 10^{-9} \\
\text{H}_2\text{TeO}_3 &= \text{HTeO}_3^- + \text{H}^+, \quad K_{a1}=1.48 \times 10^{-7} \\
\text{HTeO}_3^- &= \text{TeO}_3^{2-} + \text{H}^+, \quad K_{a3}=1.45 \times 10^{-16}
\end{align*}
\]

The total concentration of \([\text{M (IV)}]_t\) in degoldized solution is

\[
[\text{M(IV)}]_t = [\text{MO}_3^{2-}] + [\text{HMO}_3^-] + [\text{H}_2\text{MO}_3] + [\text{H}_3\text{MO}_3^-]
\]

where \([\text{M(IV)}]_t\) is the total concentration of \([\text{Se(IV)}]_t\) or \([\text{Te(IV)}]_t\). The effects of pH value on the distribution of Se(IV) and Te(IV) species are depicted respectively in Figs. 1 and 2 according to Eqs. (1)–(6).

![Fig. 1 Relationship between mole fraction of Se(IV) species and pH](image)

Apparently, in strongly acidic solution, the main existing form of Se(IV) is \(\text{H}_2\text{SeO}_3\), and that of Te(IV) is \(\text{H}_2\text{TeO}_3\) when \(\text{pH} \leq 0\). In weakly acidic and alkaline solutions, the main existing forms of Se(IV) are \(\text{HSeO}_3^-\) and \(\text{SeO}_3^{2-}\), and those of Te(IV) are \(\text{H}_2\text{TeO}_3\), \(\text{HTeO}_3\) and \(\text{TeO}_3^{2-}\).

The results of Table 1 indicate that degoldized solution contains large amounts of Se and Te, and small
amounts of Au, Pt, Pd with H⁺ concentration of 3.755 mol/L. It can be concluded that H₂SeO₃ and H₂TeO₅ are main existing forms in degoldized solution. In addition, Au, Pt and Pd exist as AuCl₄⁻, PtCl₆³⁻ and PdCl₂⁻ due to the large amounts of Cl⁻ in solution. The standard electrode potential and the actual electrode potential for involved reactions calculated based on Nernst equation and involved ion concentrations are listed in Table 2.

![Graph](image-url)  
**Fig. 2** Relationship between mole fraction of Te(IV) species and pH

**Table 2** Electrode reactions and electrode potentials of ions in solution at 25 °C

<table>
<thead>
<tr>
<th>Ion</th>
<th>Electrode reaction</th>
<th>Standard electrode potential, ( \phi^{0}/V )</th>
<th>Actual electrode potential, ( \phi/V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AuCl₄⁻</td>
<td>AuCl₄⁻ +3e⁻=Au⁺+4Cl⁻</td>
<td>1.002</td>
<td>0.864</td>
</tr>
<tr>
<td>PtCl₆³⁻</td>
<td>PtCl₆³⁻ +2e⁻=Pt⁺+4Cl⁻</td>
<td>0.758</td>
<td>0.513</td>
</tr>
<tr>
<td>H₂SeO₃</td>
<td>H₂SeO₃+4H⁺+4e⁻=Se⁺+3H₂O</td>
<td>0.740</td>
<td>0.738</td>
</tr>
<tr>
<td>PdCl₂⁻</td>
<td>PdCl₂⁻ +2e⁻=Pd⁺+4Cl⁻</td>
<td>0.620</td>
<td>0.406</td>
</tr>
<tr>
<td>H₂TeO₅</td>
<td>H₂TeO₅+3H⁺+4e⁻=Te⁺+3H₂O</td>
<td>0.558</td>
<td>0.559</td>
</tr>
</tbody>
</table>

It can be seen that AuCl₄⁻/Au has the highest actual electrode potential of 0.864 V, besides PtCl₆³⁻/Pt (0.513 V), H₂SeO₃/Se (0.738 V) and H₂TeO₅/Te (0.559 V). Relatively, the lowest actual electrode potential is 0.406 V for PdCl₂⁻/Pd.

The actual electrode potential depends on many factors including temperature, ions state and component concentration. Compared with standard electrode potential, \( \phi(\text{AuCl}_4^- / \text{Au}) \), \( \phi(\text{PtCl}_6^{3-} / \text{Pt}) \) and \( \phi(\text{PdCl}_2^- / \text{Pd}) \) are largely decreased due to the low concentration of the metallic ions in solution. Furthermore, the actual electrode potentials of various metallic ions arrange as follows: \( \phi(\text{AuCl}_4^- / \text{Au}) >\phi(\text{H}_2\text{SeO}_3/\text{Se}) >\phi(\text{H}_2\text{TeO}_5/\text{Te}) >\phi(\text{PtCl}_6^{3-} / \text{Pt}) >\phi(\text{PdCl}_2^- / \text{Pd}) \).

### 4 Results and discussion

#### 4.1 Effect of reductants

The composition of reduction products depends not only on the reduction behavior of various metallic ions, but also on the reduction capability of the reductant. In this part of the study, the reductants presented in Table 3 were used to investigate the effects of reductants on the recovery rates of Se and Te.

**Table 3** Characterization of various reductants (25 °C)

<table>
<thead>
<tr>
<th>Reductant</th>
<th>Electrode reaction</th>
<th>( \phi^{0}/V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂N₂·H₂O</td>
<td>N₂+2H₂O+4H⁺+2e⁻=2HONH₃⁺</td>
<td>−1.87</td>
</tr>
<tr>
<td>Zn</td>
<td>Zn²⁺+2e⁻=Zn</td>
<td>−0.763</td>
</tr>
<tr>
<td>Fe</td>
<td>Fe³⁺+2e⁻=Fe</td>
<td>−0.440</td>
</tr>
<tr>
<td>HONH₃Cl</td>
<td>N₂+5H⁺+4e⁻=H₂N₃N⁺</td>
<td>−0.23</td>
</tr>
<tr>
<td>SO₂</td>
<td>SO₂⁻+4H⁺+2e⁻=SO₂⁺+2H₂O</td>
<td>0.138</td>
</tr>
<tr>
<td>Cu</td>
<td>Cu²⁺+2e⁻=Cu</td>
<td>0.340</td>
</tr>
</tbody>
</table>

The occurrence of the reduction reaction was determined by the comparison of the electrode potential between reductants and metallic ions. By comparing Table 3 with Table 2, it can be found that all the candidates can meet the demand of reduction reaction. Therefore, it can be concluded that Zn, Cu, SO₂, Fe, H₂N₂·H₂O and HONH₃Cl all can be adopted as reductants to recover Se and Te from degoldized solution.

In our previous investigations [18,19], the recovery rates of Au, Pt and Pd in degoldized solution virtually reached 100%. Hence, the variation of recovery rates of Se and Te with respect to various reductants is given in Table 4 when a series of experiments were carried out at 40 °C for 3 h, and then at 80 °C for 1 h.

**Table 4** Effect of reductants on recovery rates of Se and Te

<table>
<thead>
<tr>
<th>Reductant</th>
<th>Dosage/ (mol·L⁻¹)</th>
<th>Recovery rate of Se/%</th>
<th>Recovery rate of Te/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>0.2</td>
<td>37.07</td>
<td>36.84</td>
</tr>
<tr>
<td>Fe</td>
<td>0.2</td>
<td>14.63</td>
<td>32.77</td>
</tr>
<tr>
<td>Cu</td>
<td>0.2</td>
<td>16.78</td>
<td>32.17</td>
</tr>
<tr>
<td>HONH₃Cl</td>
<td>0.2</td>
<td>80.76</td>
<td>34.08</td>
</tr>
<tr>
<td>H₂N₂·H₂O</td>
<td>0.2</td>
<td>71.23</td>
<td>76.50</td>
</tr>
<tr>
<td>SO₂</td>
<td>Saturation</td>
<td>33.90</td>
<td>37.79</td>
</tr>
</tbody>
</table>

According to Table 4, the highest recovery rates of Se and Te were respectively 71.23% and 76.50% with H₂N₂·H₂O. HONH₃Cl exhibited the highest recovery rate of Se as 80.76%, whereas the recovery rate of Te was only 34.08%. After examining the experimental results, it...
was found that H₂N₂·H₂O was the most appropriate reductant for recovering Se and Te from degoldized solution. Even though the electrode potential of H₂N₂·H₂O was −0.23 V, the liquid–liquid reaction in H₂N₂·H₂O system increased the effective contact area of the particles, resulting in increasing the collision probability of the reaction particles, which was in favor of reducing Se and Te.

4.2 Effect of reaction parameters on recovery rate in H₂N₂·H₂O reduction system

H₂N₂·H₂O was chosen as the reductant for the following experiments. Effects of relevant parameters such as H₂N₂·H₂O dosage, reaction temperature, H⁺ concentration and reaction time were reported below.

4.2.1 Effect of H₂N₂·H₂O dosage

The influence of H₂N₂·H₂O dosage on the recovery rates of Se and Te was investigated in a range of 0–0.5 mol/L, as shown in Fig. 3. The required amount of H₂N₂·H₂O to reduce Se and Te in degoldized solution was initially examined at the following parameters: reaction temperature of 85 °C and reaction time of 1 h.

![Fig. 3 Effect of H₂N₂·H₂O dosage on recovery rates of Se and Te](image)

It could be seen from Fig. 3 that the recovery rates of Se and Te increase to 72.79% and 74.72% at H₂N₂·H₂O dosage of 0.2133 mol/L. Beyond this point, increasing H₂N₂·H₂O dosage to 0.4267 mol/L caused a significant increase of Te recovery rate being 98.77%, whereas the increase of H₂N₂·H₂O dosage did not lead to any significant change in the recovery rate of Se. Considering the slight difference of Se recovery rate obtained in the H₂N₂·H₂O concentration range of 0.2133 to 0.4267 mol/L, the following experiments were carried out at H₂N₂·H₂O dosage of 0.2133 mol/L.

Based on the Nernst equation, it can be calculated that the electrode potentials of H₂N₂·H₂O were −0.1736, −0.1781, −0.1807 and −0.1825 V when H₂N₂·H₂O dosages were 0.1067, 0.2133, 0.3200 and 0.4267 mol/L, respectively. The electrode potential of H₂N₂·H₂O gradually decreased with increasing H₂N₂·H₂O dosage, resulting in the increase of the reduction capability.

4.2.2 Effect of reaction temperature

The effect of reaction temperature on recovery rates of Se and Te was investigated by varying the temperature from 20 to 95 °C, as shown in Fig. 4. In these series of experiments, H₂N₂·H₂O dosage was 0.2133 mol/L and the reaction time was 1 h.

![Fig. 4 Effect of reaction temperature on recovery rates of Se and Te](image)

Increasing reaction temperature initially caused a slow contribution on the recovery rates of Se and Te below 45 °C. Then, the recovery rates of Se and Te rapidly increased to 76.26% and 78.09% when the temperature increased from 45 to 85 °C. There was a negligible difference between 85 and 95 °C. Therefore, further tests were carried out at 85 °C.

4.2.3 Effect of H⁺ concentration

The effect of H⁺ concentration from 3.755 to 4.580 mol/L on the recovery rates of Se and Te was researched under the conditions of H₂N₂·H₂O dosage of 0.2133 mol/L and reaction temperature 85 °C, in which H⁺ ions was adjusted by sulfuric acid. The results are shown in Fig. 5.

Figure 5 showed that the recovery rate of Se increased, but that of Te decreased gradually with increasing H⁺ concentration. When H⁺ concentration increased from 3.755 to 4.580 mol/L, the recovery rate of Se increased from 35.24% to 81.23%, and the corresponding electrode potential φ(H₂SeO₃/Se) increased from 0.738 to 0.744 V, which accelerated the reduction reaction of Se.

Conversely, the recovery rate of Te decreased from 99.04% to 73.61% with H⁺ concentration varying from 3.755 to 4.580 mol/L. This unexpected situation was thought to have occurred because of importing sulfate radical which converted Te to sulfuric acid oxygen tellurium (TeOSO₄) [22]. The transformation of existing
form of Te increased the resistance of reduction reaction, which resulted in the decrease of the recovery rate of Te with increasing H⁺ concentration. Therefore, H⁺ concentration of 4.305 mol/L was chosen as the optimal condition.

4.2.4 Effect of reaction time

The effect of reaction time on recovery rates of Se and Te was inspected in the range of 0.5 to 5 h under following conditions: H⁺ concentration of 4.305 mol/L, H₄N₂·H₂O dosage of 0.2133 mol/L and reaction temperature of 85 °C. The results are shown in Fig. 6.

Apparentlly, the increase in reaction time boosted the recovery rates of Se and Te considerably. As the reaction time was 5 h, the recovery rates of Se and Te reached 90.44% and 100%, respectively. It can be concluded that longer reaction time could promote the recovery rates of Se and Te in degoldized solution. Therefore, 5 h was regarded as the optimal time.

According to the above results, the optimal process conditions of the reduction reactions in H₄N₂·H₂O system were H₄N₂·H₂O dosage of 0.2133 mol/L, H⁺ concentration of 4.305 mol/L, reaction temperature of 85 °C and reaction time of 5 h. Under these optimal conditions, the recovery rates of the valuable metals were 92.07% for Se, 97.81% for Te, 100% for Au, 100% for Pt and 100% for Pd. The compositions of reduction products are listed in Table 5. The mass fractions of Se, Te, Au and Pd were respectively 6.721%, 56.96%, 0.4930% and 0.4409%. The reduction products were costly according to the compositions.

<p>| Table 5 Chemical compositions of reduction products in H₄N₂·H₂O system (mass fraction, %) |</p>
<table>
<thead>
<tr>
<th>Se</th>
<th>Te</th>
<th>Cu</th>
<th>Au</th>
<th>Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.721%</td>
<td>56.96%</td>
<td>15.07%</td>
<td>0.4930%</td>
<td>0.4409%</td>
</tr>
</tbody>
</table>

The XRD pattern of reduction products is given in Fig. 7. Only elemental Te and Cu₃(No₃)(OH)₃ were detected. However, no other mineral phases were identified due to the small amount of them, which was in agreement with the chemical compositions of reduction products shown in Table 5. In reduction process, nitrogen in H₄N₂·H₂O was oxidized as NO₃⁻ and reacted with Cu²⁺ to generate Cu₃(No₃)(OH)₃. Hence, copper appears as Cu₃(No₃)(OH)₃ phase in reduction products.

The XRD pattern of reduction products in H₂N₂·H₂O system is shown in Fig. 8, it can be seen that the reduction products were columnar type.

4.3 Effect of combined reduction system on recovery rates of Se and Te

In order to intensify the recovery rates of Se and Te, HONH₃Cl was added in the H₂N₂·H₂O system. The recovery rates of Se and Te as a function of HONH₃Cl dosage are given in Fig. 9. The experiments were conducted at H₂N₂·H₂O dosage of 0.2133 mol/L, H⁺ concentration of 4.305 mol/L, reaction temperature of 85°C and reaction time of 5 h. Figure 9 showed that the recovery rate of Se was significantly affected by HONH₃Cl dosage. The recovery rates of Se and Te both
increased up to 97.59% and 100% respectively when HONH$_3$Cl dosage was 1.5116 mol/L. Apparently, the combined system promoted the recovery rates of Se and Te compared with H$_4$N$_2$·H$_2$O system due to the increase of the reactant concentration in unit volume.

The main phases of reduction products in combined system were elemental Te and Cu$_2$(NO$_3$)(OH)$_3$ according to XRD analysis as shown in Fig. 10. The phases of the other metals were not identified due to their low content, confirmed by the analysis of chemical compositions of reduction products shown in Table 6. The micro morphology of the reduction products in combined system presented columnar type as shown in Fig. 11. According to the above results, it could be concluded that the characteristic of the reduction products in combined system was in accordance with that of reduction products in H$_4$N$_2$·H$_2$O system.

By taking advantages of both H$_4$N$_2$·H$_2$O system and HONH$_3$Cl system, high recovery rates of Se and Te up to 97.59% and 100%, respectively, can be obtained using such a combined system which showed prospect for efficient extraction of Se and Te from degoldized solution.

**5 Conclusions**

1) The effect of various reductants (namely Zn, Cu, SO$_2$, Fe, H$_4$N$_2$·H$_2$O and HONH$_3$Cl) on recovery rates of Se and Te was investigated based on the thermodynamic analysis of various metallic ions in degoldized solution of copper anode slimes. The results indicated that the recovery rates were 71.23% and 76.50% for Se and Te, respectively by using H$_4$N$_2$·H$_2$O, which was adopted as the reductant for recovering Se and Te from degoldized solution.

2) By optimizing the process parameters of the reduction reaction in H$_4$N$_2$·H$_2$O system, the recovery rate of Se reached 92.07% and that of Te was 97.81% under the optimal process conditions of H$_4$N$_2$·H$_2$O dosage of 0.2132 mol/L, H$^+$ concentration of 4.305 mol/L, reaction temperature of 85 °C and reaction time of 5 h. XRD results revealed that the main phases of the reduction products were elemental Te and Cu$_2$(NO$_3$)(OH)$_3$, and the mass fractions of Cu, Se, Te, Au and Pd were 15.07%,
6.721%, 56.96%, 0.4930% and 0.4409%, respectively.

3) By adding HONH₂Cl into the H₂N₂·H₂O system, the recovery rate of Te reached 100% and that of Se was 97.59% when HONH₂Cl dosage was 1.5116 mol/L, which demonstrated that the combined system could efficiently extract Se and Te from degoldized solution. The main phases of the reduction products were elemental Te and Cu₃(NO₃)₂(OH)₃, and the mass fractions of Cu, Se, Te, Au and Pd were 9.82%, 3.865%, 72.78%, 0.8323% and 0.4548% respectively, which was in accordance with H₂N₂·H₂O system.

References


沉金后液回收硒、碲还原剂的选择

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摘 要：以某铜阳极泥氯化分金后的沉金后液为原料，研究能从中高效回收硒和碲的还原剂。首先，对沉金后液中有价元素的还原反应进行了热力学分析，在此基础上研究不同还原剂体系对沉金后液中硒和碲回收率的影响；然后，采用单因素实验研究水合肼还原体系中，各工艺条件对硒和碲回收率的影响；最后，在水合肼还原体系中加入盐酸羟胺来强化对硒和碲的还原效果。结果表明，水合肼对硒和碲均有良好的还原效果，硒和碲的回收率分别为 71.23% 和 76.50%；在水合肼用量为 0.2133 mol/L、H⁺浓度为 4.305 mol/L、反应温度为 85 ℃、还原时间为 5 h 条件下，硒和碲的回收率分别达到 92.07% 和 97.81%；当盐酸羟胺浓度为 1.5116mol/L 时，硒回收率为 97.59%，碲回收率达到 100%。

关键词：沉金后液；水合肼；盐酸羟胺；硒；碲；回收率

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