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Research Article

Production of Micron-Sized Particles of Bauxite by Circulating Pulverization Experiment

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A novel process involving the production of micron-sized particles of bauxite by circulating pulverization experiment is proposed. This method is through high-pressure gas infiltration, uniform and equal stress loading, and overcoming tensile strength between particles, which is different from the traditional ball milling based on overcoming compressive or shear strength. The circulating pulverization experiment is designed so that the coarse particles larger than 147 μm need to be repulverized or added to the new bauxite ores and repulverized under the same experimental conditions. The results of the first group of circulating experiments show that the proportion of particles less than 147 μm increases from 27% to 91%, which reveals that the coarse particles larger than 147 μm can be repowdered. The results of the second group of circulating experiments show that the powdering efficiency of particles larger than 147 μm is almost equivalent to the raw ore, and the proportion of particles less than 147 μm after four circulating pulverization experiments can reach 64.5%. The result is crucial for actual production because coarse particles will fill in the raw ore and be repulverized together, which can ensure continuous production and stable pulverization efficiency. Economic analysis reveals that the power consumption of the circulating pulverization experiment is estimated at 0.028$ per ton.

1. Introduction

The powder has a long history of human use. Ten thousand years ago, during the Stone Age, humans learned to grind corn using millstones. Today, almost all industrial materials such as plastics, metals, and ceramics are manufactured through the preparation and processing of powders. Besides, many and various products such as fertilizers, cement, industrial chemicals, and other goods are being manufactured in powder. The global metal powder market accounted for $3,913.49 million in 2019. The Asia-Pacific region is the fastest-growing metal powder market with the highest CAGR (compound annual growth rate) of 5.01%. China is estimated to grow faster than any other country.

Alumina (Al$_2$O$_3$) is an important basic raw material for national economic development [1]. Alumina ceramics have been widely used for various applications such as cutting tools and biomedical implants due to their high hardness and mechanical strength at high temperatures [2, 3]. The properties of ceramics strongly depend on the dimension and morphology of bauxite powder. Therefore, increasing attention has been focused on finding an effective way of producing bauxite powder [4–6].

There are approximately 3.8 billion tons of bauxite reserves in China, taking fifth place in the world next to Guinea, Australia, Brazil, and Jamaica. The bauxite deposits in China, mostly belonging to the karstic type, are mainly distributed in Shanxi, Guangxi, Henan, and Guizhou provinces [7]. The major bauxite resources in China are characterized by a high content of alumina (>55% Al$_2$O$_3$), high silica content (5%–15% SiO$_2$), and a low mass ratio of Al$_2$O$_3$ to SiO$_2$ (A/S). Table 1 shows the Al to Si ratio of bauxite ore from different sources in China, which is not suitable for the Bayer process [1, 8, 9] [10, 11], the only

TABLE 1: Al to Si ratio of Chinese bauxite ore.

Al to Si ratio	<4	4~6	6~7	7~9	9~10	>10	Total (%)
Proportion of reserves	7.42	48.59	10.94	14.43	11.65	6.97	100

Originated from [9].

commercial alumina extraction method. In China, low-grade diasporic bauxite with an Al_2O_3/SiO_2 mass ratio below 8 can be processed by sintering or through a combination of sintering and the Bayer process [12, 13]. But the sintering process and the combined process are comparatively energy-intensive and environmentally less friendly, incurring high alumina production costs [14].

Bauxite powder is almost produced by multistage crushing combined with the ball milling method, which requires reduplicative ball milling [15]. Multistage crushing together with the ball milling method has the characteristics of many processes and high energy consumption. There has been extensive research on the ball milling of ore. At present, the ball milling method focuses on the optimization of the grinding medium, roller rotation rate, steel ball or steel rod, and so on [16–19].

Max et al. [20] introduce a new comminution technology that can reduce energy consumption when compared to traditional grinding of rock by ball milling. A majority of the resulting particles exhibit larger fragments, ranging from 5 mm to 13.2 mm. 6.2% of the feed material was directly transferred to fine material <300 μm without many intermediate progeny particles. A model of particle production through repetitive crust breakage and drying cycles [21] is proposed, and the proposed mechanism could explain the production of fine particles with and without gas pulsation. Research work [22–24] has shown that natural quartz pebbles can be upgraded through a combination of microwave treatment, magnetic refinement, and chemical refinement to produce a viable feedstock for the powder production of solar grade silicon. The geopolymer precursor powder prepared via the hydrolyzed sol-gel method [25–29] can obtain geopolymer precursor powder materials with higher purity, shorter preparation time, lower cost, and higher activation activity, and hence provides useful reference information for large-scale applications. A spray drying technique [30, 31] to manufacture a new "nano-powder" morphology of pentaerythritol tetranitrate.

No one pays attention to the pulverizing mechanism of ore. Ball milling has the following characteristics: (a) "partial" loading and "external" loading; (b) overcoming the compressive strength or shear strength. Compression shear is the main failure style during the ball milling process. Compared with the ball milling method, pulverizing ore by propulsion and rapid unloading of gas has the following characteristics: (a) "uniform" loading and "internal" loading; (b) overcoming the tensile strength [32]. So much energy will be saved. Besides, this method only uses air and water, which is an absolute physical separation and does not involve any chemical changes. It is a simple mechanical size reduction method.

The particle size distribution curve obtained by the single experiment shows an R-R distribution as a whole [35]. Coarse particles larger than 0.147 mm are always present and account for almost 50%. Consequently, the coarse particles need to be repowdered. To improve the yield of fine particles of bauxite, a novel process involving the production of micron-sized particles of bauxite by circulating pulverization experiment is put forward. The circulating experiment mainly focuses on whether the coarse particles larger than 0.15 mm can be repowdered, and the overall pulverization efficiency is what we care about. Consequently, two types of experiments are designed.

2. Materials and Methods

To obtain the particle size distribution curve of the ore powder, it needs to be dried and sieved. The particle size larger than 0.147 mm can be sieved by a vibrating screen, and the particle size less than 0.147 mm can be sieved by a negative pressure vibrating screen. The sieve diameter includes 8 groups: 0.045 mm, 0.074 mm, 0.147 mm, 0.5 mm, 1 mm, 1.43 mm, 2 mm, and 4 mm.

2.1. Materials. The bauxite ore used in these experiments originates from the Shanxi deposits in China. The contents of Al_2O_3 and SiO_2 are 62.35% and 11.58%, respectively, resulting in a bauxite A/S of 5.38. The diameter of the sample was crushed to 2-3 cm and put into the high-pressure infiltration chamber for the subsequent experiments.

2.2. Circulating Pulverization Experiment of Bauxite Ore. Currently, the overall process includes air filling in the high-pressure chamber and high-pressure propulsion chamber, air substitution in the high-pressure chamber, and rapid unloading of air in the high-pressure chamber.

First, the high-pressure propulsion chamber is connected to the high-pressure chamber by a pipe. Between the two chambers, there is a piston, which is responsible for full-section propulsion. Second, the bauxite ores will be put into a high-pressure chamber, and after sealing, high-pressure air is injected. Third, dissociative air between the bauxite ores will be substituted by water and collected for cyclic utilization. Forth, bauxite ore and water will spout out of the high-pressure chamber, propelled by air in the high-pressure propulsion chamber, based on the rapid unloading actuated by the rupture disks bursting.

Why do we need circulating pulverization experiments? First of all, based on the rapid unloading of a high-pressure gas method, there are some pulverization effect differences because of the pressure gradient difference, so the particle diameter after pulverization experiments is almost R-R distribution even for homogeneous materials. If we want to obtain a uniform particle size, a circulating pulverization experiment is necessary. The method used in the circulating pulverization experiment is to fill the gaps of the new ore with coarse particles that did not meet the flotation standard. The challenge is whether the coarse particles larger than 147 μm can be repowdered.

The circulating pulverization experiments are a type of experiment which has the characteristics that the bauxite in the infiltration chamber will be propelled by the high-pressure gas in the propulsion chamber. The volume ratio of the propulsion chamber to the infiltration chamber is about $14:1$, which ensures the pressure inside the bauxite ore keeps constant or drops slightly when leaving the infiltration chamber.

The volume occupied by the natural accumulation of irregular ores is generally about 50% of the volume of the infiltration chamber. The coarse particles larger than $147\,\mu$m need to be added to the new bauxite ores and repulverized under the same experimental conditions. The first group of the circulating experiments is that the coarse particles larger than $147\,\mu$m are repowdered. The second group of the circulating experiments is that the coarse particles larger than $147\,\mu$m are put into the new bauxite ores and repowdered.

2.3. Mass Block Preacceleration and High-Pressure Propulsion. Ore can be pulverized by the rapid unloading of liquid CO_2 or high-pressure air under the condition of high-pressure air propelling [32–34]. Furthermore, the ore far from the outlet will have a higher ejection velocity when leaving the infiltration chamber because of long-time acceleration. However, there is no way to speed up the ore next to the rupture disk. So, a mass block is set between the ore and the rupture disk which can provide an acceleration distance for the one next to the rupture disk, as illustrated in Figure 1. The experimental device is illustrated in Figure 2. We have designed mass blocks of different materials and different lengths with lateral sealing to prevent rapid pressure dropping.

To realize full-section propulsion, a rubber piston with a side seal is installed behind the ore. To ensure the stability of the rubber piston, the pressure on both sides of the rubber piston is raised alternately. An explosive is fixed on the rupture disk to realize the rapid unloading.

Based on the abovementioned scheme, we select two types of iron and aluminum cylinders, whose lengths are 2 cm and 5 cm, respectively, as illustrated in Figure 3. The depths of the nylon cylinder and rupture disk is 1 cm and 0.3 cm, respectively. The density of nylon was almost the same as that of water. The mass of the ore is about 0.9 kg, and the initial pressure of the air is about 8.5 MPa.

3. Results and Discussion

The biggest advantage of this method is the short process, including ore filling, gas injection, substitution, and unloading, which can probably replace the whole process of multistage crushing and ball milling, reducing equipment investment. Based on overcoming tensile strength separately and high energy utilization because of gas penetration into micropores, the method can reduce the cost of ore pulverization. Energy consumption mainly comes from air compressors and water pumps, and the estimated total cost is 0.028 US dollars per ton of bauxite ore powder less than $147\,\mu$m.

3.1. Mass Block Preacceleration Experiment. The particle size distribution of the ore powder produced by different mass blocks preacceleration is shown in Figure 4. As a whole, with the length of the mass block increasing, the proportion of fine particles gradually increases. Firstly, we could find that d1 is about 5%, which means the length of a mass block will affect the total proportion of the particles less than $45\,\mu$m. The greater the length of the mass block preacceleration, the higher the content of fine particles. Secondly, d2 is much larger than d1, which means the fine particles between $45\,\mu$m and $74\,\mu$m obtained from long mass block preacceleration are better than those obtained from short mass block preacceleration. Thirdly, d3 is almost equivalent to d2, and the spacing between long and short mass blocks has no more noticeable changes. Furthermore, we can find that mass blocks of different materials have little influence on the ore pulverization results. It should be emphasized that the two experimental results with a length of 2 cm have a deviation of about 2%, which we judged to be experimental random errors, and theoretically, they should be coincident. So we can choose the mass block with lightweight materials to save propulsion energy. A more important effect on the manufacturing industrial equipment is that we can adopt mechanized rapid unloading rather than explosives because the mass block can maintain the high-pressure gradient characteristics when rapid unloading occurs.

3.2. Data Analysis of the Circulating Pulverization Experiment. The first group of circulating experiments is that the coarse particles larger than $147\,\mu$m are repowdered. The quality of the bauxite ore is shown in Table 2. As a whole, with the number of circulating pulverization increasing, the proportion of fine particles gradually increases, which reveals that the coarse particles larger than $147\,\mu$m produced in the last test could be repowdered. As shown in Figure 5, a1, a2, a3, and a4 represent the difference in the total proportion of fine particles less than 0.045 mm, greater than 0.045 mm, less than 0.074 mm, greater than 0.074 mm, less than 0.15 mm, greater than 0.15 mm, and less than 0.5 mm, between the first test and after four-cycle tests. We could find that a1, a2, a3, and a4 are about 29%, 49%, 64%, and 54%, respectively, which means circulating pulverization has a great effect on the total proportion of the particles less than $147\,\mu$m. Simultaneously, b1, b2, and b3 represent the difference in the total proportion of fine particles greater than 0.074 mm and less than 0.15 mm between the first test and the two cycle tests, the three cycle tests, and the four-cycle tests. We can find that b1, b2, and b3 are about 29%, 17%, and 8%, respectively, and the distance between every two adjacent lines is gradually reduced, which reveals that the difference between the first and the second experiment is significantly larger than that between the second and the third experiment, indicating that circulating pulverization contributes to the increase in the total proportion of fine particles less than $147\,\mu$m, but the difficulty is getting bigger and bigger. As a whole, the proportion of particles less than $147\,\mu$m increases from 27% to 91%, which meets the particle size requirements of beneficiation.
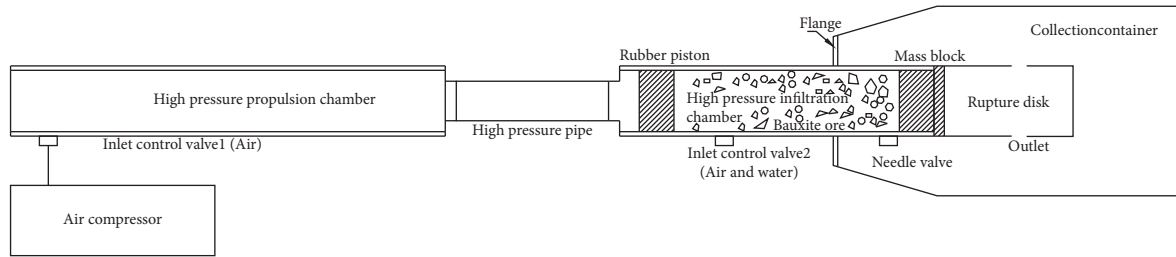
FIGURE 1: Schematic diagram of experimental apparatus.

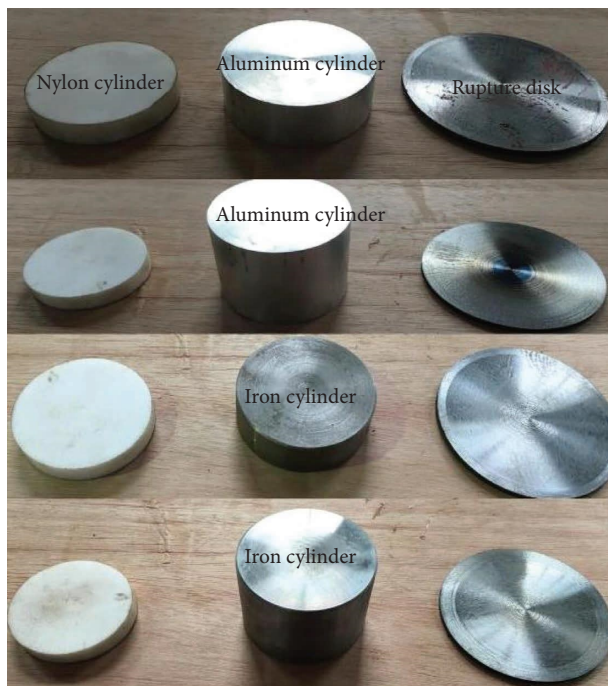FIGURE 2: Platform for bauxite ore powder production.

FIGURE 3: Iron and aluminum cylinders with different heights.

The second group of circulating experiments is that the coarse particles larger than $147 \mu m$ are put into the new bauxite ore and repowdered. The quality of the bauxite ore is illustrated in Table 3. After the first group of circulating experiments, we verify that the coarse particles larger than $147 \mu m$ can be repowdered. So we need to confirm the powdering efficiency of the coarse particles larger than

$147 \mu m$ and the raw ore. As shown in Figure 6, we can find that the percentage of single-particle size interval in each powdering experiment is almost equivalent, which reveals that the powdering efficiency of coarse particles larger than $147 \mu m$ was obtained from the first group experiment and the raw ore is almost equivalent. From the data of the first to third experiments, we can find that the total proportion of particles less than $500 \mu m$ from the label value is about 50.9%, 54.3%, and 55.7%, as shown in the circle with a different color in Figure 6. 50.9 is the total of $14.0 + 9.9 + 8.0 + 19.0$, marked with the green circle. 54.3 is the total of $18.9 + 7.2 + 8.3 + 19.9$, marked with the red circle. 55.7 is the total of $18.5 + 8.4 + 6.7 + 22.1$, marked with the blue circle. If it is assumed that the proportion of each pulverization of new ore is certain, which means that the powdering efficiency of particles larger than $147 \mu m$ is slightly better than raw ore because of the existing damage inside of them. This conclusion is crucial for actual production because coarse particles larger than $147 \mu m$ will fill in the raw ore and be repulverized together.

As shown in Figure 7, e1, e2, e3, and e4 represent the difference in the total proportion of fine particles less than 0.045 mm, greater than 0.045 mm and less than 0.074 mm, greater than 0.074 mm, less than 0.15 mm, greater than 0.15 mm, and less than 0.5 mm, between the first test and after four-cycle tests. We can find that e1, e2, e3, and e4 are about 19%, 32%, 36% and 28%, respectively, which means circulating pulverization has a great impact on the total proportion of the particles less than $147 \mu m$ and is similar to the first group of circulating experiments. Simultaneously, f1, f2, and f3 represent the difference in the total proportion of fine particles greater than 0.074 mm and less than 0.15 mm between the first test and the two-cycle tests, three-cycle
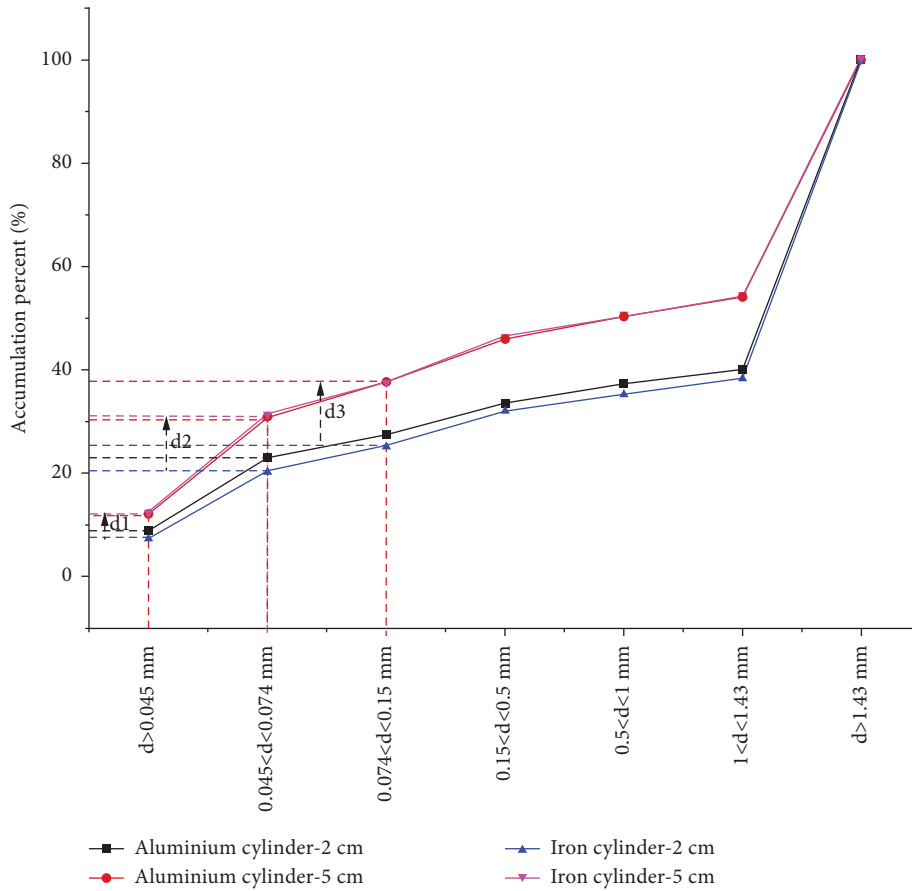
FIGURE 4: Comparison of the pulverization effects of mass blocks of different lengths and materials.

TABLE 2: The quality of the bauxite ore in the first group of circulating experiments.

	Bauxite ore for experiments (kg)	$d < 0.15$ mm (kg)	$d > 0.15$ mm (kg)	Percent less than 147 μm (%)
The first	2.500	0.675	1.825	
The second	1.825	0.725	1.000	
The third	1.000	0.550	0.450	91
The forth	0.450	0.325	0.125	
The total		2.275		

tests, and four-cycle tests. We can find that f1, f2, and f3 are about 16%, 12%, and 9%, respectively, and the distance between every two adjacent lines is gradually reduced, which reveals that the difference between the first and the second experiment is significantly larger than that between the second and the third experiment, which indicates that circulating pulverization contributes to the increase in the proportion of fine particles less than 147 μm, but the difficulty is getting bigger and bigger. Particle sizes less than 147 μm account for 64.5% of the particles.

By comprehensively comparing the two types of experimental data, we will find that the first experiment of the two groups is almost equal. As the number of cycles increases, the total amount of particle sizes less than 147 μm in the first group is larger than that in the second group because the quality of the first group is decreasing. We will find that the powdering efficiency of particles larger than 147 μm is almost equivalent to the raw ore, which is crucial for continuous production.

After comprehensively analyzing the data about the first group and the second group experiments, we can find that the coarse particles larger than 147 μm can be repowdered, and the efficiency of particles larger than 147 μm is almost equivalent to the raw ore.

Comparing Figures 5 and 7, we can find that the interval between every two lines in Figure 5 is much larger than that in Figure 7. This is because the total quality of ore in the first type is only 2.5 kg, and the first group of quality of ore in the second type of test is 2.5 kg, new ore is added in each cycle, and the total quality of ore is 4.73 kg, as shown in Tables 2 and 3.

3.3. Economic and Efficiency Analysis. Power consumption is a linear function of compressed air usage. The amount of air used to produce ore powder varies based on the scale of production. If the porosity is about 1%, which means 99% of
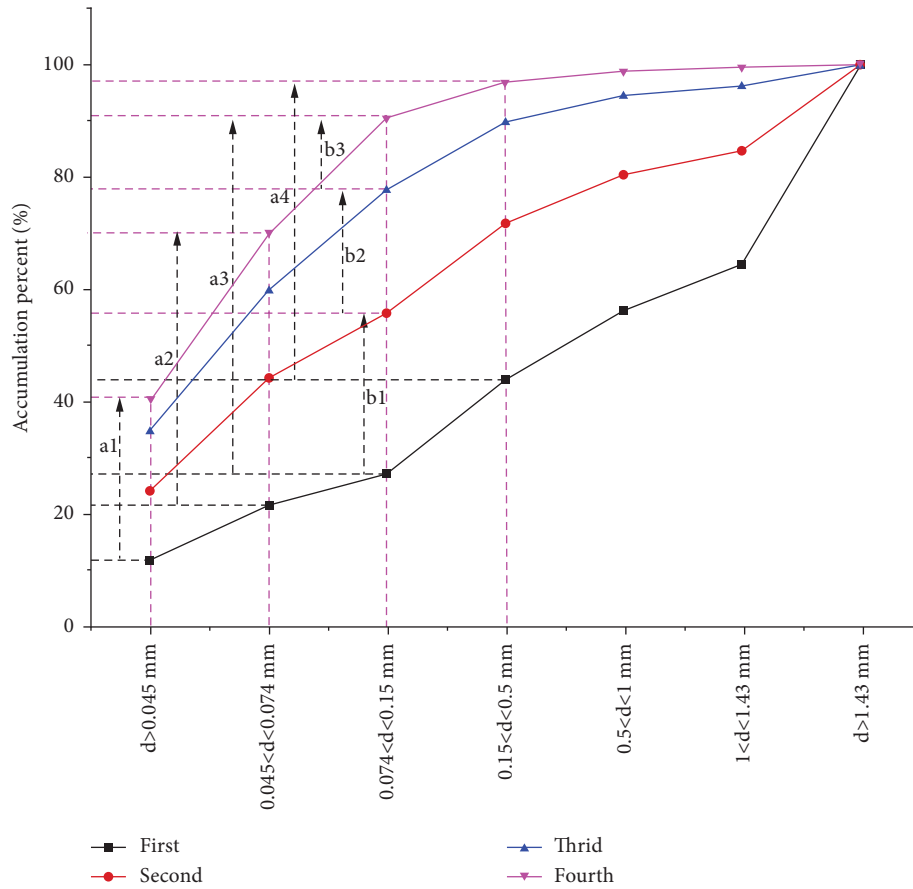
FIGURE 5: The cumulative size distribution of the first group of cyclic powdering (diasporic bauxite).

TABLE 3: The quality of the bauxite ore in the second group of circulating experiments.

	Bauxite ore for experiments (kg)	New bauxite ore (kg)	$d < 0.15$ mm (kg)	$d > 0.15$ mm (kg)	Percent less than 147 μm (%)
The first	2.500	2.500	0.700	1.800	
The second	2.500	0.700	0.720	1.780	
The third	2.500	0.720	0.810	1.690	64.5
The forth	2.500	0.810	0.820	1.680	
The total		4.730	3.050		

the air can be recycled by the substitution process. Take the propulsion pressure of 25 MPa, the infiltration pressure of 20 MPa, and the ore volume ratio of 56% as an example; the power consumption used for propulsion and air filling is about 6.5 kWh and 20 kWh per ton, respectively, and the power consumption used for substitution is about 2.3 kWh. The power price in China is 0.063\$ per kWh for industrial usage. The final result is that the particle sizes less than 147 μm account for 64.5% of the particles, so the power consumption for one ton of ore is about 0.063 ∗ (6.5 + 20 + 2.3)/64.5% = 2.8 because the air consumption is only 1%, the power consumption is estimated as 2.8 ∗ 0.01 = 0.028.

3.4. Discussion. The method of constant pressure propulsion and circulating pulverization can produce bauxite ore powder. The key to constant pressure propulsion is to maintain the high-pressure gradient inside the ore. The two types of cyclic powdering experiments illustrated above show that the circulating pulverization method is applicable.

Based on the comparison of pulverizing experiments with different cyclic styles, there is now a consensus that the particles larger than 147 μm could be repowdered and the pulverizing efficiency is almost equivalent to the raw ore, which is very important for the process design of the automatic powder production because it is related to the automatic control of the quality of the incoming material.
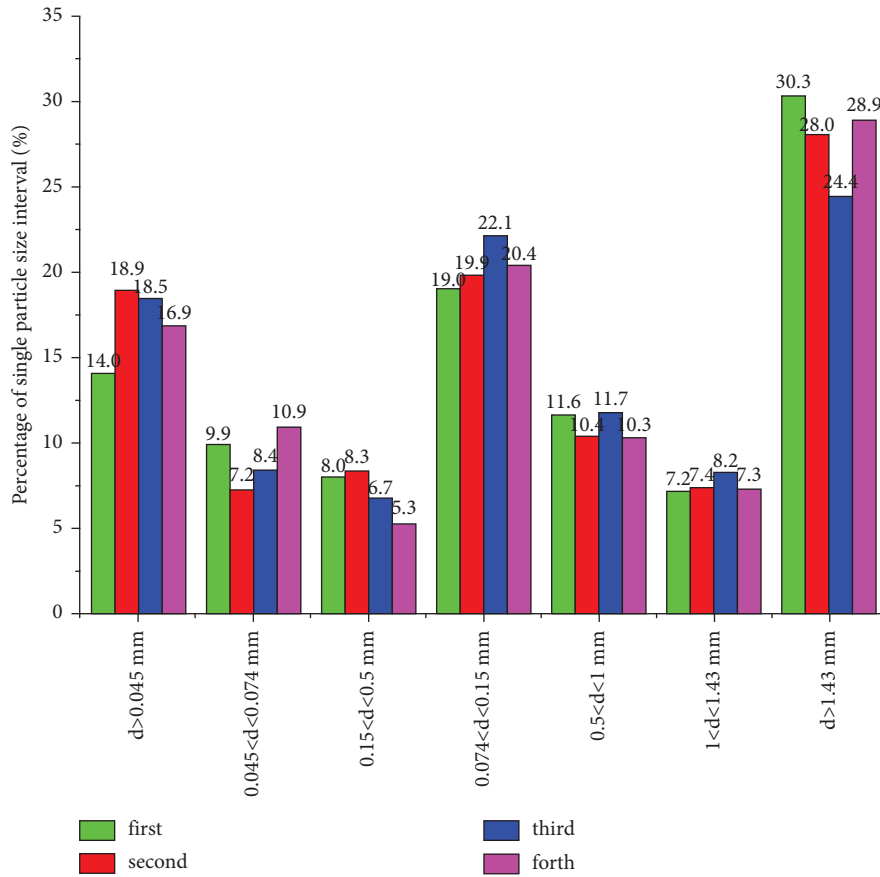
FIGURE 6: The percentage of single-particle size interval (diasporic bauxite).
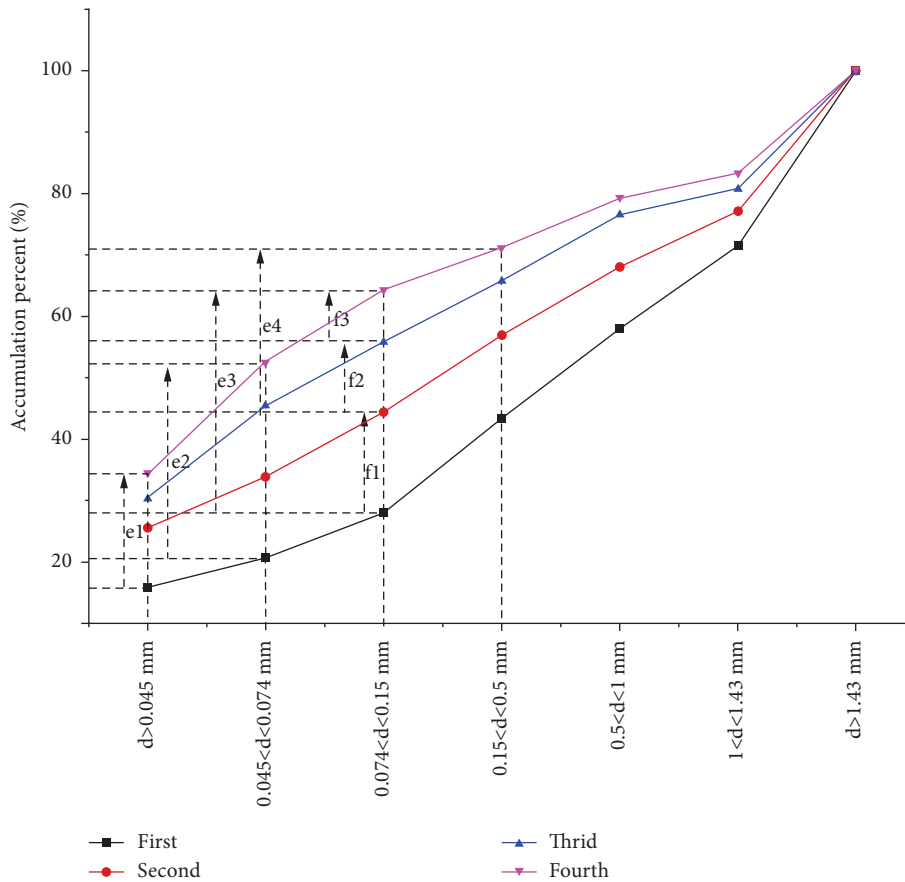

FIGURE 7: The cumulative size distribution of the second group of cyclic powdering (diasporic bauxite).

Further studies are needed to recycle the propulsion gas; the best way is that the propulsion gas does not spray out with the ore and can be compressed and recycled again. In this case, we only consume a little energy for compressing gas inside the infiltrating chamber to the propulsion chamber, so it can be considered to add a rubber piston between the two chambers. Water injection can be considered to reset the rubber piston because initialization also requires high-pressure water.

Circulating powder can consider adding to the total quality of the ore because particles larger than $147\,\mu$m can fill more pores between the ores. If, as the quality increases, the proportion of fine particles less than $147\,\mu$m in a single experiment can be maintained unchanged, the ore pulverization efficiency can be greatly improved.

4. Conclusions

A novel process involving the production of micron-sized particles of bauxite by circulating pulverization experiment is introduced. Simultaneously, the experiment of mass block preacceleration with different materials and lengths is conducted.

The greater the length of the mass block preacceleration, the higher the content of fine particles. The fine particles between $45\,\mu$m and $74\,\mu$m obtained from the long mass block preacceleration are better than those obtained from the short mass block preacceleration.

Through the contrastive analysis of the two circulating experiments, we have confirmed that the coarse particles larger than $147\,\mu$m can be repowdered, and the powdering efficiency of particles larger than $147\,\mu$m is almost equivalent to that of the raw ore.

Through the second group of experiments, the proportion of particles less than $147\,\mu$m after four circulating pulverization experiments can reach 64.5%, which is crucial for actual production because coarse particles will fill in the raw ore and be repulverized together, which can ensure the continuous production and the stable pulverization efficiency. Economic analysis reveals that the power consumption of the circulating pulverization experiment is estimated as $2.8 * 0.01 = 0.028$ [21].

Data Availability

The data used to support the findings of this study are included within the article.

Additional Points

(1) Ore pulverization only requires high-pressure air and water. (2) "Internal" and "equal stress" loading on the ore is different from ball mining's "external" and "partial" loading. (3) The particles larger than $147\,\mu$m can be repowdered. (4) The powdering efficiency of particles larger than $147\,\mu$m is equivalent to the raw ore.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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