Isothermal Enriching Perovskite Phase from CaO–TiO$_2$–SiO$_2$–Al$_2$O$_3$–MgO Melt by Super Gravity

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A new approach to enriching perovskite phase from CaO–TiO$_2$–SiO$_2$–Al$_2$O$_3$–MgO melt by super gravity was investigated. The samples obtained by the gravity coefficient $G \geq 600$, time $t \geq 20$ min and temperature $T \geq 1578$ K appear significant layers and perovskite phase present gradient size distribution in the sample along the super gravity. The layered sample was central cut and characterized by metallographic microscopy, and it is hardly to find any perovskite particles in the upper area of the sample and the perovskite phase gathers at the middle and bottom areas of the sample. The mechanism of moving speed of perovskite particles in super gravity field was also discussed, and the conclusion indicates that the moving speed of perovskite particles is proportional to the square of the perovskite particle size. As a result, large size perovskite particles move a farther distance than the small ones and gather at the bottom of the sample, while small size perovskite particles accumulate in the middle of the sample. Under the hypothesis that the titanium exists in the slag in terms of TiO$_2$, with the gravity coefficient $G=600$, time $t=20$ min and temperature $T=1578$ K, the mass fraction of TiO$_2$ in the concentrate is up to 34.97%, while that of the tailing is just 11.16%. Considering that the mass fraction of TiO$_2$ is 22.34% in the parallel sample, the recovery ratio of Ti in the concentrate is up to 74.16% by centrifugal enrichment.

KEY WORDS: centrifugal enrichment; super gravity; perovskite phase; perovskite crystals; titanium bearing blast furnace slag; gravity coefficient.

1. Introduction

It is well known Panxi region is China’s treasure-house of mineral resources, which is especially rich vanadium-titanium bearing magnetite ore that contains 9.12–12.03% (mass fraction) TiO$_2$. After mineral processing, about 53% TiO$_2$ in the vanadium-titanium bearing magnetite ore is in the iron concentrate, which transforms into vanadium-bearing hot metal and titanium bearing blast furnace slag that contains 20–25% TiO$_2$ (mass fraction) after smelting process.$^{1,2}$ Nevertheless, titanium bearing blast furnace slag, a typical man-made resource, can hardly resort to traditional separating technique resulting from the dispersed distribution of titanium component in various mineral phases, very fine grains(<10 $\mu$m) and complex interfacial combination. So far, titanium bearing blast furnace slag has been accumulating 70 million tons and it is still increasing at a rate of 3 million tons per year, resulting in a great waste of titanium resources and environment pollution.$^{3–5}$

Fortunately, several studies and practices in a pilot plant on the slag have been throwing light on titanium separation and comprehensive utilization of titanium bearing blast furnace slag. A novel technique based on three continuous selective processes, namely, selective concentrating, selective growing and selective separating was proposed by Sui et al.$^{5,7}$ to recover Ti component from Ti-bearing blast furnace slag. As for the selective concentrating and selective growing process, Wang et al.$^{8,9}$ Li et al.$^{10}$ and Jung et al.$^{11}$ considered perovskite phase combined with the appropriate increase of slag basicity, lower cooling rate together with the presence of some additives, such as CaF$_2$, MnO, Fe$_2$O$_3$ and Si–Fe powder to be the best choice. That is the appropriate increase of slag basicity, lower cooling rate together with the presence of some additives, such as CaF$_2$, MnO, Fe$_2$O$_3$ and Si–Fe powder are benefited to early precipitating perovskite with large volume fraction and grain size from titanium bearing blast furnace slag. When it comes to selective separating process, several mineral and metallurgy methods to separate perovskite phase from the titanium bearing blast furnace slag, such as magnetic separation, flotation and gravity separation$^{12,13}$ have been investigated. However, none of the traditional separating technique can effectively separate perovskite phase from the titanium bearing blast furnace slag. Considering that the perovskite is solid at 1578 K and the room temperature density of 4.10 $\times$ 10$^3$ kg/m$^3$ is adopted,$^{13}$ while the high temperature density of the titanaugite is 3.10 $\times$ 10$^3$ kg/m$^3$ calculated by Archimedean method$^{14}$ (that is an amount of 400 grams of the pre-melted slag was put into a cylindrical alumina crucible (I.D.: 60 cm and H.: 80 cm) and heated to 1578 K in the tube resistance electric furnace. After the temperature was stabilized at...
1 578 K for 60 min, a quartz tube with the inner diameter of 3 mm was put into the bottom of the cylindrical alumina crucible, then took out of the quartz tube and measured the height of the melt adhered to the quartz tube. Finally, the volume of the melt can be calculated and then the high temperature density of the melt can be achieved), they can be separated by super gravity. What’s more, super gravity technology has been successfully applied in the preparation of functionally gradient materials and removing impurities from alloy melt. Based on the above characteristics, it would be possible to separate perovskite phase that was early precipitated from the titanium bearing blast furnace slag by super gravity. This fundamental study aims at examining the possibility of super-gravitational separation of the perovskite phase from CaO–TiO2–SiO2–Al2O3–MgO melt. Simultaneously, the influence of the gravity coefficient, time and temperature on the motion of perovskite phase and the recovery ratio of Ti in the products by centrifugal enrichment have also been investigated.

2. Experimental

2.1. Slag Preparation

The chemical composition of the slag at the condition of natural cooling in Panzhihua Iron and Steel Corporation was listed in Table 1. In order to gain large volume fraction and grain size of perovskite phase, the slag basicity defined as CaO/SiO2 has been adjusted from 1.1 to 1.3 by increasing the mass fraction of CaO based on the experimental results of Li et al. and Sun et al. As a result, the five composition of the slag was displayed in Table 2. The dry chemical agent powder based on the Table 2 was well mixed and then put into a molybdenum sheet lined graphite crucible and heated in the muffle furnace that was controlled by a program controller with an R type thermocouple, within the observed precision range of ±3 K. The experimental material was melted in the muffle furnace under argon gas at 1 773 K for 30 minutes in order to make it fully melted and then rapidly cooled to 1 623 K at a cooling rate of 20 K/min, then the cooling rate was adjusted to 0.5 K/min for 120 min, and finally water quenched the slag. Consequently, the slag achieved in this process was called pre-treated slag.

Table 1. Chemical composition of the slag at the condition of natural cooling in Panzhihua Iron and Steel Corporation (mass fraction,%).

<table>
<thead>
<tr>
<th>CaO</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>MgO</th>
<th>TFe</th>
<th>V2O5</th>
<th>MnO2</th>
<th>P2O5</th>
<th>SO</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.64</td>
<td>25.44</td>
<td>23.35</td>
<td>11.09</td>
<td>7.06</td>
<td>0.20</td>
<td>0.75</td>
<td>0.022</td>
<td>0.12</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

2.2. Sample Preparation and Analytical Procedure

The super gravity field was generated by the centrifugal apparatus whose Schematic diagram was illustrated in Fig. 1, with the heating furnace and the counterweight fixed symmetrically onto the horizontal rotor. The temperature was controlled by a program controller with an R type thermocouple, within the observed precision range of ±3 K. The gravity coefficient was calculated as the ratio of super-gravitational acceleration to gravitational acceleration via Eq. (1).

\[
G = \frac{\sqrt{g^2 + (\omega^2 R)^2}}{g} = \sqrt{\frac{g^2 + \left(\frac{N\pi^2 R}{900}\right)^2}{g}} \quad (1)
\]

When the rotating speed of the centrifugal \(N=0\) r·min\(^{-1}\), \(G=1\). When the rotating speed of the centrifugal \(N>0\) r·min\(^{-1}\), substituting the distance from the centrifugal axis to the centre.

Table 2. Five composition of the slag (mass fraction,%).

<table>
<thead>
<tr>
<th>CaO</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>MgO</th>
<th>Sum</th>
<th>Basicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.07</td>
<td>25.44</td>
<td>23.34</td>
<td>11.08</td>
<td>7.06</td>
<td>100</td>
<td>1.3</td>
</tr>
</tbody>
</table>
3. Results and Discussion

3.1. Macro and Micro Structure of the Sample Obtained by Centrifugal Enrichment

Figure 2 shows cross-section of the samples obtained by centrifugal enrichment with the gravity coefficient $G=600$, $t=20\text{ min}$, $T=1578\text{ K}$ compared with the parallel sample at the gravity coefficient $G=1$, $t=20\text{ min}$, $T=1578\text{ K}$. As illustrated in Fig. 2(b), layered structures appear significantly in the sample obtained by the gravity coefficient $G=600$, $t=20\text{ min}$, $T=1578\text{ K}$ compared with the parallel sample at $G=1$, $t=20\text{ min}$, $T=1578\text{ K}$. Hence: $G=2.80\times10^{-4}\text{N}^2$

An amount of 40 grams of the pre-melted slag was put into a graphite crucible with the inner diameter of 19 mm as shown in Fig. 1 and heated to target temperature for heat preservation, and then the centrifugal apparatus was started and adjusted to the specified angular velocity. The centrifugal apparatus was not shut off until the target time, then took out of the graphite crucible, and finally water quenched the slag. The sample obtained in this process was sectioned longitudinally along the center axis. One part was crossly divided along the interface between the white area and black area as illustrated in Fig. 2(b) into two parts, which were characterized by XRD (TR III from Rigaku Corporation) and XRF (XRF-1800X from Shimadzu Corporation) in order to obtain the respective mineral composition and chemical component. The other part was measured on the metallographic microscope (Laitz DMRX) and image analyzer (LEICA Qwin500) by the line intercept method (average of 20 fields) in order to gain the volume fraction and equivalent diameter of perovskite phase. Simultaneously, the parallel experiment was carried out at 1578 K for 30 minutes without centrifugal treatment, and the sample achieved in this process was called parallel sample.

4. Generally speaking, the size of perovskite crystals increases with the area approaching to the bottom of the sample, that is, the gradient size distribution of perovskite crystals presents in the samples along the super gravity after centrifugal enrichment. Meanwhile, there are two size transition areas as shown in Figs. 4(d) and 4(f), with one side fine equi-axed crystals and the other side large equi-axed crystals or dendrite, and the white area as shown in Fig. 4(e) is mainly shaped by fine equi-axed crystals of perovskite phase. As shown in Fig. 4, it’s practically impossible to find perovskite phase in the areas ranged from area (a) to area (e). However, the perovskite crystals with the characteristic of fine dispersing floc or spicule appear in the upper part of area (d), while the lower part of area (d) is the fine equi-axed crystals, which is also the typical morphology of perovskite crystals in the area (e). The co-existence region occurs in the interfacial area (d) can be explained as follows: during the “slag preparation” process, the precipitation and growth of perovskite are successive, and the early precipitation of perovskite are of dispersed dendriform, which transform into equi-axed phase during the cooling process according to the classical theory of dendritic coarsening, while the last precipitation of perovskite keep the characteristic of fine dispersing floc or spicule, so the centrifugal force on the last precipitating perovskite will be smaller than that of the early ones in the super gravity filed and the last precipitation of perovskite need much more time to move the same distance than the early ones. As a result, the co-existence region occurs in the interfacial area (d), with the upper part fine dendriform and the lower part large equi-axed crystals. Moreover, the size of equi-axed phase is larger in (d) than in (e) can be explained: as illustrated in Fig. 1, there is a gradient temperature distribution in the well-type furnace with the length of heating zone 0.10 m and the supercooling is in proportion to the growth of the crystals.

With the area approaching to the upper of the well-type furnace, the supercooling increases and perovskite crystals grow fast. Hence, the equi-axed phase of perovskite in (d) is a little larger than in (e). When it comes to the area (i) that has the similar size transition morphology of perovskite phase as the area (d), with the upper part fine equi-axed crystals and the lower part large equi-axed crystals. As for
the areas ranged from (g) to (i), the size of equi-axed crystals increases with the area approaching to the bottom of the sample and the peak value lies in area (i) of the sample.

3.2. Volume Fraction and Equivalent Diameter of Perovskite Phase

Tables 3, 4 and 5 present the variations of volume fraction of perovskite phase in different areas of the samples with different gravity coefficient at t=20 min, T=1578 K, with different centrifugal time at G=600, T=1578 K and with different temperature at G=600, t=20 min respectively, while the corresponding equivalent diameter of perovskite phase in different areas of the samples are showed in Figs. 5, 6 and 7. It is in evidence that the volume fraction of perovskite phase is approaching to zero from area (a) to area (c) with the gravity coefficient G≥600, t≥20 min and T≥1578 K as showed in Tables 3, 4 and 5. However, the volume fraction of perovskite phase increase slightly from area (g) to area (i) and the peak value appears in area (e). The peak value presents in area (e), rather than area (i), and the reasons can be expressed the relative small size of perovskite crystals resulting in a great number of perovskite crystals accumulating in area (e). Consequently, the maximum volume fraction of perovskite phase is found in area (e). It is observed from Figs. 5, 6 and 7 that the particle distribution of perovskite phase varies in different areas of the sample obtained by centrifugal enrichment. Generally speaking, the equivalent diameter of perovskite crystals increases with the area approaching to the bottom of the sample and the peak value appeared in area (i). When perovskite crystals are assumed to be spherical in shape, the motion equation of perovskite crystals in the melt can be calculated by the Stokes’ law,24,25

$$\frac{\pi}{6}d^3(\rho_p - \rho_m)\omega^2 - 3\pi\eta d \frac{dr}{dt} = \frac{\pi}{6}d^3\rho_p \frac{d^2r}{dt^2} \text{ ... (2)}$$

If the inertial terms on the right-hand side of Eq. (2) is neglected, then

![Fig. 4. Micrographs of nine areas of the sample achieved by centrifugal enrichment at G=600, t=20 min, T=1578 K.](image)
Thus: ............................. (3)

If assuming $\omega$ is a constant, ................................. (4)

Thus: ................... (5)

where, 

Substituting the density of perovskite crystals $\rho_p=4.10 \times 10^3 \text{ kg/m}^3$, the density of melt $\rho_l=3.10 \times 10^3 \text{ kg/m}^3$, the viscosity of the melt $\eta=1 \text{ N s/m}^2$, $220 \text{ N} \cdot \text{s/m}^2$, $N=1465 \text{ r/min}$, $r=0.27 \text{ m}$ and $r'=0.23 \text{ m}$ into Eq. (5):

Hence: .............................. (6)

When $d=100 \mu\text{m}$, thus $t=13.82 \text{ s}$

When $d=30 \mu\text{m}$, thus $t=153.6 \text{ s}=2.56 \text{ min}$

When $d=10 \mu\text{m}$, thus $t=1382.4 \text{ s}=23.04 \text{ min}$

Table 3. Variations of volume fraction of perovskite phase in different areas of the samples with different gravity coefficient at $t=20 \text{ min}$, $T=1578 \text{ K}$.

<table>
<thead>
<tr>
<th>Gravity coefficient</th>
<th>Areas (a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(e)</th>
<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>8.29</td>
<td>10.06</td>
<td>13.96</td>
<td>37.72</td>
<td>22.48</td>
<td>28.17</td>
<td>31.26</td>
</tr>
<tr>
<td>300</td>
<td>0</td>
<td>9.02</td>
<td>13.58</td>
<td>38.61</td>
<td>25.5</td>
<td>30.4</td>
<td>34.06</td>
</tr>
<tr>
<td>450</td>
<td>0</td>
<td>0</td>
<td>9.43</td>
<td>39.9</td>
<td>28.51</td>
<td>31.72</td>
<td>36.77</td>
</tr>
<tr>
<td>600</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>43.26</td>
<td>35.74</td>
<td>38.85</td>
<td>41.29</td>
</tr>
<tr>
<td>750</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>46.17</td>
<td>31.81</td>
<td>33.15</td>
<td>36.44</td>
</tr>
</tbody>
</table>

Table 4. Variations of volume fraction of perovskite phase in different areas of the samples with different time at $G=600$, $T=1578 \text{ K}$.

<table>
<thead>
<tr>
<th>Time/min</th>
<th>Areas (a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(e)</th>
<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>7.54</td>
<td>10.36</td>
<td>14.46</td>
<td>40.13</td>
<td>33.89</td>
<td>37.17</td>
<td>40.47</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>6.89</td>
<td>12.58</td>
<td>42.17</td>
<td>34.5</td>
<td>37.4</td>
<td>40.56</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>43.26</td>
<td>35.74</td>
<td>38.85</td>
<td>41.29</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>44.86</td>
<td>36.29</td>
<td>39.42</td>
<td>41.93</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>46.17</td>
<td>36.81</td>
<td>40.15</td>
<td>42.44</td>
</tr>
</tbody>
</table>

Table 5. Variations of volume fraction of perovskite phase in different areas of the samples with different temperature at $G=600$, $t=20 \text{ min}$.

<table>
<thead>
<tr>
<th>Temperature/K</th>
<th>Areas (a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(e)</th>
<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1518</td>
<td>2.25</td>
<td>4.77</td>
<td>5.06</td>
<td>47.89</td>
<td>37.42</td>
<td>39.17</td>
<td>41.37</td>
</tr>
<tr>
<td>1548</td>
<td>0</td>
<td>6.89</td>
<td>12.58</td>
<td>42.59</td>
<td>34.5</td>
<td>37.4</td>
<td>40.56</td>
</tr>
<tr>
<td>1578</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>43.26</td>
<td>35.74</td>
<td>38.85</td>
<td>41.29</td>
</tr>
<tr>
<td>1608</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>36.31</td>
<td>31.08</td>
<td>37.45</td>
<td>41.05</td>
</tr>
<tr>
<td>1638</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>34.89</td>
<td>30.81</td>
<td>38.75</td>
<td>40.44</td>
</tr>
</tbody>
</table>

$$
\frac{dr}{dt} = \frac{d^2 (\rho_p - \rho_l)}{18\eta} \omega^2 r
$$

Thus:

$$
V_r = \frac{d^2 \Delta \rho}{18\eta} \omega^2 r
$$

................................. (3)

If assuming $\omega$ is a constant,

$$
r = r'e^{\omega t} (4)
$$

Thus:

$$
t = 900 \frac{\ln \frac{r}{r'}}{A\omega^2} \frac{\ln \frac{r}{r'}}{A\pi^2 N^2}
$$

................................. (5)

where, 

$$
A = \frac{d^2 \Delta \rho}{18\eta}, \quad \Delta \rho = \rho_p - \rho_l
$$

Substituting the density of perovskite crystals $\rho_p=4.10 \times 10^3 \text{ kg/m}^3$, the density of melt $\rho_l=3.10 \times 10^3 \text{ kg/m}^3$, the viscosity of the melt $\eta=1 \text{ N s/m}^2$, $220 \text{ N} \cdot \text{s/m}^2$, $N=1465 \text{ r/min}$, $r=0.27 \text{ m}$ and $r'=0.23 \text{ m}$ into Eq. (5):

Hence: $t = 1.38 \times 10^{-7} \frac{1}{d^2}$

Fig. 5. Variations of equivalent diameters of perovskite phase in different areas of the samples with different gravity coefficient at $t=20 \text{ min}$, $T=1578 \text{ K}$.

Fig. 6. Variations of equivalent diameters of perovskite phase in different areas of the samples with different time at $G=600$, $T=1578 \text{ K}$.

Fig. 7. Variations of equivalent diameters of perovskite phase in different areas of the samples with different temperature at $G=600$, $t=20 \text{ min}$. 
That is the moving speed of perovskite particles in the melt is proportional to the square of the perovskite particle size as shown in Eq. (3), which can be increased order of magnitude of the distance between large size perovskite particles and the small ones under the action of super gravity field as shown in Eq. (4). As a result, large size perovskite particles gather at the bottom of the sample, while the small ones accumulate in the middle of the sample, and the gradient size distribution of perovskite crystals appears in the sample along the super gravity. What’s more, Eq. (5) shows the arrival time to certain positions with respect to the size difference of perovskite crystals, when substituting the density of perovskite crystals and the melt, the viscosity of the melt, angular velocity with the constant into Eq. (5), it needs 13.82 s for the perovskite particles with the equivalent diameter of 100 μm moving from the position of 0.23 m to 0.27 m under the action of super gravity field, while it needs 2.56 min and 23.04 min for the perovskite particles with the equivalent diameter of 30 μm and 10 μm respectively. It seems that the estimation of the arrival time is smaller than the experiments done in this study, which is mainly due to the assumption that perovskite crystals are spherical in shape. In fact, perovskite crystals are mainly dendriform and equi-axed shapes as seen in Fig. 4, which will experience more viscous resistance than the spherical perovskite crystals. In addition, the volume fraction of perovskite phase is more than 30% in the melt from area (e) to area (i) as shown in Tables 3, 4 and 5, which would increase the probability of inter-particle collision that will delay perovskite crystals moving along the direction of super gravity. As a result, the estimation of the arrival time is smaller than the experiments done in this study.

### 3.3. Components of Layered Sample and Recovery Ratio of Ti after Centrifugal Enrichment

As shown in Fig. 8, there are mainly perovskite, diopside and pyrope phases in the parallel sample. After centrifugal treatment with the parameter of $G=600$, $t=20$ min, $T=1578$ K, an overwhelming majority of perovskite phase accumulates in the bottom of the sample as concentrate, while diopside and pyrope phases occupy the upper side of the sample as tailing. Under the hypothesis that the titanium exists in the slag in terms of TiO$_2$, with the gravity coefficient $G=600$, time $t=20$ min and temperature $T=1578$ K, the mass fraction of TiO$_2$ in the concentrate is up to 34.97%, while that of the tailing is just 11.16% as listed in Table 6.

Considering that the mass fraction of TiO$_2$ is 22.34% in the parallel sample, the recovery ratio of Ti in the concentrate is up to 74.16% by centrifugal enrichment as shown in Table 7. The recovery ratio of Ti in the concentrate and tailing are calculated via Eqs. (6) and (7).

$$
epsilon_r = \frac{m_r \times \omega_r}{m_c \times \omega_c + m_r \times \omega_r} \times 100\% \quad \text{(6)}$$

$$
epsilon_r = \frac{m_r \times \omega_r}{m_c \times \omega_c + m_r \times \omega_r} \times 100\% \quad \text{(7)}$$

### 4. Conclusions

It was confirmed by the experimental results that isothermal enriching perovskite phase from CaO–TiO$_2$–SiO$_2$–Al$_2$O$_3$–MgO melt by super gravity was an effective method. The sample obtained by the gravity coefficient $G \geq 600$, time $t \geq 20$ min and temperature $T \geq 1578$ K appears significant layers and perovskite phase presents gradient size distribution in the sample along the super gravity.

With the gravity coefficient $G \geq 600$, time $t \geq 20$ min and temperature $T \geq 1578$ K, it is hardly to find any perovskite particles in the upper area of the layered sample and the perovskite phase gathers at the middle and bottom areas of the sample. The moving speed of perovskite particles in the melt is proportional to the square of the perovskite particle size and large size perovskite particles gather at the bottom of the sample, while the small ones accumulate in the middle of the sample.

Under the hypothesis that the titanium exists in the slag in terms of TiO$_2$, with the gravity coefficient $G=600$, time $t=20$ min and temperature $T=1578$ K, the mass fraction of TiO$_2$ in the concentrate is up to 34.97%, while that of the tailing is just 11.16%. Considering that the mass fraction of TiO$_2$ is 22.34% in the parallel sample, the recovery ratio of Ti in the concentrate is up to 74.16% by centrifugal enrichment.

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**Table 6.** XRF result of separation products by centrifugal enrichment (mass fraction, %).

<table>
<thead>
<tr>
<th>Products</th>
<th>CaO</th>
<th>TiO$_2$</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrate</td>
<td>37.42</td>
<td>34.97</td>
<td>15.09</td>
<td>7.55</td>
<td>4.98</td>
</tr>
<tr>
<td>Tailing</td>
<td>26.85</td>
<td>11.16</td>
<td>35.62</td>
<td>17.43</td>
<td>8.94</td>
</tr>
<tr>
<td>Parallel sample</td>
<td>30.88</td>
<td>22.34</td>
<td>25.28</td>
<td>13.08</td>
<td>7.19</td>
</tr>
</tbody>
</table>

**Table 7.** Recovery ratio of Ti in the products by centrifugal enrichment and the parallel sample.

<table>
<thead>
<tr>
<th>Products</th>
<th>Productivity/ Chemical compositions of TiO$_2$%</th>
<th>Recovery ratio of Ti%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrate</td>
<td>47.81</td>
<td>34.97</td>
</tr>
<tr>
<td>Tailing</td>
<td>52.19</td>
<td>11.16</td>
</tr>
<tr>
<td>Parallel sample</td>
<td>100</td>
<td>22.34</td>
</tr>
</tbody>
</table>
Acknowledgement

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Nomenclature

<table>
<thead>
<tr>
<th>Units in SI System</th>
<th>A (d^2(\Delta \rho/18\eta))</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>d Diameter of perovskite crystals</td>
<td>G Gravity coefficient</td>
<td>—</td>
</tr>
<tr>
<td>g Gravitational acceleration</td>
<td>(m_c) Mass fraction of the concentrate</td>
<td>%</td>
</tr>
<tr>
<td>(m_r) Mass fraction of the tailing</td>
<td>N Rotating speed of the centrifugal</td>
<td>r·min (^{-1})</td>
</tr>
<tr>
<td>R Distance from the centrifugal axis to the centre of sample</td>
<td>r Radius of rotation of perovskite crystals at the time of (t)</td>
<td>m</td>
</tr>
<tr>
<td>R’ Initial radius of rotation of perovskite crystals</td>
<td>(V_r) Velocity of perovskite crystals</td>
<td>m/s</td>
</tr>
<tr>
<td>(\eta) Viscosity of melt;</td>
<td>(\rho_i) Density of the melt</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>(\rho_p) Density of perovskite crystals</td>
<td>(\Delta \rho) Density difference between perovskite crystals and melt</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>(\omega) Angular velocity</td>
<td>(\omega_c) Mass fraction of TiO(_2) in the concentrate</td>
<td>%</td>
</tr>
<tr>
<td>(\omega_r) Mass fraction of TiO(_2) in the tailing</td>
<td>(\varepsilon_c) Recovery ratio of Ti in the concentrate</td>
<td>%</td>
</tr>
</tbody>
</table>
| \(\varepsilon_r\) Recovery ratio of Ti in the tailing | REFERENCES

15) Y. Xie, C. M. Liu, Y. B. Zhai, K. Wang and X. D. Ling: Rare Metals, 28 (2009), 405.