Study on Energy Consumption Evaluation for Production of High-Titanium Slag

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Abstract. High-titanium slag is not only the substitute for the gradually depleted natural rutile resources but also the important raw material for the clean production of titanium industry. In this paper, a modeling of energy consumption evaluation for production of high-titanium slag using the ilmenite as raw material was proposed, then the energy consumption of high-titanium slag production by direct reduction-melting and separation process (two-stage process) was measured on production site. The energy consumption of high-titanium slag was converted into standard coal energy or electric energy by the energy value method and the energy equivalent method, respectively, on the base of data collected from the plant. The electric energy consumption of high-titanium slag produced by the two-stage process was 1661.6 kWh per ton slag with the energy value method. Due to the energy value conversion method more reflects the value of electricity, which is suitable for applying to the energy consumption evaluation of high-titanium slag production.

1. Introduction

At present, due to the rapid development of the titanium industry, natural rutile resources are increasingly exhausted, and the ilmenite has gradually replaced rutile as the main raw material for the titanium industry. In recent years, with the rapid development of titanium dioxide by the chlorination process and titanium sponge, the demand for titanium-rich materials such as high-titanium slag is increasing significantly. Now the mass content of TiO₂ in the titanium concentrate obtained by the beneficiation process is only about 42~ 47% and it is very difficult to directly use it to produce titanium sponge or titanium dioxide. It is necessary to enrich the ilmenite into a high-grade titanium-rich material after iron removal[1-4]. The process for producing titanium slag can be divided into the conventional electric furnace smelting process (one-stage method) and the new direct reduction-melting and separation process (two-stage method) [5-7]. The titanium slag production process is a complex physical and chemical process consisting of multiple processes. It is characterized by intensively consumption of resource and energy. The manufacturing process of high-titanium slag is accompanied by a large amount of material and energy emissions. At present, there are many researches on the energy consumption of iron and steel production[8-10]. However, the energy consumption evaluation method for production of titanium slag has not been reported. In this paper,
the energy value conversion method and the energy equivalent conversion method are applied to study the process energy consumption of high titanium slag produced by the two-stage process.

2. Process Flow of High-titanium Slag Production

The raw material for the production of high-titanium slag is the ilmenite and the pulverized coal. The chemical composition and the size distribution of the ilmenite are listed in Table 1 and Table 2, respectively. The chemical composition and the size distribution of the pulverized coal are listed in Table 3 and Table 4, respectively. Whether it is the production of titanium slag by one-stage or two-stage process, firstly the iron oxides in the ilmenite is reduced to metal iron by reducing agent coal at high temperature. Then the metal iron is to be integrated into the iron phase, and the titanium oxide enters the slag phase to form high-titanium slag at the liquid phase, thereby obtaining molten iron and high-titanium slag, respectively. Therefore, the production of high-titanium slag requires the coal and the electricity.

Table 1. Chemical composition of the ilmenite.

| Content | Fe | FeO | Fe₂O₃ | TiO₂ | Al₂O₃ | CaO | MgO | V₂O₅ | P | S |
|---------|----|-----|-------|------|-------|-----|-----|------|---|---|
| Mass fraction (Dry), wt.% | 34.22 | 25.58 | 20.46 | 46.87 | 1.92 | 0.46 | 4.64 | 0.04 | 0.02 | 0.01 |

Table 2. Size distribution of the ilmenite.

| Size/mm | <0.075 | 0.075~0.125 | 0.125~0.180 | >0.180 |
|---------|--------|-------------|-------------|--------|
| Wt.%    | 12     | 55          | 28          | 5      |

Table 3. Chemical composition of the pulverized coal.

| Content | C | SiO₂ | Al₂O₃ | CaO | FeO | Volatile | S |
|---------|---|------|-------|-----|-----|----------|---|
| Mass fraction (Dry), wt.% | 80.0 | 6.5 | 5.1 | 1.8 | 1.1 | 5.0      | 0.2 |

Table 4. Size distribution of the pulverized coal.

| Size/mm | <0.075 | 0.075~0.125 | 0.125~0.180 | >0.180 |
|---------|--------|-------------|-------------|--------|
| Wt.%    | 23     | 56          | 15          | 6      |

The detailed process flow for the production of high-titanium slag by the two-stage method is shown in Figure 1. It shows that the whole process can be divided into briquetting, direct reduction and melting and separation from Figure 1.

(1) Process of Briquetting: Before the reduction process, briquetting of the ilmenite ore powder using pulverized coal was carried out. The ilmenite, coal powder and adhesive were mixed according to certain ratio. The mixtures were put into briquetting machine to press into carbon-containing pellets.

(2) Process of direct reduction (first stage): The dried carbon-containing pellets were transported into the hearth of the rotary hearth furnace (RHF) for direct reduction. Carbon-containing pellets were turned into metalized pellets after reduction at high temperature. In this first stage, most of Fe oxide were reduced in the RHF at 1250 ~ 1350°C in solid phase.

(3) Process of melting and separation (second stage): Metalized pellets were discharged from the RHF and sent into the specific electric arc furnace. In this second stage, the remaining Fe oxide mainly in association with FeO were further reduced in the molten pool of the electric furnace at 1500 ~ 1700°C in liquid phase. The molten iron and titan ferrous slag were effectively separated due to the
density separation and electromagnetic stirring. Metal Fe entered into the molten iron phase while Ti entered into the titaniferrous slag. The main product, high-titanium slag and by-products pig iron were obtained after metal tapping and slagging, respectively.

![Process flow diagram.](image)

3. Modeling of Energy Consumption Evaluation

According to the process flow of the Figure 1, the energy consumed by high-titanium slag production can be divided into two types: the first type is direct-use fuel or energy power for heating; the second type is coal used as the reducing agent for reduction reaction of $\text{Fe}_3\text{O}_4$. The energy consumption $G$ of high titanium slag was the summation of all above energy in each process.

The actual amount of various energy consumed in a specified period of time, such as 1 hour, is summed and converted into the same energy unit. Then the summation of energy consumed is divided by the output per hour of high titanium slag. When there is secondary energy supply in the production, such as electric furnace gas, this energy consumption needs to be deducted. The equation of the energy consumption evaluation is shown as following Eq. 1.

$$G = \frac{\sum_{i=1}^{n} H_i \cdot \rho - E_w}{P}$$

Where, $G$ is the energy consumption per ton of high titanium slag, kwh / (t slag); $H_i$ is the energy consumption of each process, actual unit; $\rho$ is the energy conversion coefficient, kWh/actual unit; $E_w$ is the amount of energy converted into electricity outside the process; $P$ is the hourly high titanium slag output, t/h.
The main energy consumption of the blast furnace was coke, which generally uses standard coal (kgce) consumption. Unlike the blast furnace ironmaking, the main energy consumption of producing titanium slag was electricity, so the electricity consumption (kWh) was universally used in the titanium slag industry according to industry practice. All the primary energy consumed by titanium slag production is usually converted into the electricity energy.

4. On-site Energy Consumption Measurement of High-titanium Slag Production
After several months of construction, equipment commissioning and debugging work, the direct reduction-melting and separation process production line was directly carried out in a steel plant in Shandong Province, China. The ilmenite, coal powder and adhesive were mixed and the mixtures were placed to briquetting machine to press into carbon containing pellets. Thereafter, carbon-containing pellets were taken into the hearth of the RHF using belt conveyor for reduction. Following the reduction for 30 minutes at 1350°C, carbon-containing pellets turned into metalized pellets after direct reduction in RHF. Metalized pellets were discharged from RHF and sent into the specific electric furnace using soaking tank. Metalized pellets melt and FeO was deep reduced at 1500°C ~ 1700°C in the electric furnace. Different density of molten iron and titanium slag lead to natural separation in the molten pool. The main product, high-titanium slag and by-products pig iron were obtained after metal tapping and slagging, respectively.

Figure 2. The RHF of the production line.

Figure 3. The specific electric furnace of the production line.
The RHF with middle diameter of 15 m, the hearth width of 5 m, and the hearth height of 1.5 m was used in industrial trial production. On the other hand, the electric furnace with diameter of 4 m, hearth height of 2.5 m, power of 6300kVA was used. All on-site process data, such as temperature, gas flow, gas pressure and electric power, were collected by instruments corresponds to China standards. The photos of the RHF and the specific electric furnace on the production site are shown in Figure 2 and Figure 3, respectively. According to the field data collected during the period of one month production by automation instruments, the statistics of actual energy consumption of each process are as following.

1) Process of Briquetting
The equipment for the raw material processing is mainly dosing machine, mixing machine, briquetting machine, drying machine, conveying belt and so on. The total electricity capacity of these equipment is 255kw. In this briquetting process, the reductant coal consumed for carbon containing pellets is 1045.5kg/h

2) Process of direct reduction
The equipment used in the direct reduction process is the RHF. The fuel used in the RHF is the producer gas with a calorific value of 6992 kJ/m3. According to the on-site monitoring data by automation instruments, the hourly average fuel quantity of the RHF is 5230m3. The calculated calorific value is 3.66 ×107kJ/h, namely, 1249.5kgce.

3) Process of melting and separation
The equipment used in the melting and separation process is the electric furnace with the power capacity of 6300kVA. Under the condition that the pellet material is hot-loaded into the melting furnace, the average power consumption of the electric furnace is 5500kw. In this process, the weight of the coal as supplementary reductant is 994.5kgce/h.

The above data collected on-site was summarized as shown in table 5. All the reductant coal used in the preparation of raw material process and melting and separation process were summed and listed separately in the reductant coal column of table 5.

It can be seen from Table 5 that the energy units of each process of high-titanium slag production are different, so it is necessary to convert them into the same unit of energy. There are two energy conversion methods, namely the energy value method and the energy equivalent method. The energy value is the calorie of another energy product consumed for producing one unit energy product. 1 per kilowatt-hour (kWh) corresponding to the equivalence standard coal is 0.33 kgce by the energy value method. The energy equivalent is the calorific capacity of per unit energy product. For example, 1 per kilowatt-hour (kWh) corresponding to the equivalence standard coal is 3600 kJ (or the calorific value of 860 kCal), which is equal to 0.1229 kgce by the energy equivalent. It can be seen that the amount of standard coal corresponding to 1 kWh by the energy value method is about three times of the results calculated by the energy equivalent method. It is due to the conversion efficiency of primary energy coal to secondary energy electricity. Primary energy is produced naturally, such as coal, and secondary energy is produced by primary energy, such as electricity. In general, the efficiency of coal-fired power generation is 30~40%. So the energy equivalent method ignores the energy conversion efficiency between coal and electric energy. The production of titanium slag cost large amount of electric energy, and it is unreasonable to evaluate the energy consumption of titanium slag by equivalent method.

The output of production line was 5.8t high titanium slag per hour. According to the Eq.1, the energy consumption with kgce unit or kWh unit of each process was converted and listed in Table 6 and Table 7 by the energy value method and the energy equivalent value method, respectively.

Table 5. Raw data of actual energy consumption per hour.

| Preparation of raw material | direct reduction procedure | Melting and separating procedure | Reductant coal |
|-----------------------------|-----------------------------|---------------------------------|----------------|
| 255 kWh                     | 1249.5kgce/h                | 5500kWh                         | 2040kgce/h     |
Table 6. Energy consumption per ton high-titanium slag by the energy value method.

| Energy consumption | Preparation of raw material | Direct reduction process | Melting and separating process | Reductant coal | Total |
|--------------------|-----------------------------|--------------------------|-------------------------------|----------------|-------|
| Standard coal Kgce/(t slag) | 14.6 | 216.2 | 314.0 | 3.53 | 548.3 |
| Electricity kWh/(t slag) | 44.1 | 655.2 | 951.6 | 10.7 | 1661.6 |

Table 7. Energy consumption per ton high-titanium slag by the energy equivalent method

| Energy consumption | Preparation of raw material | Direct reduction process | Melting and separating process | Reductant coal | Total |
|--------------------|-----------------------------|--------------------------|-------------------------------|----------------|-------|
| Standard coal Kgce/(t slag) | 5.4 | 216.2 | 116.9 | 3.5 | 342.0 |
| Electricity kWh/(t slag) | 44.1 | 535.1 | 289.4 | 8.7 | 877.3 |

After the actual energy consumption of the production line is converted according to the energy value and the energy equivalent method, the energy consumption per ton of titanium slag is 1661.5 kWh/(t slag) and 877.3 kWh/(t slag). From this data, the energy consumption of titanium slag calculated by equivalent value is about 2 times that of the equivalent method. This is due the energy equivalent method ignores the inherent value of electricity. Electricity is a secondary energy. In the process of thermal power generation, there are problems such as power generation efficiency, transmission efficiency, and environmental pollution. Therefore, the author holds that the energy consumption of high-titanium slag should use the energy value method.

5. Conclusion

The energy evaluation method for producing high-titanium slag using the ilmenite as raw material was proposed, and the energy consumption of high-titanium slag production by direct reduction-melting process (two-stage process) was evaluated on production site. The energy consumption of high-titanium slag was calculated and converted into the same energy unit (kgce or kWh) by the energy value method and the energy equivalent method respectively on the base of data collected on-site from the plant. The energy consumption of high-titanium slag by the two-stage process was 1661.6 kWh/(t slag) by the energy value method. However, the energy consumption of high titanium slag was only 877.3 kWh/(t slag) by the energy equivalent method. Due to the energy equivalent method ignores the energy conversion efficiency between coal and electric energy; the energy consumption evaluation of high-titanium slag production is more suitable for using the energy value method.

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