Aluminum Blast Furnace Process Ⅱ. Midget Furnace

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Abstract

Reduction of bauxite has been investigated in a small experimental furnace with three oxygen lances. It was found that the bridge formation, caused by the votatilized aluminum and silicon components in bauxites and cokes, became appreciably mild with larging the furnace diameter. Bauxite briqutles however showed an unexpected movement and chemical behavior in the furnace: Briquettes dropped directly to the coke combustion zone. Reactions between bauxites and cokes proceeded only in the combustion zone where oxygen existed abundantly; the main reaction was the volatilization and the the yield of aluminum alloys produced was limited to extremely low. Several attemps were made to examine the behavior of briquetted bauxite in the coke combustion zone, and revealed that the aluminum component volatilized not when bauxite was reduced, but when briquette encountered with an oxidative atmosphere in the zone. These features can be ascribed to the fact that although the present furnace was equipped with three lances, there formed no place where the temperature was high enough to reduce bauxite (>2270 K). These suggested that it is essential to create, outside the combustion zone, an area at high temperatures and at a low oxygen partial pressure to obtain alloys of a high aluminum content.

I. INTRODUCTION

The investigation of reducing bauxite with coke combustion started with a prototype furnace (Part I). Results obtained using this furnace revealed that because of the low furnace temperature, a combined hollow-raceway channel was formed and transferred bauxites directly to the combustion zone; this was the main reason for a very low aluminum yield. Since it was hoped to use a well thermal-insulated furnace, a small midget furnace was built with three oxygen lances to aim at forming a high temperature zone in the center of a furnace; this furnace was designed to have better thermal insulation.

In the present paper, we report results of the investigation of the reduction of bauxite in this new furnace. Since the previous results implied a possibility that coating briquettes with a coke layer may protect the briqutles from the volatilization by oxygen attack to some extent, objectives of the reduction experiments have been selected as follows:

(1) examining effects of enlarging a furnace diameter on the formation of reduction and combustion zones;
(2) examining the chemical behavior of various types of briquettes in the coke/oxygen combustion zone at the oxidative atmosphere; especially to examine the applicability of coating briquettes with a layer of cokes to protect the briquettes and alloys from oxygen attack;
(3) examining effects of adding slags.

II. EXPERIMENTAL

A. *Experimental Furnace.*

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Experimental runs in this report are designated as BR-1 to 8. Figure 1 shows the schematic diagram of the midget furnace. In the initial three runs (BR-1 to 3), a graphite crucible (200 mm in diameter, 1000 mm in length) was used as an inner wall; in BR-4 to 8, the graphite crucible was replaced with a new graphite hearth, which was set at the bottom of the furnace as shown in Fig. 1. The total inner height was 1450 mm from hearth to ceiling. A graphite grate with many holes (10 mm in diameter) was set about 50 mm below tuyeres. The furnace was equipped with three oxygen lances; the structure of the lance was the same as that described in Part I. The outlet diameter of the tuyeres was fixed at 10 mm except 5 mm for BR-8. A tap hole was closed with a graphite plug and sealed by a steel frange. A hopper was equipped with a ball valve to prevent CO gas jets and back fires. A steel rod was inserted through three poking holes to inspect a burden bed. A pilot chimney was furnished, in addition to a main gas exhaust, to observe the flame of off gas. Six sets of W-W/Re 26% thermocouple were inserted into the furnace at selected locations as shown in Fig. 1.

B. *Furnace Operation*.

The operational characteristics are listed in Table 1. The operation procedure was almost the same as in Part I. The temperature of a burden bed was measured directly in BR-4 and 8; a W-W/Re 26% thermocouple insulated with an alumina tube was inserted through the poking hole into a burden bed. An attempt was made to tap products under an Ar gas flow. During tapping (it took about 30 min), the hearth temperature descended rapidly. Probably because of this low hearth temperature, any product was not flowed out spontaneously nor was scratched out by a steel rod.

C. *Materials and Analysis*.

Several types of briquettes were prepared as listed in Table 2. Other procedures of analysis and briquetting were essentailly the same as in Part I.

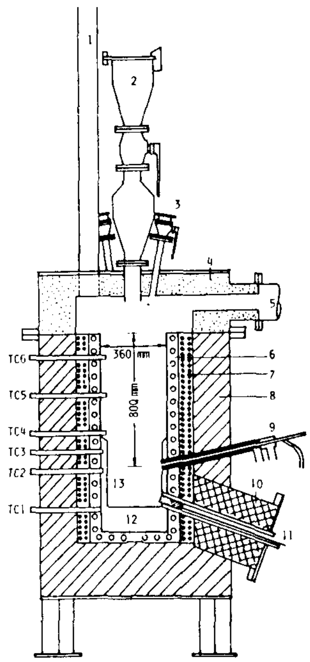

Fig.1 Midget furnace for BR-4 to 8:
1, Pilot chimney;
2, Hopper;
3, Poking hole;
4, Shamot castable;
5, Main gas exhaust;
6, Alumina castable wall;
7, Fusion cast alumina bubble;
8, Corrundum castable;
9, Oxygen lance;
10, Alumina fiber;
11, Tapping hole;
12, Graphite hearth; a graphite crucible (200 mm in diameter, not shown) was instead set for BR-1;
13, Graphite grate.

Table 1. Operational characteristics of BR runs.

condition	unit	Run No. BR-1	BR-2	BR-4	BR-6	BR-7	BR-8
Shaft diameter	(mm)	200	200	360	360	360	360
Tuyere diameter	(mm)	10	10	10	10	10	5
Blast rate	3x(dm^3/min)	180	90	180	180	270	210[a]
Temperature at race way	(K)	2550	2300	2540	2625	2600	2330
Feeding method	(-)	Ordinary	Center setting	Ordinary	Ordinary	Ordinary	Ordinary
Operation period	(h)	5.5	17.25	7.75	8.5	10	11.33
Coke input	(kg)	69	50	106.1	160	200	296
Briquette[b]	(kg/type)	8/BF	3.9/LB	16.9/BC	6.2/BPC	11/BP	40/BC
Slag flux[b]	(kg/type)	10/$CaCO_3$	0	0	0	11/MgC	0
Reacted briquette[c]	(kg)	8	3.9	16.9	6.2	11	27.9
Alloys produced	(kg)	2.2	0.9	3.9	1.3	2.5	6.4
Shape of race way	(-)	Separate	Combined	Separate	Separate	Combined	Combined
State of shaft & tuyere level	(-)	Combined void	Flooding	Separate channel	Loosely packed	Combined void	Combined void

(a) CO_2 (24 dm^3/min) was added in oxygen blast.
(b) Type of briquette is listed in Table 2.
(c) Reacted briquette = Introduced briquette - Non reacted briquette.

Table 2. List of briquettes used in the BR series of experiments. Raw materials are given in relative mass to that of bauxite and metal ratios are given in atomic ratio.

Type	Run No.	Raw Materials: Bauxite[a]	Iron[b]	Coke-I[c]	Coke-II[c]	Metal Ratio: Al/Fe	Si/Fe	Remarks
BP	BR-7	1000	0	0	0	6.9	0.34	bauxite ptcl. (Φ2-4 mm)
BPC	BR-6	1000	0	0	880	6.9	0.34	Coated bauxite (Φ5-10 mm)
BF	BR-1	1000	62	300	0	4	0.59	Non coated ball (Φ20-25 mm)
LB	BR-2,3	1000	62	300	0	4	0.59	column (20x65x800 mm)
BC	BR-4	1000	0	300	1150	6.9	0.34	Coated ball (Φ25-30 mm)

(a) Bauxite powder(-24 mesh) was used except particle for BP and BPC.
(b) Iron powder(-12 mesh) was used.
(c) Coke powder(-24 mesh) was used for reducing (Coke-I) and coating (Coke-II) material.

Table 3. Elemental analysis of products. Total contents are given in mass percent and contents of the metallic state are also given in mass percent.

products	Total content							Metallic		$Y^{(c)}$
	Al	Fe	Si	C	Ti	Ca	Balance	Al	Fe	
BR-1 (a,b)										
DP	2.0	8.1	4.3	3.0	-	53.3	29.2	-	-	-
RW, Bottom	26.6	8.7	7.7	22.8	-	4.2	30.0	-	-	-
Bridge	7.0	0.2	5.9	62.9	0.3	1.1	22.9	-	-	-
Dust	14.2	0.2	11.8	35.2	0.4	2.8	35.7	-	-	-
BR-4										
DP	7.2	47.2	15.9	9.6	9.4	0.18	20.1	3.5	27.3	0.58
RW, Bottom	-	-	-	-	-	-	-	5.3	32.1	1.14
Bq in RW	27.2	10.7	3.2	25.2	-	-	33.7	19.0	13.6	1.09
(partly broken) (Al_4C_3=8)										
Bq in RW	31.1	11.6	5.1	23.7	-	-	28.5	-	-	-
Bq in ST	25.8	9.9	2.8	29.4	-	-	32.1	-	-	-
BR-5										
DP	2.2	82.0	11.5	4.0	0	0.7	0.4	0.6	83.5	0.63
BR-6										
RW (inner wall)	2.5	46.7	26.3 (SiC=15.1)	21.3	-	-	3.2	1.4	28.6	0.89
BR-7										
RW (metallic particle)	3.3	58.5	18.6	11.3	1.9	Mg =0.5	6.2	1.8	25.2	0.68
BR-8										
DP (below lance)	29.8	21.7	12.1	16.4	3.4	-	16.6	3.7	9.3	1.03

(a) DP = dropped product; RW = race way; ST = shaft; Bq = briquette
(b) In BR-1 to 3, no metallic product was found in a H_2 evolving test.
(c) Y is the ratio of the dissolved amounts of Al and Fe to the evolved H_2 amount; see Part I for details.

III. RESULTS

The present experiments, BR-1 to BR-8, were carried out with the following aims:

- BR-1 : the first run in the midzet furnace;
- BR-2 and -3: try to feed the long briquette at the center of the furnace to avoid the direct drop of briquettes to the race way;
- BR-4 to 8 : effect of enlargement of the shaft diameter;
- BR-7 : effect of adding slag components.
- BR-8 : effect of lowering combustion temperature.

The main results can be summarized as follows:

(1) The bridge formation became much milder in the present furnace than in the prototype furnace equipped with a single lance;

(2) The feature of the formation of raceways became more complicated. However, temperature was still low outside the raceways;

(4) Briquetts dropped directly to the combustion zone, and the aluminum component in briquettes volatilized after the coating of briquettes was completely destroyed.

The followings are the detailed observations for the important features.

A. *Dust and Bridge.*

A large amount of grey dust was exhausted with CO gases. The composition of dusts was almost the same as that of bridged substances (Table 3, BR-1). Bridges were formed very frequently. Evidently, the volatilization of Al_2O and SiO induced the dust generation and the bridge formation. It should be noted

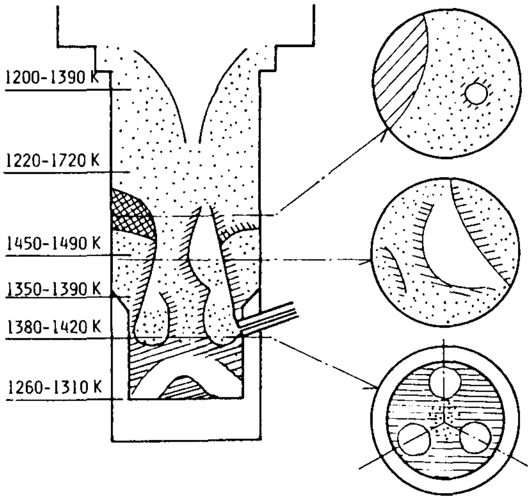

Fig.2 Dissection diagram of BR-4 with wall temperatures:
Hatched area, firmly coalesced part; Dotted area, loosely packed part; Blank, void; Burden bed temperatures observed were 1763 K, 1713 K, 1623 K, 1543 K, 1503 K, 1523 K, 1563 K, and 1343 K at upward interval of 10 cm from the tuyere level, respectively.

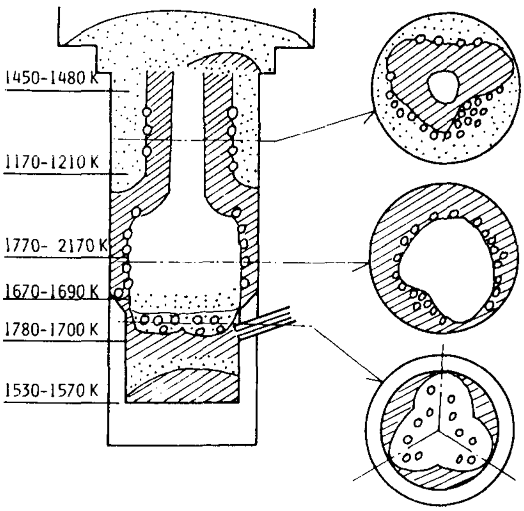

Fig.3 Dissection diagram of BR-8 with wall temperatures:
Hatched area, firmly coalesced part; Dotted area, loosely packed part; Blank, void; Burden bed temperatures observed were 1910 K, 1680 K, 1700 K, 1670 K, 1730 K, 1690 K, 1430 K, and 1310 K at upward interval of 10 cm from 10cm above the tyuere level.

that bridging has become milder after the furnace diameter was enlarged; that is, poking was required frequently to continue operation in BR-1 to 3, whereas in BR-4 to 8 bridges collapsed spontaneously without poking.

B. *Temperature Profile.*

Anomalous drifts in wall temperatures, accompanied with corresponding drifts in oxygen blast pressure, were observed when bridges were formed. The profiles of the mean wall temperature for BR-4 and 8 are shown in Figs. 2 and 3, respectively; the directly measured burden-bed temperatures, given in the figure captions, were lower than 2270 K both in BR-4 (max.1760 K) and BR-8 (max.1910 K); this indicates that there was no area at a higher temperature than 2270 K outside the combustion zone.

The temperature of burning cokes in the combustion zone are listed in Table 1. The highest temperature was usually about 2700 - 2900 K except for the following runs: The low combustion temperature was observed in BR-2 and 3 in which long briquettes (LB) were used; this was because the briquettes and products flooded around tuyeres and caused the lack of fuel cokes around the combustion zone. In BR-8, CO_2 gas was mixed with oxygen blast (CO_2/O_2 = 24/210 in volume ratio) to aim at lowering temperatures, and the temperature about 2300 ± 230 K was actually achieved.

C. *Dissection of Furnace.*

Figures 2 and 3 show the schematic diagrams of furnace dissection after operations. In BR-2 and 3, long briquettes "LB" melted and flooded; no distinct combustion zones were formed. In BR-1 and 4-6, the combustion zones like bird nest were formed in front of each tuyere (Fig. 2). The feature of the formation of channels above the combustion zone depended on the operation conditions. One channel remained in BR-1, and in BR-4 (Fig. 2) three separate channels did, whereas no channel was found in BR-5 and 6. In BR-7 and 8, the combustion zones were combined into a large dome-like void as shown in Fig. 3. Fragments of broken bridges were found in the furnace shaft in every case.

D. *Analysis of Products.*

Results of analyses are summarized in Table 3. In BR-1 to 3, no metallic product was found. In the other runs, alloys and slags were found below the graphite grate and at the bottom of combustion zones. The aluminum metal contents were low in these crude alloys. The utmost aluminum metal content in the present experiments was only 11.7 % in BR-8. The total aluminum contents in the dropped products were usually less than that in the original bauxite (Table 3).

Results on briquetts in various parts in the furnace in BR-4 showed the interesting feature: that is, any appreciable decrease in aluminum content was not observed in the coated briquettes found in the combustion zone even though their coatings were partly destroyed; on the other hand, the aluminum content decreased in *alloys* found at the bottom of combustion zones and in dropped products. The higher silicon content in the alloys than that in the raw bauxite was undoubtedly due to the reduction of silica in coke ash; a large portion of silicon existed in the form of SiC in the crude alloys as shown in Table 3 (BR-6). When a magnesia slag flux was used, only a trace amount of magnesium was found in products by elemental analysis (Table 3, BR-7).

IV. DISCUSSION

A. *Stability of operation*

Although dusts were generated also in the present midzet furnace, the bridge formation became appreciably mild; this made it possible to operate the furnace in a relatively steady state. Since the midget furnace has three lances, instead of a single lance in the prototype furnace, the temperature inside the furnace is expected to increase considerably. The direct measurements of the burden bed temperature confirmed that the bed temperature was about the same as that of the furnace walls. This indicates that the temperature distrubution inside the furnace was nearly flat. This seems the main reason for the mildness of the bridge formation.

B. Combustion zone and its relation to mass transfer

As pointed out in Part I, the scheme of the formation of the combustion zone affects strongly the mass transfer and chemical behavior of bauxite to be reduced. In the present study, this situation became more complicated because oxygen blast was made through three lances. The scheme of the formation of race ways can be categolized into the following two type:

(1) Usually, a bird-nest-like combustion zone was formed in front of each tuyere. These combustion zones extended to the center to form a dome-like hollow in the furnace shaft; in some cases, there formed a complicated path of gases and burdens above the combustion zones (see Fig. 2);
(2) Combustion zones were combined to form a big dome-like zone.

These features seem to depend on the following operation conditions: (1) shaft diameter, (2) oxygen blast rate, and (3) additives (calcia or magnesia). However, any definitive relation between these factors and the scheme of the fomation of the combustion zone cannot be derived only from the present results except for the case of MgO addition, which will be discussed later.

In any case, briquettes moved down finally to the combustion zone. As described above, the burden bed temperature was about 1700 – 1900 K even in the level of tuyere. In this temperature region, bauxite cannot be reacted with cokes except for the reduction of iron oxides. The major reaction of alumina component in bauxite therefore took place in the combustion zone; this reaction scheme is essentially the same as that in the prototype furnace. When the big dome like race way was formed, the volatilization occurred considerably.

As one of possible methods of improving the movement of bauxite, an attempt was made to prevent briquettes from dropping directly to the combustion zone by setting a long briquette at the center of furnace in BR-2 and 3; however, this did not work well, because the briquette melted and flooded.

C. Volatilization

As pointed out in Part I, one of the technological key points in establishing a blast furnace process is how the volatilization can be reduced.[1-3] Although the present furnace condition is not appropriate to study on the reduction behavior as described above, attempts were made to investigate the behavior of bauxite in a rather oxidative atmosphere, that is, in the vicinity of combustion zone.

The first examination was made on effects of coating briquettes with a layer of coke powder on the volatilization of the aluminum and silicon components. Although the aluminum metal content was not appreciably improved on coating briquttes (BR-4), the following interesting feature was observed:

(1) The aluminum content in the *partly* broken briquettes was still the same as that in the initial bauxite;
(2) The volatilization occurred only after the coated layer was *completely* destroyed.

In the presence of exess cokes, alumina is reduced to aluminum carbide. When iron is present, a part of alumina is reduced to iron-aluminum alloys. However, it is observed that the content of the metallic aluminum did not depend on the initial atomic ratio of Al/Fe in briquetts. This indicates that the aluminum content in the present samples was determined, not by the equilibrium condition at the reductive atmosphere, but by a reaction at a rather oxidative atmosphere.

Since the results of Part I indicated some possibility that lowering temperature at the combustion zone would be effective in retarding the Al_2O generation, the same attempt by mixing CO_2 into oxygen was made in BR-8 on coated briquettes; the results showed some effectiveness of these attempts; aluminum metal content increased to 11.7 %.

BR-6 was carried out to investigate the possibility of direct use of bauxite without briquetting, since briquetting is a fairly complicated procedure. Bauxite particles, coated with coke powder, were however burst and pulverized in the furnace due to the vigorous dehydration of bauxite.

D. Addition of slags

The aims of addition of calcia are as follows:

(1) Depressing the volatilization of ash in cokes; it will be appropriate to extract ash to slag before cokes descend to the combustion zone;
(2) Preventing the bridge formation; it will be desired to trap the condensable gaseous species such as Al_2O and SiO in liquids which can be formed in a burden bed;
(3) Protecting alloys produced from being attacked by oxygen blast; some appropriate liquid flux will be needed;
(4) Making briquettes fluid in order to separate their movement from that of cokes.

These aims were not achieved in the present study. This is mainly because the burden bed temperature was lower than our expected one. Calcia reacted with alumina component in bauxite to form double oxides, but the oxides did not form melts in a burden bed nor were reduced in the combustion zone.

The addition of magnesia was examined with the following aims:

(1) Magnesia can be reduced with cokes even at a CO atmosphere to form magnesium vapor and CO. When magnesium vapor ascends and is cooled, the back reaction takes place and evolves a reaction heat. There is therefore some possibility that the presence of magnesia can act as heat conveyer from an oxidative zone to a reductive zone.
(2) The chemical thermodynamic considerations suggests that there will be some temperature region in which magnesium vapor reacts with alumina in the presence of iron to form aluminum-iron alloys and aluminum-magnesium double oxide (details will be published elsewhere).

The present experiment using magnesia slag showed that addition of magnesia did really act as heat conveyer; however, the big dome like combustion zone was formed instead of a hot reductive zone.

V. CONCLUSION

A midget furnace with three lances has been found to be inadequate to obtain a high temperature zone (>2270 K) outside the combustion zone because of a small size of furnace. The reduction proceeded inevitably in the oxygen/coke combustion zone, resulting in the very low aluminum metal yield. Several attempts were made to examine the behavior of bauxite in the oxidative combustion zone; among others, results of coating briquettes imply that when an appropriate way can be established of preventing the produced alloys form the oxygen attack, the appreciable reduction of the volatilization can be achieved. It has been concluded that the investigation with a much larger furnace will be needed in order to clarify the possibility of an aluminum blast furnace.

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