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Fine Ore Injection into Blast Furnace through Tuyeres

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Abstract

To determine the maximum rate of fine ore injection into a blast furnace while maintaining a desired deadman temperature, we developed a test apparatus capable of simulating the heat transfer and reaction behavior in the lower part of a blast furnace, and injected fine ore through a lance inserted through a blow pipe. The following results were obtained. Injected with the same amount of pulverized coal, the maximum injection amount of non pre-reduced ore can be 70 g/Nm³. By single injection, 60% pre-reduced fine ore can be injected up to 175 g/Nm³, but the maximum injection amount falls to 115 g/Nm³ when injected together with the same amount of pulverized coal. With a real blast furnace, the maximum injection amount is expected to be higher owing to its large heat capacity.

1. Introduction

Injection of fine iron ore into a blast furnace through tuyeres was actively studied in the 1980s as a promising next-generation blast furnace seed technology. At that time, the studies focused on injection of ore in small quantities, approximately 50 kg per ton of pig iron, as a measure to decrease the Si content in the hot metal[1-3], but as the demands for higher productivity and improved production flexibility became stronger, the focus shifted to injection of 100 kg/t or more of fine ore[4-6].

Around 1987, IRSID (presently Arcelor), who took the lead in the study of applying plasma to blast furnace operation, proposed a technology of fine ore injection through tuyeres, by the name of the plasma tuyere minerali produit (PTMP) process[4]. Nippon Steel Corporation also studied the technology as a possible next-generation blast furnace process, and constructed a large-scale hot model to test it[5].

2. Advantages of Fine Ore Injection through Tuyeres in Large Quantities

Injecting fine iron ore or pulverized coal into a blast furnace through tuyeres in large quantities brings about the following advantages compared with conventional blast furnace operating methods:

1) The charging of sinter from the furnace top can be decreased, which reduces the load on a sintering machine significantly, leading to a decrease in the required number of operating machines in a long term. The lighter load on a sintering machine also enables increased use of iron ores of poor sintering properties as the burdens.
2) The unit consumption of hot blast can be decreased remarkably, leading to an increase in production. The injection amount can be controlled easily, and this gives increased flexibility in the control of production.
3) As the direct reduction of ore in front of tuyeres increases with the ore injection, the ore reduction load in the furnace shaft decreases, and for this reason, use of low-quality burden can be increased, and in a long run, the shaft height of a blast furnace can be decreased.

3. Method of Fine Ore Injection through Tuyeres in Large Quantities

3.1 Analysis model

To quantitatively examine the blast furnace operation data with the fine ore injection through tuyeres, a simplified blast furnace evaluation model was configured[7], wherein the inside of a blast furnace

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was divided into zones UA and UB, the reduction and melting zones of the ore was charged from the furnace top, and zone L, the reduction and melting zone of the ore were injected through the tuyeres (see **Fig. 1**).

The following conditions were assumed in the model:

(1) The temperatures of gas, solid and liquid at the entry to and exit from zones UA, UB and L are the same as those in the current blast furnace operation, and the heat loss is constant.
(2) The sinter charged from the furnace top is decreased by an amount corresponding to the total Fe (T.Fe) of the ore injected through tuyeres.
(3) The amount and composition of the gangue in sinter are controlled so that the compound basicity ((CaO + MgO) / (SiO_2 + Al_2O_3)) of blast furnace slag is kept at 1.05.
(4) The Fe loss to the furnace-top dust and the slag is constant, and is excluded from the process balance calculation.
(5) The shaft efficiency is 0.96 and ηco = ηH_2 in a base case (e.g. Case 1 in **Fig. 2**).
(6) The Si concentration in hot metal changes depending on the amount of injected fine ore (PF), according to the equation [%Si] = 0.2 exp (–0.01386 • PF) + 0.1.

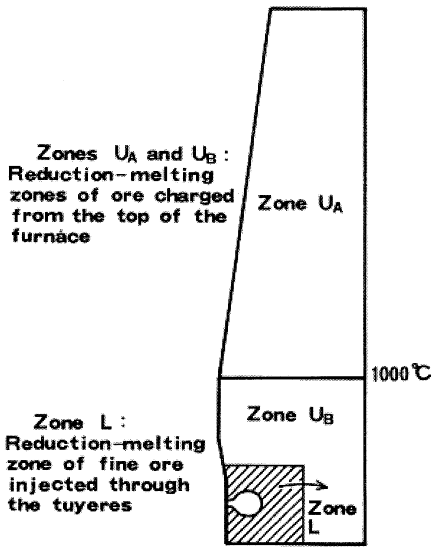

Fig. 1 Division of the blast furnace into zones for developing a mathematical model

Besides the above, it was also assumed that enrichment oxygen would be injected through tuyeres in addition to the fine ore and pulverized coal, and introduced a term to account for the external heating by plasma to the model. **Table 1** shows the chemical compositions of the sinter, lump ore and coke to be charged from the furnace top, the fine ore and pulverized coal to be injected through tuyeres and the hot metal used in the model analysis.

3.2 Fine ore injection to maintain stable packing structure in furnace shaft

The latest blast furnace constitutes a massive process and is incapable of flexibly responding to changing production requirements.

		①	②	③	④	⑤	⑥
Blast temperature	(℃)	1100	1100	1300	1800	1800	1800
Blast humidity	(g/Nm³)	36	15	15	15	15	15
O_2	(Nm³/t)	0	110	90	80	80	82
PC	(kg/t)	0	87	80	87	87	85
Pre-reduction degree	(%)	0	0	0	0	35	60

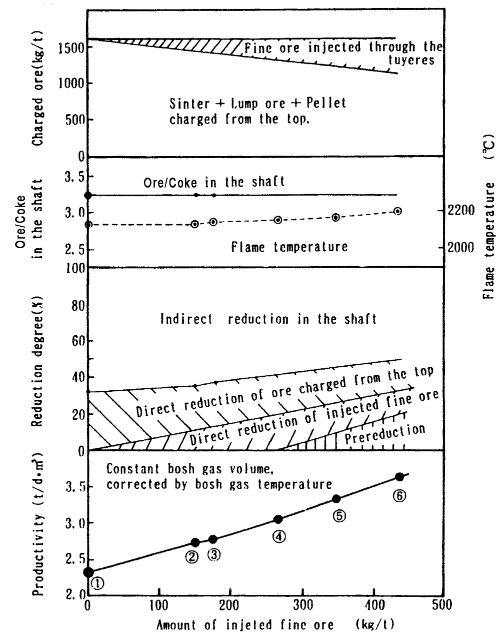

Fig. 2 Example of blast furnace operation injected with fine ore from the tuyere

Table 1 Chemical compositions of pig iron, iron ores and fuels

(wt%)

	T. Fe	SiO_2	Al_2O_3	CaO	MgO	Others
Lump ore	65.0	2.5	1.5	-	-	3.1
Pellet feed	68.0	0.8	0.6	-	-	1.4
Sinter	57.4	5.5	2.0	8.9	1.5	-

	C	H	SiO_2	Al_2O_3	CaO + MgO	Fe	O
Coal	77.1	5.2	3.8	1.3	0.2	0.4	9.8
Coke	88.0	0.5	6.3	3.5	0.4	0.6	

Hot metal: Fe: 94%, C: 4.8%, Si = 0.2exp (−0.01386 • PF) +0.1%

This is because, once the packing structure (such as ore/coke) in the shaft is changed, it takes some days for furnace operation to attain a new steady state. In addition, a tangible change in the furnace operation usually requires many delicate actions on various operation parameters. However, if it is possible to change the operating condition of a blast furnace only through actions at the tuyeres without having to change the shaft packing structure (especially, ore/coke in relation to the fine ore injection), then it becomes possible to change the rate of production promptly.

The tuyere injection of fine ore offers the above possibility, especially when combined with such measures as the enrichment of blast oxygen, control of blast temperature and humidity and change in the injection amount of pulverized coal.

Fig. 2 shows some examples of the simulation of blast furnace operation using the developed model. The productivity (t/d•m^3) of Cases 2 to 6 are those with the blast volume so controlled as to keep the bosh gas volume (as corrected by the flame gas temperature) unchanged from that in the base case (Case 1). As the fine ore injection amount increased, the productivity increased from 2.3 t/d•m^3 of the base case, and reached as high as over 3.5 t/d•m^3 under the following conditions (Case 6): the blast temperature was raised to 1800 ℃ by application of plasma; blast humidity controlled to 15 g/Nm^3; the fine ore pre-reduced to 60% and injected at a rate of 455 kg/t; the blast oxygen enriched by 82 Nm^3/t; and pulverized coal injected with the fine ore at a rate of 85 kg/t. This means that the above actions taken at the tuyeres enabled a quick change in the production rate from 2.3 to over 3.5 t/d•m^3. What is more, the amount of sinter charged from the furnace top in Case 6 was only two-thirds that in the base case, and the indirect reduction degree in the shaft also decreased. For this reason, one can expect that the loads on sintering machines will decrease, and in a long term, the blast furnace shaft height be made smaller.

3.3 Maximum amount of fine ore injection through tuyeres

3.3.1 Blast furnace operation data with injection of fine ore and pulverized coal through tuyeres

Table 2 shows the blast furnace operation data with fine ore and pulverized coal injected through tuyeres at different rates calculated under a condition that appropriate heat and material balances are maintained in the tuyere front portion and the entire furnace. The calculation shows that the heat balance of the furnace is adequately maintained and the Si content lowers by roughly 0.1% when the fine ore is injected at a rate of 60 kg/t to decrease the Si content in the hot metal and the blast humidity is decreased from 36 to 15 g/Nm^3.

When fine ore is injected in large quantities, on the other hand, it is necessary to raise the blast temperature or enrich oxygen to keep the flame temperature Tf substantially unchanged. Fine ore injection of 144 kg/t is estimated to be possible with the maximum blast temperature (1350℃) achievable with the present equipment condition, and the estimated maximum ore injection amounts change as follows with the respective additional measures: 268 kg/t with 9.1% oxygen enrichment (100 Nm^3/t); 184 kg/t with 100 kg/t of pulverized coal injection (PCI); and 100 kg/t with 200 kg/t of PCI. When the blast temperature is raised to 1800℃ by application of plasma, the estimated maximum ore injection amount further increases as follows with the respective additional measures: 365 kg/t with 10.3% oxygen enrichment; 465 kg/t with 27.4% oxygen enrichment; 473 kg/t with 35% pre-reduction of the fine ore and oxygen enrichment by 100 Nm^3/t (425 kg/t in terms of the ore weight after the pre-reduction); and 594 kg/t with 60% pre-reduction of the fine ore and the same oxygen enrichment (490 kg/t in terms of the ore weight after the pre-reduction).

3.3.2 Maximum amount of fine ore injection with pulverized coal at air ratio of 1

The maximum injection amount of fine ore and the productivity of a blast furnace with the injection of pulverized coal in large quantities were studied while securing good combustibility of the injected coal. **Fig. 3** shows the results. Under the condition of the same bosh gas amount, whereas the maximum productivity coefficient without the PCI was estimated at 2.5 t/d•m^3, the maximum productivity with a blast temperature of 1300℃ were approximately 3.3 and 3.8 t/d•m^3 when the pre-reduction rates of the injected fine ore were 0 and 60%, respectively. A further improvement in the productivity is expected when the blast temperature is raised to 1800℃ by applying plasma.

3.3.3 Experimental study on maximum amount of fine ore injection through tuyeres

In view of the above estimation results by the simplified blast furnace evaluation model and to clarify the problems in the blast furnace operation with the tuyere injection of fine ore and verify the maximum injection amount through experiments, a test apparatus was constructed that could simulate the reaction heat transfer inside a blast furnace 3000 m^3 in inner volume on a 1/5 scale (see **Fig. 4**). The apparatus had a horizontal section in a quadrant shape and one tuyere at the arc. **Table 3** shows the test conditions, and **Table 4** the quality of the materials injected into the apparatus for the tests.

At the tests, the temperature inside the deadman fell even in cases where thermal compensation in the raceway was secured, and this

Table 2 Estimated operational data of blast furnace injected with fine ore and PC from the tuyere

Base condition

Blast temp.	Blast humidity	Shaft efficiency	Pre-reduced ratio	Pellet feed	Pulverized coal	Enriched oxygen	Coke rate	Blast volume	Bosh gas volume	Top gas		η co	η H_2
										Wet	Dry		
Tg (Blast) (℃)	BH_2O (l/Nm^3 • air)	η shaft (-)	RPF (-)	PF (kg/t)	PC (kg/t)	GO_2 (Nm^3/t)	CR (kg/t)	GB (Nm^3/t)	GL (Nm^3/t)	GUW (Nm^3/t)	GU (Nm^3/t)	ETCO (%)	ETH_2 (%)
1100	36	0.96	0.0	0	0	0	500	1182	1569	1746	1708	47.5	47.5

Bosh gas composition		Top gas composition (dry)			Sinter ore	Sized lump ore	Slag volume	Direct reduced	Flame temp.	Slag basicity	Ore to coke	Heat loss
FCOB (-)	FH_2B (-)	FCOT (-)	FCO_2T (-)	FH_2T	SO (kg/t)	LO (kg/t)	SLAG (kg/t)	DR (%)	TFM (℃)	C/S (-)	D/C (-)	
0.353	0.052	0.225	0.204	0.025	1224	360	283	33.3	2111	1.62	3.168	126.5

Table 2 Estimated operational data of blast furnace injected with fine ore and PC from the tuyere

Calucutated conditions

Tg (Blast)	BH_2O	η shaft	RPF	PF	PC	GO_2	CR	GB	GL	GUW	GU	ETCO
1100.0	15	0.96	0.0	60	0	0	491	1173	1519	1693	1670	47.6
1100.0	15	0.96	0.0	202	0	100	526	843	1365	1485	1465	44.0
1100.0	15	0.96	0.0	122	100	100	425	807	1354	1487	1443	44.9
1350.0	15	0.96	0.0	144	0	0	476	1079	1434	1592	1570	47.0
1350.0	15	0.96	0.0	268	0	100	515	771	1302	1409	1390	43.4
1350.0	15	0.96	0.0	184	100	100	412	727	1279	1400	1358	44.5
1350.0	15	0.96	0.0	100	200	100	310	688	1263	1397	1331	45.5
1800.0	15	0.96	0.0	265	0	0	454	939	1307	1441	1421	46.0
1800.0	15	0.96	0.0	365	0	100	497	657	1198	1286	1269	42.6
1800.0	15	0.96	0.0	465	0	200	540	375	1090	1131	1116	39.8
1800.0	15	0.96	0.0	279	100	100	396	622	1186	1288	1248	43.6
1800.0	15	0.96	0.0	188	200	100	293	581	1164	1282	1218	44.8
1800.0	15	0.96	0.0	272	0	0	468	959	1335	1480	1462	42.4
1800.0	15	0.96	0.0	373	0	100	512	680	1231	1330	1313	39.4
1800.0	15	0.96	0.0	283	100	100	410	639	1209	1326	1288	40.4
1800.0	15	0.96	0.0	201	200	100	312	616	1214	1343	1283	41.2
1800.0	15	0.96	0.35	308	0	0	424	886	1222	1347	1328	46.1
1800.0	15	0.96	0.35	425	0	100	456	585	1082	1158	1142	42.4
1800.0	15	0.96	0.35	323	100	100	365	568	1099	1192	1153	43.5
1800.0	15	0.96	0.35	105	200	0	240	851	1253	1411	1340	48.5
1800.0	15	0.96	0.35	222	200	100	273	549	1112	1223	1159	44.7
1800.0	15	0.96	0.60	354	0	0	390	827	1125	1242	1224	46.3
1800.0	15	0.96	0.60	490	0	100	410	508	956	1018	1004	42.0
1800.0	15	0.96	0.60	371	100	100	329	505	996	1080	1042	43.5
1800.0	15	0.96	0.60	254	200	100	248	504	1039	1144	1081	44.7
1800.0	15	0.96	0.60	122	200	0	228	831	1219	1374	1303	48.7

ETH_2	FCOB	FH_2B	FCOT	FCO_2T	FH_2T	SO	CaO (kg/t)	SLAG	DR	TFM	C/S	D/C	Top gas temp. (℃)
47.6	0.357	0.033	0.225	0.204	0.016	1156	2	276	33.8	2138	1.66	3.09	152
44.0	0.479	0.033	0.296	0.233	0.017	999	14	264	26.1	2263	1.88	2.58	147
44.9	0.458	0.072	0.287	0.234	0.037	1085	5	266	28.2	2207	1.71	3.40	159
47.0	0.373	0.033	0.234	0.207	0.016	1060	6	263	32.7	2195	1.74	2.98	157
43.4	0.499	0.033	0.308	0.236	0.018	924	17	253	24.5	2333	1.97	2.49	157
44.5	0.477	0.074	0.299	0.239	0.039	1014	8	255	27.2	2268	1.77	3.33	146
45.5	0.453	0.116	0.290	0.242	0.060	1105	0	257	29.5	2214	1.61	4.73	147
46.0	0.399	0.033	0.249	0.212	0.016	923	12	242	30.7	2313	1.87	2.83	163
42.6	0.533	0.033	0.329	0.244	0.018	813	22	236	22.0	2462	2.12	2.36	157
39.8	0.694	0.034	0.430	0.284	0.020	704	32	230	11.4	2687	2.47	1.97	154
43.6	0.508	0.078	0.318	0.246	0.042	907	13	239	24.9	2373	1.88	3.20	159
44.8	0.482	0.123	0.308	0.250	0.065	1005	3	242	28.0	2301	1.68	4.66	139
42.4	0.400	0.033	0.267	0.197	0.017	916	14	244	33.6	2305	1.90	2.73	149
39.4	0.530	0.034	0.347	0.225	0.019	805	24	238	25.0	2450	2.17	2.28	151
40.4	0.506	0.077	0.337	0.228	0.043	903	14	241	28.3	2370	1.91	3.08	132
41.2	0.479	0.120	0.326	0.228	0.067	992	5	244	30.5	2289	1.72	4.33	163
46.1	0.394	0.033	0.246	0.211	0.016	833	15	226	30.9	2399	1.95	2.81	160
42.4	0.539	0.034	0.333	0.245	0.018	689	26	213	21.2	2630	2.31	2.30	159
43.5	0.510	0.081	0.320	0.247	0.044	814	15	222	24.7	2483	1.97	3.22	161
48.5	0.347	0.116	0.227	0.214	0.056	1082	−5	242	35.5	2212	1.53	6.01	165
44.7	0.482	0.128	0.309	0.249	0.068	937	5	231	27.7	2359	1.73	4.75	157
46.3	0.386	0.033	0.242	0.208	0.016	734	17	208	31.3	2512	2.06	2.81	155
42.0	0.546	0.034	0.337	0.244	0.019	550	30	188	20.1	2869	2.63	2.22	167
43.5	0.513	0.086	0.322	0.248	0.047	710	18	203	24.5	2622	2.09	3.25	148
44.7	0.482	0.134	0.309	0.250	0.071	867	7	218	27.9	2435	1.77	4.95	144
48.7	0.343	0.119	0.266	0.214	0.057	1046	−4	236	35.7	2237	1.55	6.17	165

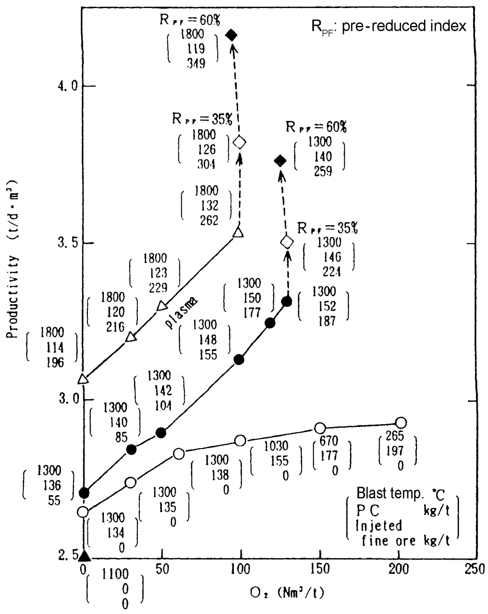

Fig. 3 Productivity in the operation injected a maximum amount of fine ore mixed with pulverized coal

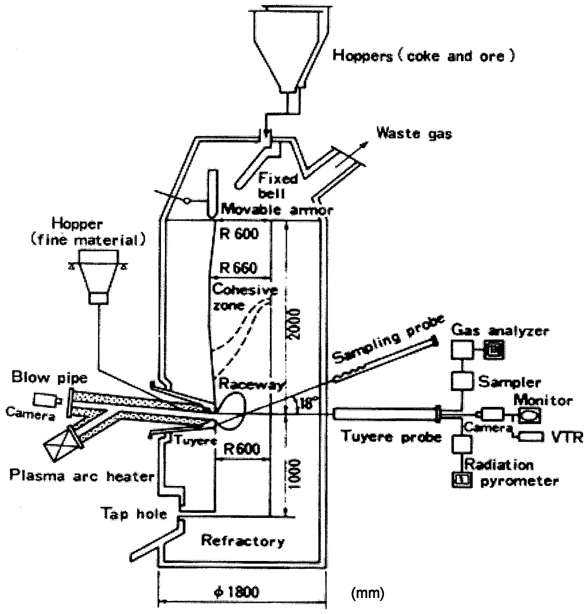

Fig. 4 Experimental apparatus

Table 3 Experimental conditions

Fine material	Pre-reduction degree (%)	Blast temp. (℃)	Blast humidity (g/Nm³)	Oxygen enrichment (%)	Fine material conc. (g/Nm³)	Fine material rate (kg-pig)	Coke rate (kg/t-pig)	Flame temp. (℃)
All coke	-	1090 - 1120	1 - 6	0	0	0	593 - 601	2392 - 2475
Ore alone	0	1220	2	0	63	104	588	2337
	0	1320, 1300	2.5	0.1	135, 169	206, 270	583, 610	2238, 2148
Ore & coal	0	1270, 1285	2	0	66, 91	107, 159	518, 525	2360, 2286
mixture (*)	0	1330, 1340, 1345	2	0.2, 5.4	136, 183, 263	203, 267, 336	461, 457, 438	2225, 2212, 2212
Ore alone	60	1225	6	0	79	142	603	2334
	60	1320, 1315, 1330	2, 2, 6	0	158, 166, 169	170, 211, 255	432, 487, 540	2322, 2303, 2288
Ore & coal	60	1260	6	0.8	163	258	438	2171
mixture (*)	60	1305, 1310, 1310	6, 5, 5	0, 0, 2, 9	163, 172, 277	266, 354, 560	436, 508, 477	2163, 2159, 2116
	60	1320	1	0, 3, 6	177, 274, 349	294, 368, 395	428, 385, 362	2180, 2157, 2177

(*) Mixing rate (weight) = 1.1, Blast flow rate = 130 Nm³/h

Table 4 Chemical compositions of fine ore and pulverized coal (dry base, %)

Material	T. Fe	M. Fe	FeO	CaO	SiO_2	Al_2O_3	MgO	Pre-reduction degree
Fine ore (Ore M)	68.12	-	0.20	0.02	0.78	0.46	0.13	0.0
Fine ore (Ore R)	76.65	38.72	29.91	0.30	5.61	2.78	0.46	60.0
Fine ore (Ore C)	78.33	38.41	32.20	0.43	2.93	0.93	0.51	60.0

Material	C	H	O	SiO_2	Al_2O_3	Ash	Volatile	Fixed C
Pulverized coal	74.10	4.70	8.50	5.41	3.10	10.4	32.4	57.2

was conspicuous especially in the case of the injection of 0% pre-reduced ore (see **Fig. 5**). A reason for this was presumably that fine ore grains that did not fully react in the raceway and settled in the deadman reacted there endothermically, and the permeability of the deadman was deteriorated by the depositing.

Since the fall of the deadman temperature was likely to hinder the smooth dripping of slag, we defined the maximum injection amount of fine ore as that with which the thermal compensation in the raceway was secured and the temperature inside the deadman did not fall. The deadman temperature was measured with a ther-

Mark	Fine ore rate (kg/t)	Blast temp. (℃)	Flame temp. (℃)	Coke rate (kg/t)
○●	0	1120	2475	601
△	104	1220	2337	588
□	202	1320	2238	573

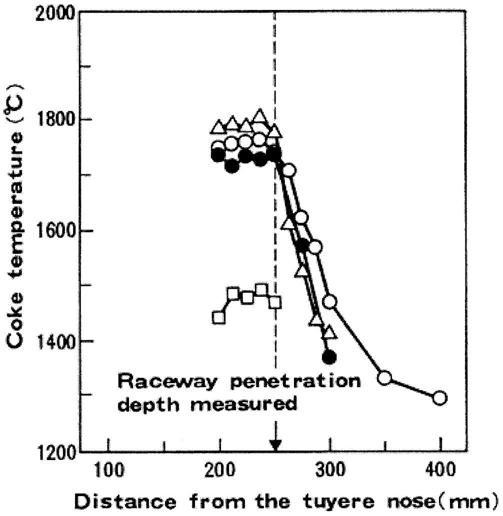

Fig. 5 Coke temperature measured in the raceway and deadman (injection of 0% pre-reduced fine ore)

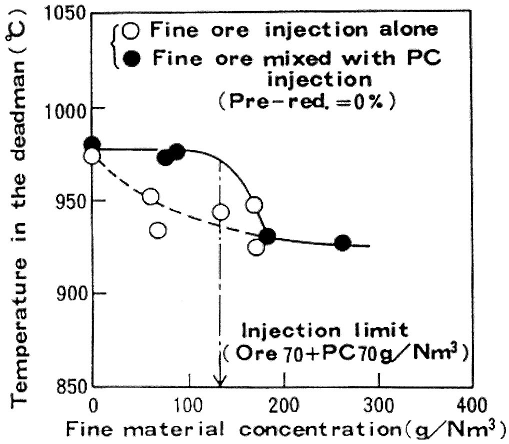

Fig. 6 Relationship between the fine material concentration and the deadman temperature during injection of 0% pre-reduced fine ore alone or mixed with pulverized coal

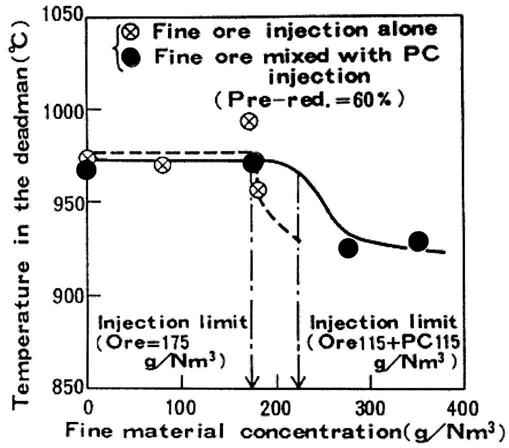

Fig. 7 Relationship between the fine material concentration and the deadman temperature during injection of 60% pre-reduced fine ore alone or mixed with pulverized coal

mometer provided at the tuyere level and 600 mm from the tuyere nose (at the furnace wall surface opposite the tuyere); since the measured raceway depth was approximately 250 mm at all our tests, the temperature measurement position well corresponded to the inside of the deadman.

(1) Maximum fine ore injection amount at single injection

Fig. 6 shows the relationship between the concentration of 0% pre-reduced fine ore and the deadman temperature under single injection of the fine ore (open circles). The deadman temperature fell monotonously as the fine ore injection amount increased, and the deadman temperature was always lower than that of all-coke operation as far as the fine ore was injected at all. On the other hand, with single injection of 60% pre-reduced fine ore, the deadman temperature was higher than that of all-coke operation up to an injection amount of 175 kg/Nm³ (circles marked with ⊗ in **Fig. 7**), and then the temperature lowered as the injection amount increased. Hence, 175 kg/Nm³ was considered the maximum injection amount of the single injection of 60% pre-reduced fine ore.

(2) Maximum fine ore injection amount at mixed injection with pulverized coal

When 0% pre-reduced fine ore was injected together with the same amount of pulverized coal, the deadman temperature was kept at the level of all-coke operation up to a certain injection amount (solid circles in Fig. 6). Defining the maximum injection amount as the middle value between the largest injection amount with which the deadman temperature was kept at the level and the smallest injection amount with which the deadman temperature fell significantly, it is 140 kg/Nm³ (70 kg/Nm³ of fine ore and 70 kg/Nm³ of pulverized coal).

In the case of 60% pre-reduced fine ore, on the other hand, when injected together with the same amount of pulverized coal, the deadman temperature was kept at the level of all-coke operation up to approximately 230 kg/Nm³ (solid circles in Fig. 7). Thus, injection of 115 kg/Nm³ of fine ore and 115 kg/Nm³ of pulverized coal were considered the maximum.

As a conclusion, mixed injection of fine ore together with pulverized coal is effective. This is presumably because the combustion of the injected pulverized coal accelerates the heating of the fine ore, improves the fluidity of slag in the raceway, and keeps the deadman temperature at the high level.

4. Prospects for Next-generation Blast Furnace Operation

Table 5 shows prospected blast furnace operation data in the near future aiming at minimizing the coke rate; here the operation data of Nippon Steel's Oita No. 2 Blast Furnace (productivity coefficient 2.3 t/d·m³, reducing agent rate 486 kg/t) were adopted as the base case.

Since decreasing the coke rate is one of the most essential requirements in blast furnace operation, a pulverized coal injection

Table 5 Prediction of operation data in the future blast furnace

No.	TB (℃)	MO (g/Nm³)	O_2 (Nm³/t)	PC (kg/t)	CR (kg/t)	IFO (kg/t)	RFO (%)	Q (kcal/t)	TR (℃)	η shaft (%)	Scrap (kg/t)
Base	1200	35	22.8	79.5	406.6	0	0	125000	980	96.5	0
1	1300	5	22.8	200.0	279.6	0	0	125000	980	96.5	0
2	1300	5	22.8	200.0	274.6	0	0	99000	980	96.5	0
3	1300	5	22.8	200.0	267.6	0	0	99000	980	98.5	0
4	1300	5	22.8	200.0	250.6	0	0	99000	900	98.5	0
5	1300	5	22.8	200.0	243.6	70	60	99000	900	98.5	0
6	1300	5	22.8	200.0	227.6	98	90	99000	900	98.5	0
7	1300	5	22.8	200.0	229.6	0	0	99000	900	98.5	65

TB: Blast temp., MO: Blast moisture, IFO: Injected fine ore, RFO: Pre-reduction degree,
Q: Heat loss, TR: Temperature at thermal reserve zone

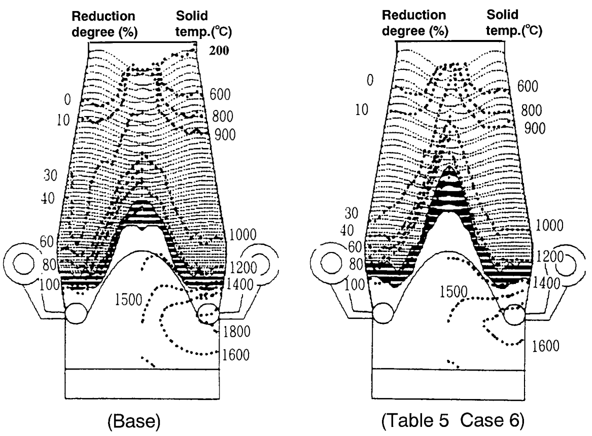

Fig. 8 Simulation results of reduction behavior in the future blast furnace

amount of 200 kg/t was assumed for all the prospected cases. The following additional conditions were set out: (1) a maximum blast temperature of 1300℃ and a blast moisture of 5 g/Nm³ for Cases 1 to 7; (2) a 20% decrease in the heat loss through furnace shells by burden distribution control for Cases 2 to 7; (3) use of high-reducibility sinter to improve the shaft efficiency to 98.5% for Cases 3 to 7; (4) use of high-reactivity small-size coke to lower the thermal reserve zone temperature to 900℃ aiming at a shaft efficiency of 98.5% for Cases 4 to 7; (5) injection of pre-reduced fine ore through tuyeres for Cases 5 and 6; and (6) charging of scrap iron from the furnace top for Case 7. With the measures (1) to (4), a coke rate of as low as 250 kg/t is achievable under the current equipment conditions. The coke rate can be further lowered by adding the measure of (5) or (6): with injection of 90% pre-reduced fine ore at a rate approximately of 100 kg/t or charging 65 kg/t of scrap iron, a coke rate below 230 kg/t is attainable.

Fig. 8 compares the reduction behavior inside a blast furnace in Case 6 of Table 5 simulated by a blast furnace total model with that in the base case. The position and shape of the cohesive zone in Case 6 are substantially the same as those in the bases case, and therefore, the prospected future blast furnace operation is considered technically viable.

5. Summary

The tuyere injection of fine iron ore into a blast furnace, which constitutes the core of combined tuyere blowing technology, is an important seed technology for a future blast furnace. It is a quickly working measure to remarkably enhance the production flexibility of a blast furnace, especially to change the production rate while maintaining the packing structure in the furnace shaft basically unchanged. Since the fine ore injection decreases the charging of sinter from the furnace top, it offers the possibility of increasing the use of poor-quality ore brands.

Blast furnace operation data under tuyere injection of fine ore was estimated to study the maximum injection amount of fine ore using a purpose-built, hot-model test apparatus, and to obtain the following findings:

1) Under the condition that appropriate heat and material balances are maintained in the tuyere front portion and the entire furnace, the maximum ore injection amount was calculated as follows: 144 kg/t when the blast temperature is raised from the present 1100 to 1350℃, the maximum attainable under the current equipment condition, and the blast moisture decreased by approximately 20 g/Nm³; and approximately 268 kg/t when oxygen is enriched by 9.1% (100 Nm³/t) in addition to the above. In the case where pulverized coal is injected together with the fine ore, the maximum fine ore injection amount is approximately 184 and 100 kg/t with 100 and 200 kg/t of PCI, respectively.
   In addition, in the case where the blast temperature is raised to 1800℃ by applying plasma, the maximum injection amount of 35% pre-reduced fine ore is 473 kg/t (425 kg/t in terms of the weight after the pre-reduction), and that of 60% pre-reduced fine ore is 594 kg/t (490 kg/t in terms of the weight after the pre-reduction). In the last case, a 27.8% production increase from the base case is attainable.
2) As a result of tests on the hot-model apparatus (under a blast temperature of 1300℃, the same blast moisture as that of current blast furnace operation and oxygen enrichment up to 5%), the maximum fine ore injection amount with which the temperature inside the deadman is kept unchanged from that with the blast temperature of 1100℃ is as follows.
   0% pre-reduced fine ore: Single injection
   ---- injection impossible
   Mixed injection with the same amount of pulverized coal
   ---- 70 g/Nm³ (+ 70 g/Nm³ of PCI)

60% pre-reduced fine ore: Single injection
---- 175 g/Nm^3
Mixed injection with the same amount of pulverized coal
---- 115 g/Nm^3 (+ 115 g/Nm^3 of PCI)

The fine ore injection into a blast furnace through tuyeres was studied more than 10 years ago, but owing to the concern at that time about the wear of the transportation and injection ducts, the process did not become popular. However, thanks to the advance in material technology such as that of ceramics, the problem of the wear can be solved more easily these days. Now that the deterioration of iron ore resources is expected to become a serious problem shortly, the fine ore injection is an important technology to support the blast furnace operation in the future.

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