Aluminium Blast Furnace Process III. Bench Scale Furnace

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Abstract

A bench scale blast furnace (600 mm in diameter and 2290 mm in height) has been built to investigate key points clarified in our previous studies; that is, (1) creation of a reductive and hot zone required to reduce bauxite, and (2) control of mass tranfer of briquettes. An attempt to feed briquettes into the central part of the furnace shaft was failed because a center feeder narrowered the effective cross section area of the shaft and induced heavy bridging. Another attempt was made to make clear suitable conditions of furnace operations, especially of creating a hot and reductive zone; the oxygen partial pressure in the furnace was measured and the heat loss from waters for cooling oxygen lances was evaluated. After improvements with (1) an increase of oxygen blast rate, (2) a decrease of the lance number, (3) use of larger cokes, and (4) an increase in the amount of a calcia slag flux, the temperatures at the combustion zone and at the furnace center were raised to more than 3570 K and 2270 K, respectively, and the oxygen concentration became less than 1 %. The content of aluminum in crude alloys increased to 30 % under these conditions.

I. INTRODUCTION

An aluminum blast furnace will be feasible only when commercially pure aluminum or silumin can be extracted from crude alloys. Although many extraction processes have been proposed,[1-8] the common feature among processes can be derived as that the aluminum yield in any extraction process largely depends on an initial content of aluminum in crude alloys. Efforts should therefore be focused on obtaining alloys of a high aluminum content in a blast furnace process.

Experiments using a prototype furnace (Part I) and a midget furnace (Part II) produced only low aluminum alloys; the aluminum content was only of an order of 10 %. This is because there was no reductive place where temperature was higher than 2270 K. This is closely related with another feature that solid cokes and briquettes moved together to the combustion zones where cokes were consumed.

These features should be compared with the main features of the iron blast furnace. In the iron blast furnace, CO gas reduces iron ores in the furnace shaft during descent of the solid ores, and the ferrous oxide/pig iron mixture can flow down as the liquid state. In an aluminun blast furnace, however, alumina stays in the solid state untill the main reduction occurres. Without any suitable method of controlling the movement of briquetts, bauxite briquettes cannot move separately from cokes that drops directly into the combustion zone.

In the present study, the investigation has been made with a larger furnace (bench scale furnace) to seek an appropriate way of surmounting the probles described above. The first attempt was made using a '*center feeder*', which was

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designed with an aim at supplying briquettes into the furnace center mandatorily. This feeder did not work satisfactory, since the furnace was still too small in scale. Another attempt was made to raise the furnace temperature to create the reduction zone and to make briquettes fluid by adding calcia slags with some success; high aluminum alloys (30 %) were obtained after these improvements.

II. EXPERIMETNTAL

A. *Experimental Furnace.*

Experimental runs in this report are designated as AR-1 to 5 and 14. Figure 1 shows the diagram of an experimental bench furnace. The furnace consists of three parts, that is, a bottom, a shaft, and a ceiling deck. They were connected with steel franges. A shell was made of 6 mm thick steel plates. The total inner height was 2290 mm from hearth to ceiling. The hearth was made of a graphite crucible of 150 mm in depth, 480 mm in diameter, and 50 mm in thickness, which was set below the tuyere level. A casted alumina crucible (99 % alumina) was used for the bottom part. The shaft and the bottom were both made of alumina castable and were 600 mm in inner daimeter. The ceiling was made of clay castable. Other materials of furnace were described in Fig. 1.

The furnace was equipped with six oxygen lances. The diameter of a tuyere was adjusted to 7, 10 or 14 mm by inserting blass tips. A tap hole was furnished at

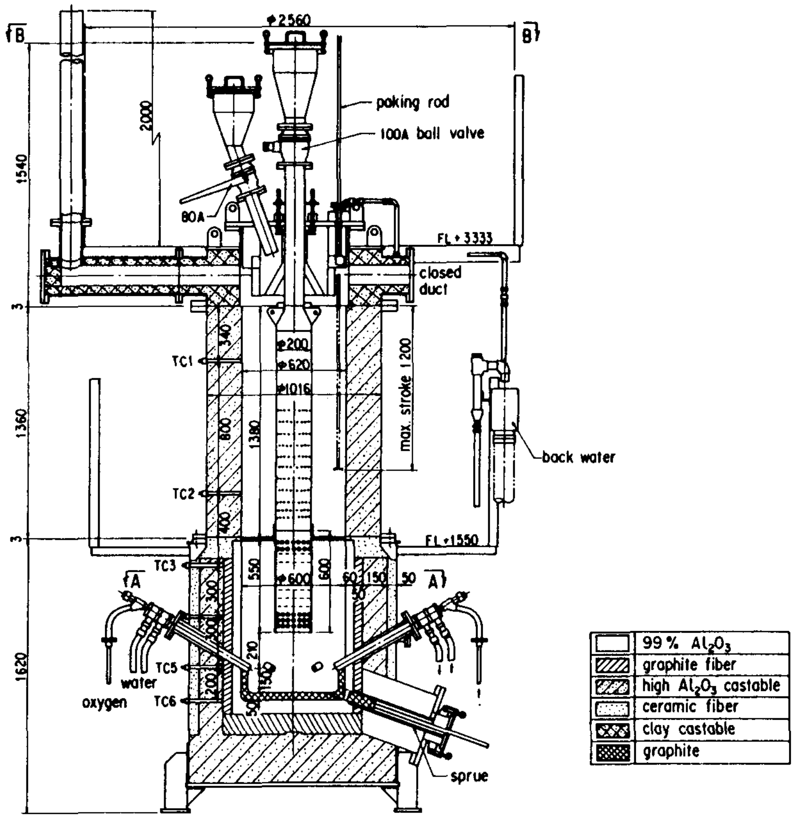

Fig. 1 Schematic diagram of Bench Scale furnace

the bottom of hearth. A sprue was made of a graphite tube of 80 mm in diameter and 800 mm in length. The tap hole was sealed by a graphite rod and a steel frange. Four hoppers, one at the center and the others at the side on the ceiling deck, were furnished to supply cokes, briquettes, and slags. Three poking rods were furnished on the ceiling deck to measure the height of a burden bed and to destroy bridges, if formed. Two sets of W/W-Re 26 thermocouple (TC-1,-2) were inserted about 50 mm into the furnace, and the other four sets were inserted at the inner surface of furnace walls (TC-3 - 6) as shown in Fig. 1.

In AR-1 and 3, two types of briquette supplying pipes called "center feeder" were attached to the center hopper (200 mm diameter) to supply briquettes into the furnace center; one was made of steel with many holes (Fig. 1, AR-1), and the another was made of thin graphite plates (Fig. 2, AR-3). The center feeders were extended down to about 200 mm above the tuyere level. Cokes were supplied from side hoppers when the center feeder was used in AR-1 and 3. After AR-3, both cokes and briquettes were supplied by the center hopper.

The alumina crucible at the hearth happened to be cracked and fall down in AR-3. On rebuilding, a probe lance was furnished to measure the temperature inside the furnace directly and also to sample gases out of the furnace at the position shown in Figs. 3 and 4, that is, at 200 mm above the tuyere level and 250 mm inside the furnace. The probe lance had almost the same structure as the oxygen lance reported in Part I, and its inside diameter was 10 mm.

B. *Furnace Operation.*

Table 1 summarizes the operational conditions. The operation was made in a similar way to that in Part I. Six oxygen lances were used except three for AR-14. Oxygen was supplied from liquid oxygen reservoirs through an evaporator at a pressure of 1.0 - 1.6 atm. In AR-4, carbon dioxide (10 %) was mixed in the oxygen blast to lower the combustion temperature. The temperatures at the combustion zone and at the center of furnace were observed through the oxygen and the probe lances. Since tapping was made three times on AR-4, the temperature of the hearth was measured during tapping. In AR-5 and 14, the heat loss from waters for cooling the oxygen lances was evaluated from the flow rate of water and the temperature difference between inlet and outlet waters. The composition of gases sampled through the probe lance was also measured.

In AR-14, the operation conditions were changed in four points; the use of larger cokes (15 - 25 mm), a high blast rate (500 dm^3/min per lance), use of only three oxygen lances to reduce heat loss, and an increase in the amount of a calcia slag flux.

C. *Raw Materials and Analysis.*

The analytical procedure was reported previously in Part I. The composition of bauxite and blast furnace cokes is given in Table 2. Small cokes were used in AR-1 to 4, larger ones being used in AR-5 and 14 (see Table 1). The briquettes were prepared as follows; bauxite and coke powder (-24 mesh, 1000 g / 250 g) were mixed, kneaded, and pelletized manually to small balls (20 - 30 mm in diameter); these pellets were then dried at 470 K for a night. The briquettes were coated with a 2 - 4 mm thick layer of coke powder using benzene-coaltar as paste, dried and baked at 770 - 970 K. Lumps of calcium carbonate (15 - 30 mm in diameter) were used as a slag flux in AR-1 to 4. Since calcium carbonate was found to be decomposed and pulverized in the furnace, well calcined calcia (9 -30 mm) was used in AR-14.

III. Results

A. *Use of center feeder.*

Results of the first attempt, use of center feeders, can be summarized as follows: The center feeder narrowed the gas stream path and caused the formation of a very hard bridge. After the bridge was formed, the temperature increased at the shaft anomalously; finally, the steel center feeder was melted down

Table 1. Operational characteristics

condition	Run No.				
	AR-2	AR-3	AR-4	AR-5	AR-14
Feeding method (-)	ordinary	center feed	ordinary	ordinary	ordinary
Tuyere diameter (mm)	10	10	7	14	14
Lance number (-)	6	6	6	6	3
Blast speed (m/s)	32	32	35-52(a)	5	11
Blast pressure (MPa)	1.1-1.3	1.0-1.4	1.0-1.4	1.0-1.1	1.0-1.1
Tuyere temp. (K)	2510-2750	2450-2570	2280-2770	2170-2470	>3570
Center temp. (K)	-	-	2110	1300	2160-2370
Max. wall temp. (K)	1870	2070	2070	1640	2020
Heat input (kJ/min)	-	-	-	470	1795
Heat loss (kJ/min)	-	-	-	390± 140	965± 125
O_2 (%)	-	-	85	2.0- 4.6	0.27
CO_2 (%)	-	-	0	24.5-47.7	0
CO (%)	-	-	0	47.7-73.5	99.7
Operation (h)	7	9.5	48	10	4.75
Coke input (kg)	540	459	1260	380	660
diameter (mm)	4-7	4-7	1-4	15-20	15-25
Briquette (kg)	108	32	258	32	120(b)
Slag input (kg)	18	0	20	-	60(c)
Alloy/Slag (kg/kg)	-	-	0/101	-	76/25(b)
Race way & shaft (-)	ant-hill race way	void below bridge	void over products	void below bridge	no raceway

(a) CO_2(10%) was mixed.
(b) bauxite/coke/coating coke = 1000/250/250 in mass ratio.
(c) calcined at 1670 K.

between TC-1 and 2 in AR-1. In AR-3, a heavy bridge was formed again, and a very large dome-like void remained. The graphite center feeder was burnt only at its tip as shown in Fig. 2. The inside alumina crucible was however destroyed; several fragments, found among the cokes at the tuyere level, were sampled and analysed as shown in Fig. 2 and Table 2. The analytical results showed that the aluminum contents were high in the slaggish parts especially in the layers between the fragments of alumina wall and coke, while the aluminum content was low in the metallic products (Table 2); this indicates that the oxygen attack is one of the essential factors of the severe volatilization, since the aluminum content was high in the parts protected from oxygen attack.

B. *Dust and Bridge.*

A large amount of gray powder was found in exhaust gases as had been found with the small furnaces. The composition of dusts is shown in Table 2 (AR-2, dust).

A bridge grow to a very solid and large one in AR-5 in which a large amount of burdens was supplied at once. In AR-2, 4 and 14, bridging did not occur frequently and a bridge, if formed, collapsed spontaneously.

C. *Temperature and Heat Loss.*

Temperature profiles of each run are summarized in Table 1. The temperatures at the center of furnace were found to be far lower than 2270 K in AR-4 and 5. The wall temperature showed the maximum at TC-3 throughout all the runs. The direct measurement of the hearth temperature during tapping showed that it was as low as 1770 K in AR-4.

Table 2. Elemental Analysis of Products and Burdens. Total contents are given in mass percent.

	Al	Fe	Si	C	Ti	Ca	Balance(a)
Bauxite	28.8	9.15	2.67	0.35	0.80	0.18	24.5(b)
Coke	1.70	0.68	2.60	87.8	0.14	0.56	
Briquette	27.2	11.0	2.70	26.1	2.6	1.2	30.59
AR-2							
dust	16.2	5.11	16.1	21.9	0.22	0.86	39.6
metal	4.92	74.4	19.7	1.10	1.92	0.07	0
slag	15.2	19.0	16.9	0.76	1.09	8.48	38.57
AR-3(c)							
metal-A	0.21	82.7	11.1	0.18	0.14	-	5.67
slag-A1	29.4	34.2	28.8	2.17	1.01	-	4.42
slag-A1'	10.0	43.8	33.4	0.82	1.47	-	10.51
slag-A2	46.4	5.05	8.62	4.75	0.55	-	34.63
slag-A2'	42.2	6.49	7.23	22.3	1.40	-	20.38
metal-B1	0.14	72.2	17.7	0.17	0.28	-	9.51
metal-B2	0.63	59.7	34.4	0.25	1.84	-	3.18
slag-B	36.3	5.42	12.7	2.21	0.58	-	42.79
metal-C	0.64	56.1	29.3	0.14	1.82	-	12.0
metal-D	0.25	79.0	15.4	0.19	0.45	-	4.71
AR-4(d)							
top	31.4	12.6	5.19	5.51	2.85	-	42.45
middle	7.69	42.4	19.5	12.2	4.48	-	13.73
bottom	4.07	42.4	18.3	7.26	0.67	-	27.3
tapped	0.14	79.6	16.5	0.84	0.46	-	2.46
AR-14							
slag	32.9	19.1	10.1	7.26	3.18	8.00	19.46
metal	33.0	42.3	20.8	1.27	1.56	0.52	0.55

(a) Oxygen is balance fraction. (b) Ig.Loss (c) see Fig. 2. (d) see Fig. 3.

Results of heat loss measurement in AR-5 indicated that the cooling water carried away much portions of input heats: The enthalpy of CO gas (298 K) corresponding to the inlet oxygen blast was 470 kJ/min compared to the measured heat loss of 390 kJ/min. After this recognition, the number of oxygen lances to be actually used was decreased to three and the blast rate per lance was raised not to lower the heat generattion rate; in AR-14, the heat loss decreased appreciably as shown in Table 1 and correspondingly, the temperatures at the center and the combustion zone became very high as shown in Table 1.

D. *Furnace Dissection and Products.*

In AR-2, no trace of a bridge remained, and six combustion zones (300 - 400 mm in height and 200 mm in inside diameter) were formed in front of tuyeres; their wall was composed of firmly coalesced cokes and slags. The whole shape was like an ant-hill.

The contents of metallic aluminum were little in the products of AR-1 to 4.

In AR-4 and 5, large dome-like voids remained. The gases were also sampled through the probe lance and the results are shown in Table 1. In AR-4, a long-term operation was carried out. When the tap hole was open, about 1 kg of ferrosilicon was flowed out spontaneously (Table 2, AR-4, tapped). Some amount of ferrosilicon was also found in the sprue. Since the remaining substance was very viscous, it was difficult even to scratch out. Products were therefore accumulated up to 400 mm above the tuyere level as shown in Fig. 3. Since the sample gas was taken from the layer of the accumulated products located below

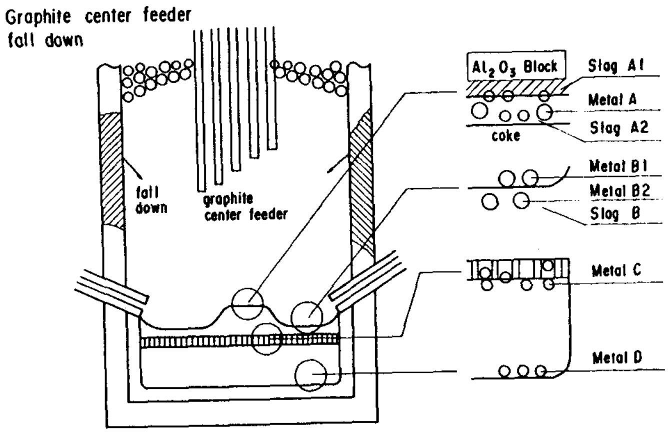

Fig. 2 Schematic dissection diagram of AR-3: A part of furnace walls fell down and the graphite center feeder was burnt at the tip.

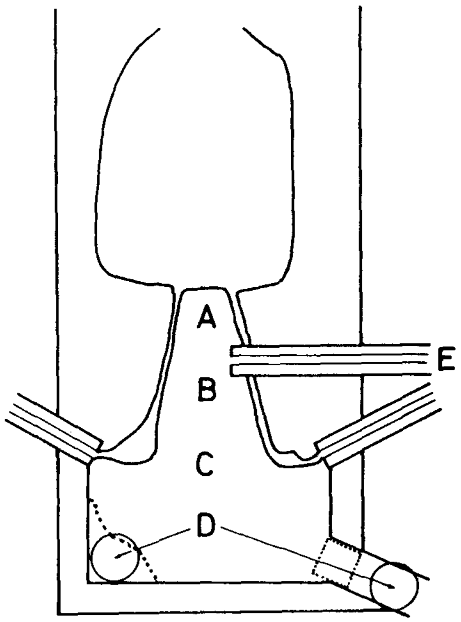

Fig. 3 Schematic dissection diagram of AR-4: Oxygen migrated path was formed in the accumulated products. For compositions of samples at A – D, see Table 2.

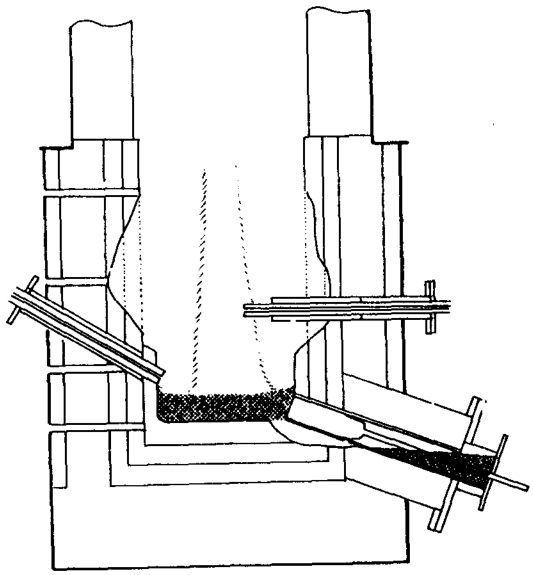

Fig. 4 Schematic dissection diagram of AR-14: The wall alumina was melted and the products flowed into the hearth and tap hole. There was no gas stream inside a cone formed at the center of furnace.

the dome-like combustion zone, the observed high oxygen concentration seems to be consistent with the fact that cokes did not remain in the accumulated bed in front of tuyeres. The content of aluminum in the accumulated substances decreased from top to bottom as shown in Table 2 (AR-4). This decrease of the aluminum content was apparently due to oxygens migrating among the flooded products.

In AR-5, the concentration of the oxidative gases were also as large as 40 - 60 %. Evidently, the gas was sampled from the dome-like combustion zone where the oxygen and carbon dioxide existed abundantly. Products were not obtained in an appreciable amount.

Figure 4 shows that in AR-14, the furnace walls were damaged appreciably by melts formed from calcia slags and briquettes; products spread over the hearth and some parts of products flew down to the tap hole. The fluidity of products was fairly high compared to the case of AR-4. There was no distinctly formed combustion zone as was found in the other runs. However, tracks of gas stream remained outside a cone formed from the tuyere level to the TC-3 level (see Fig. 4), whereas there was no gas stream inside the cone. The oxygen concentration was very low and alloys of a high aluminum content were obtained.

An attemp was made to evaluate the material balance in AR-14. Out of the amounts loaded as briquetts, cokes, and slags, about 68 % for Al, 93 % for Fe, 25 % for Si, and 27 % for Ca can be found in the products in the hearth; since the wall materials damaged were not taken into account in this evaluation, these values are not accurate especially for aluminum. Nevertheless, we can see that the volotilization of silicon and calcium components was severe and this in turn caused some effects of depressing the volatilization of the aluminum component.

IV. Discussion

A. *High temperature operation.*

To reduce bauxite in a blast furnace, it is crucial to create a high temperature reduction zone outside the combustion zone. The analytical results on heat loss (AR-5) revealed a surprising fact that a large part of the combustion heat was carried away by cooling waters; this is apparently the reason for the relatively low temperature at the center of the furnace (AR-4). To make clear the fundamental features of the combustion of cokes with oxygen, a theoritical investigation of the mass transfer and temperature distribution in raceways was made and compared with results obtained in another series of experiments of studying the coke combustions under various conditions (details will be published elsewhere[9]). The main results showed that when the heat loss is lowered and larger cokes are useed, it will be possible to create a reductive and hot (above 2270 K) zone outside the combustion zone. AR-14 was thus operated to increase the net heat input by lowering the number of lances and using larger cokes. The results of AR-14 confirmed that the blast furnace can actually provide a hot and reductive zone required to reduce bauxite without sub-electrical heating.

B. *Behavior of Briquette*

The experiments in Part I and II clarified the problem of the mass transfer in a blast furnace: Bauxite stays in solid state in low temperature shaft zones and is carried, without being reduced, to the combustion zone together with cokes. To surmount it, we have tried two methods: The first one, '*Center Feeder*', was failed as described above. The second attempt was the addition of calcia slags to form melts of aluminum calcium double oxides. Although the formation of double oxide melts increases the temperature required to reduce the oxides, the melts may move separately from cokes as pointed out in Part II. The high temperature achieved in AR-14 made it possible to reduce the stabilized alumina; this success suggests that to prevent briquettes from oxygen attack, it is crucial to make briquettes fluid and to make it easy for alloys produced to separate from the movement of cokes down to the combustion zone.

C. *For further Investigation*

Summarizing the present series of investigations from Part I to III, we can conclude that the first objectives given below are achieved:
(1) create a hot and reductive zone in a blast furnace;
(2) reduce bauxite in the presence of excess cokes and under a CO flow.
Nevertheless, our understanding of behavior of an aluminum blast furnace is still limited and it should be recoginized that the following questions still remain to be answered:

(1) Can an aluminum blast furnace be operated in a steady state?
(2) Can a high aluminum yield be achieved?
(3) Can the content of metallic aluminum be improved to 40 or 50 % in order to extract commercially pure aluminum from the crude alloy?

In order to operate an aluminum blast furnace in a steady state, the scheme of the mass tranfer in the furnace should be well established including loading and tapping methods. In particular, the present success was achieved in the presence of calcia slags. Thus, it will be necessary to investigate the behavior of the slags especially in relation with those of cokes and briquettes. There has arised a new problem from the high temprature operation: The calcia slag flux damaged the furnace walls. It remains uncertain whether the cold-wall method can be adopted with a much larger furnace to protect the furnace wall.

In order to increase the aluminum yield and the aluminum content in alloys produced, it will be necessary to clarify the behavior of oxidative atmosphere in the furnace; we think that the present values for the aluminum yield and the aluminum content are limited by the presence of an oxidative atmoshere in the vicinity of the reduction zone. The chemical thermodynamic considerations have been made to take account of the volatilization under a CO flow and showed that higher values were evaluated for the aluminum yield and the aluminum content.

V. Conclusion

A "*super*" high temperature operation was successful to obtain alloys of a high aluminum content; this is closely related to the success in creating the high temperature and low oxygen region outside the combustion zone, and in transferring the briquettes to this reductive zone. The addition of a large amount of a calcia slag flux seems to be effective in forming liquid mixtures; this prevented briquettes and reduced alloys from dropping directly to the combustion zone. It is still difficult to conclude only from these results that the aluminum blast furnace process is feasible. However, it has been suggested that the possibility lies in the direction of elevating the furnace temperature.

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