IEAGHG/IETS Iron & Steel Industry CCUS & Process Integration Workshop

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Development of Ferro-Coke Process for Mitigating CO2 Emissions in Ironmaking

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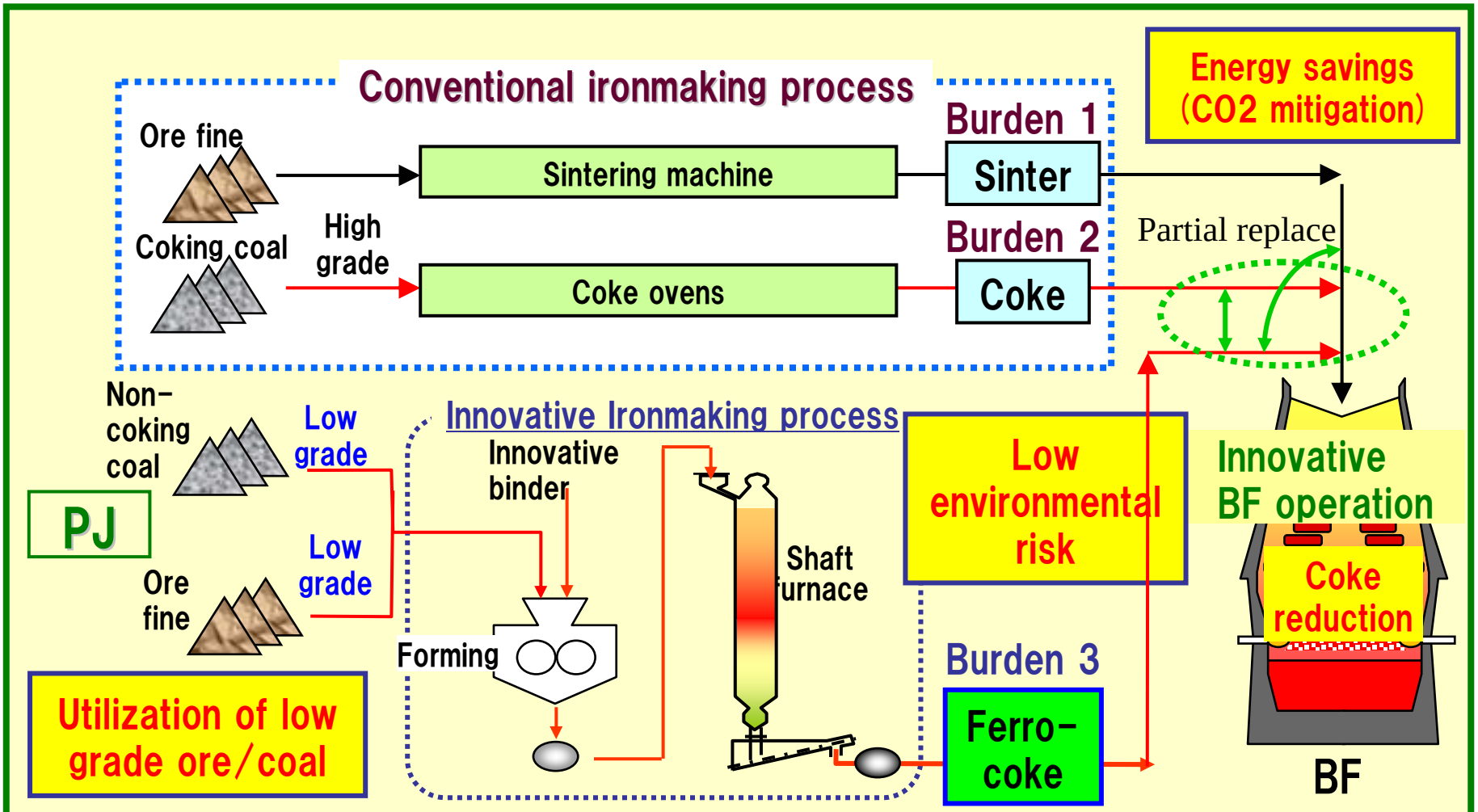
Kobe Steel, Ltd.

Concept of Innovative ironmaking process

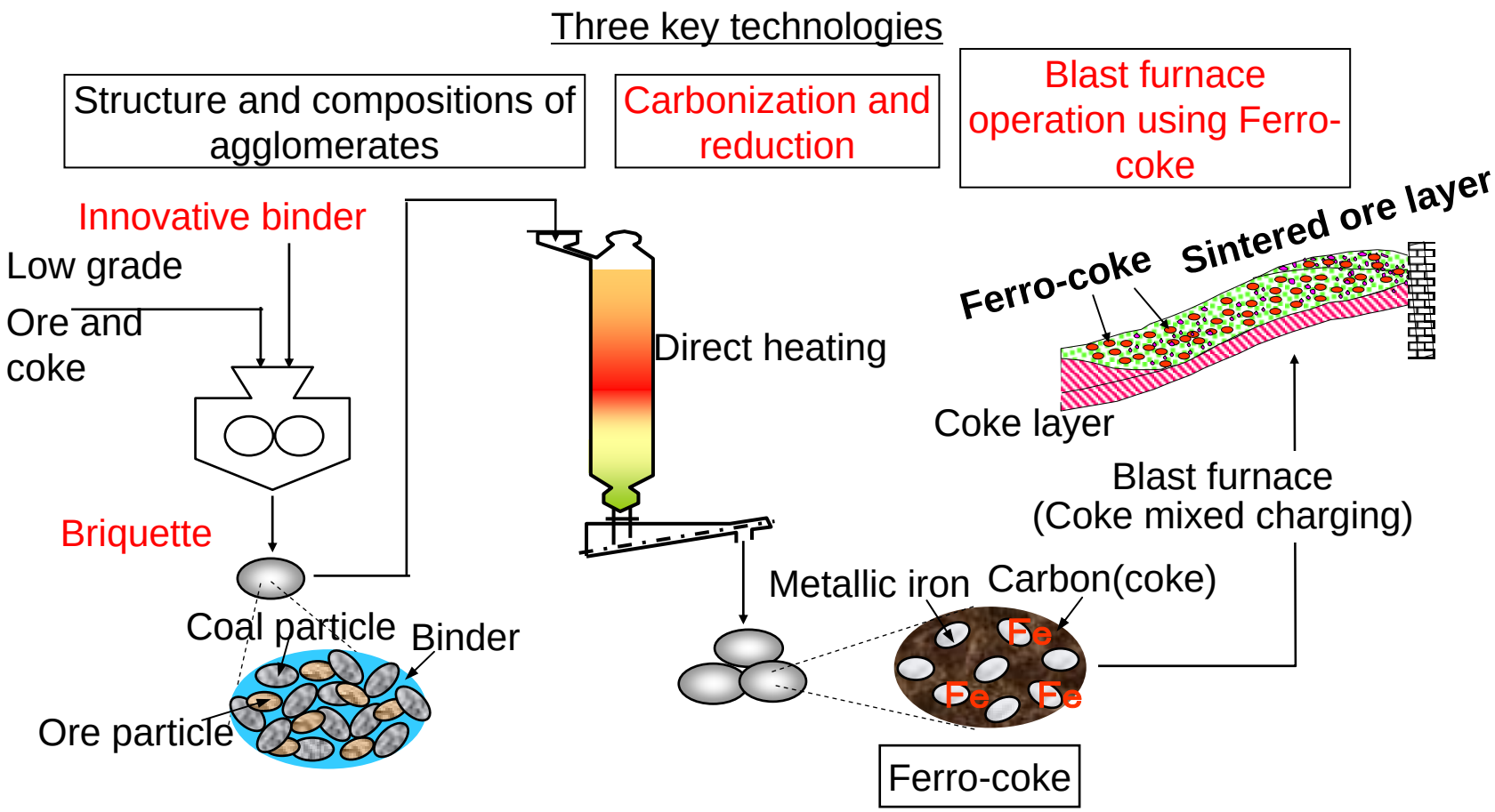
CO_2 mitigation and usage of low grade resources in ironmaking process



NEDO/METI grant project : Period: FY2009/10 , FY2011/12 :Grant ratio : 1/2

Participants: JFE Steel, Nippon Steel, Sumitomo Metals, Kobe Steel, Major Japanese Universities

Development of innovative ironmaking process



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Properties of coal and ore

Coal Properties (VM,Ash：dry base)

Coal	Ro(%)	VM(%)	MF(ddpm)	Ash(%)
A	0.72	36.1	307	8.4
B	1.80	11.2	0	8.6

Coal A ：Slightly caking coal
Coal B ：Non caking coal

Ore Properties (mass%)

	T.Fe	FeO	CaO	SiO_2	Al_2O_3	MgO	P	S	Na	K
A	67.5	0.21	0.01	0.49	0.73	0.01	0.033	<0.01	<0.01	<0.01

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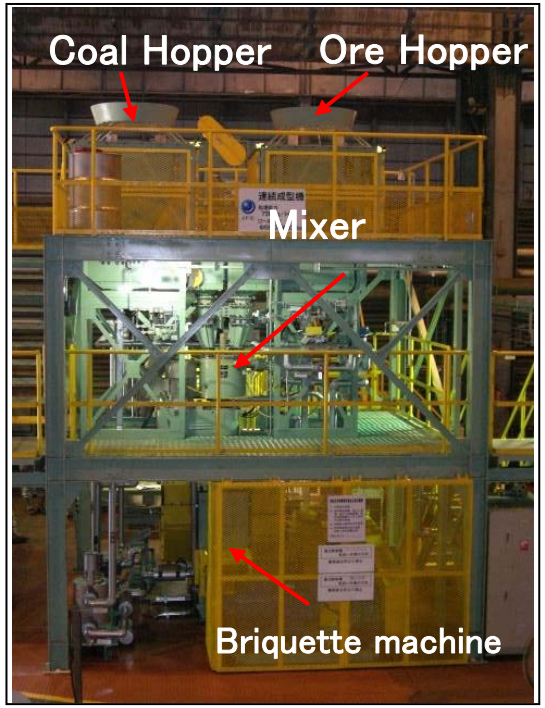
Hot briquetting test in bench plant



Briquette conditions

Total roll power	30～50ton
Briquetting pressure	3～5 t/cm
Roll diameter	650mm
Roll speed	6 rpm
Briquetting temp.	100～120℃
Cup volume	6cc
Coal/ore（mass%）	Coal/ore = 7/3
Binder（mass%）	SOP+ASP=5-9%
Particle size	Coal；-3mm, Ore A；-250μm B；-1mm
Total sample weight	20kg-dry/batch

Discharge

Mixer

Size：30x25x15mm

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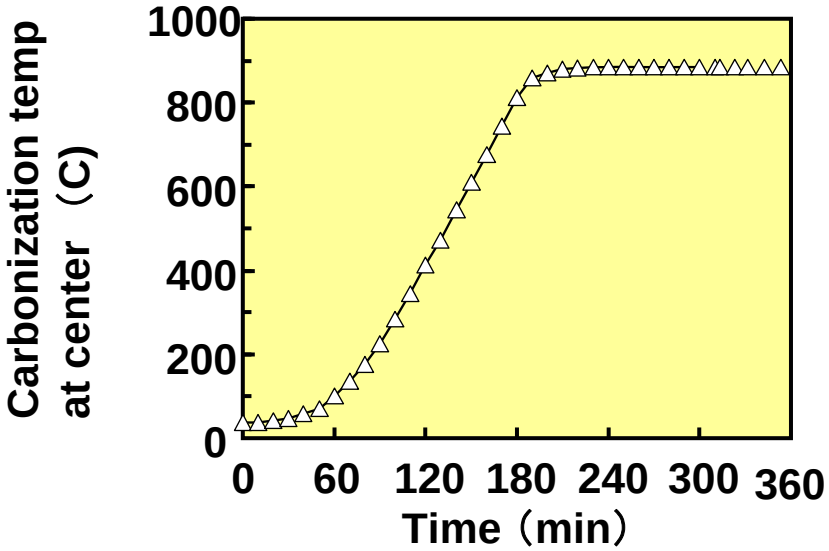
Carbonization tests in batch furnace

Carbonization test conditions

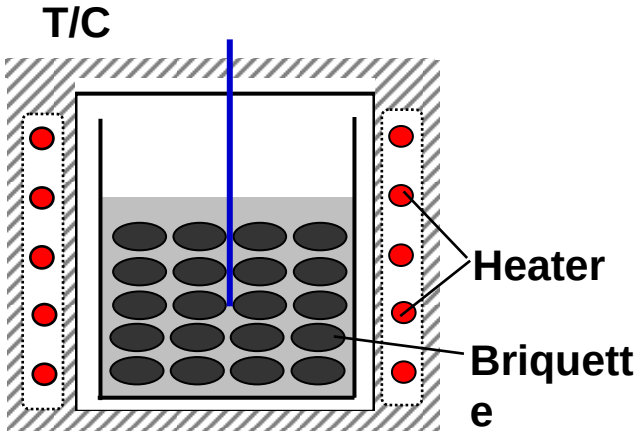
Carbonization temp (at wall) ；1000℃

Carbonization time ；6h

Packing ；with/without coke breeze

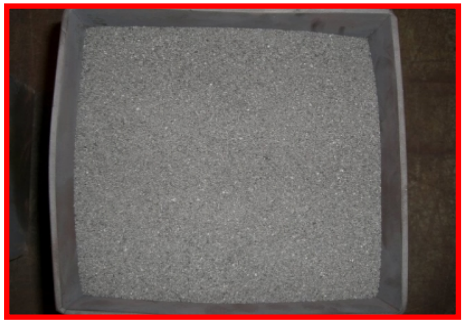


Carbonization temperature



Schematics of carbonization furnace

Without coke fine



Embedded to coke fine

Packing conditions

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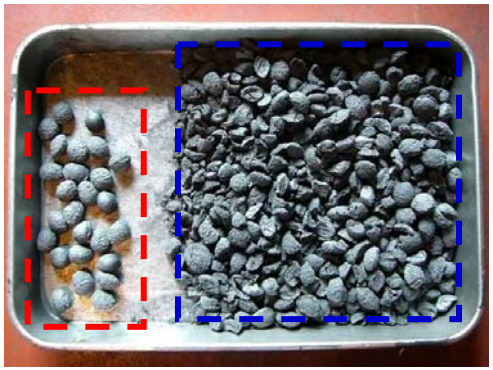
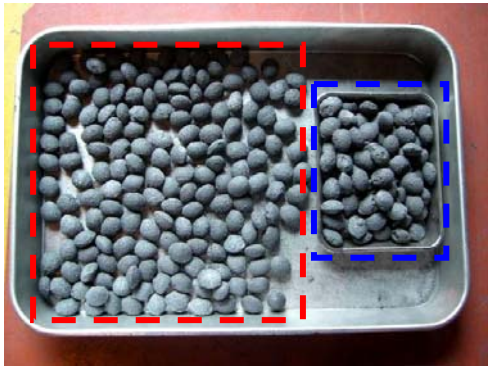
Effect of coal and ore ratio on adhesion and swelling

Coal : A/B = 70/30（mass%） **Carbonized in coke fine**

	Ore; 0mass%	Ore; 10mass%	Ore; 30mass%
Coal A 100%			
Coal A 70% + Coal B 30%			

Adhesion ratio of the ferro-coke at the blending ratio of 30% and 70%

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Development of an innovative binder for Ferro-coke

Objectives

To develop a innovative binder for Ferro-coke by utilizing the KSL's proprietary coal solvent extraction technology (Hyper-coal)

Targets

Higher Ferro-coke strength compared to a conventional asphalt pitch binder (ASP)

Features of the innovative binder process

1. No hydrogenation, mild reaction conditions (ca. 400°C, 2MPa)
2. Product separation by gravity settling
3. Recycled use of naphthalene-based solvent

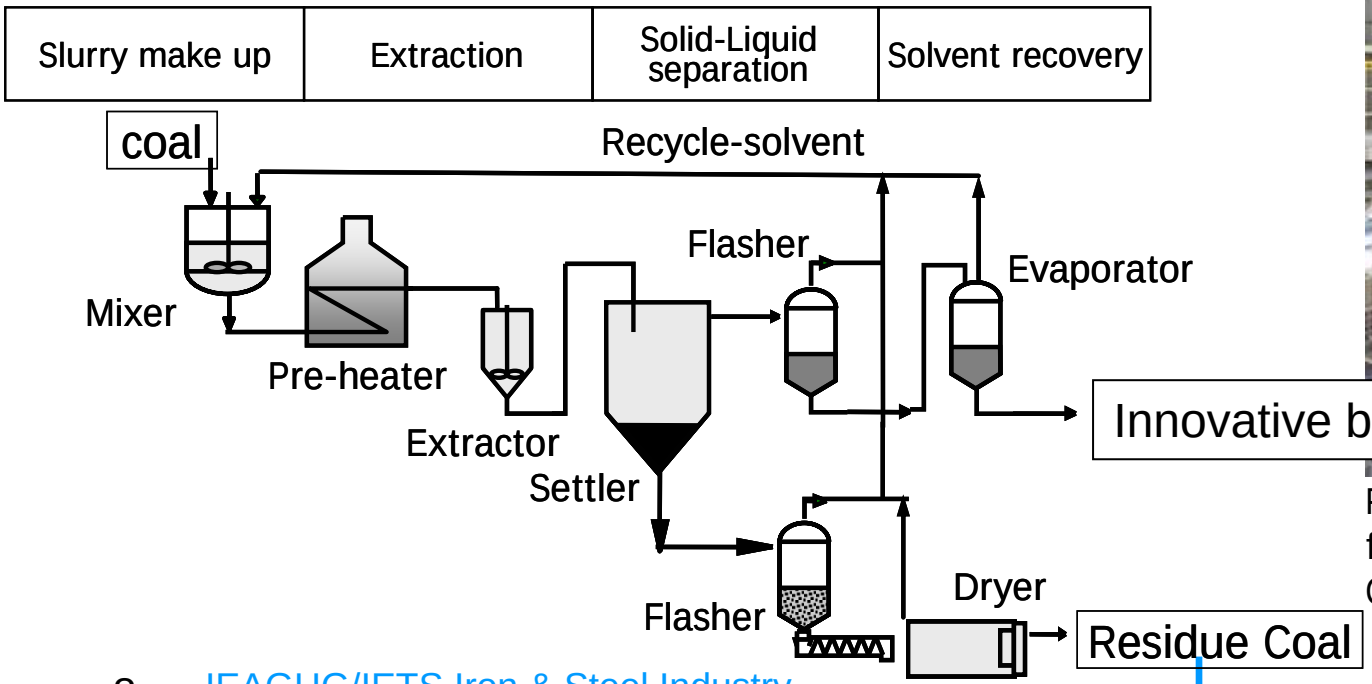

Photo Test production facility for the innovative binder
Capacity: 0.1 ton-coal/day

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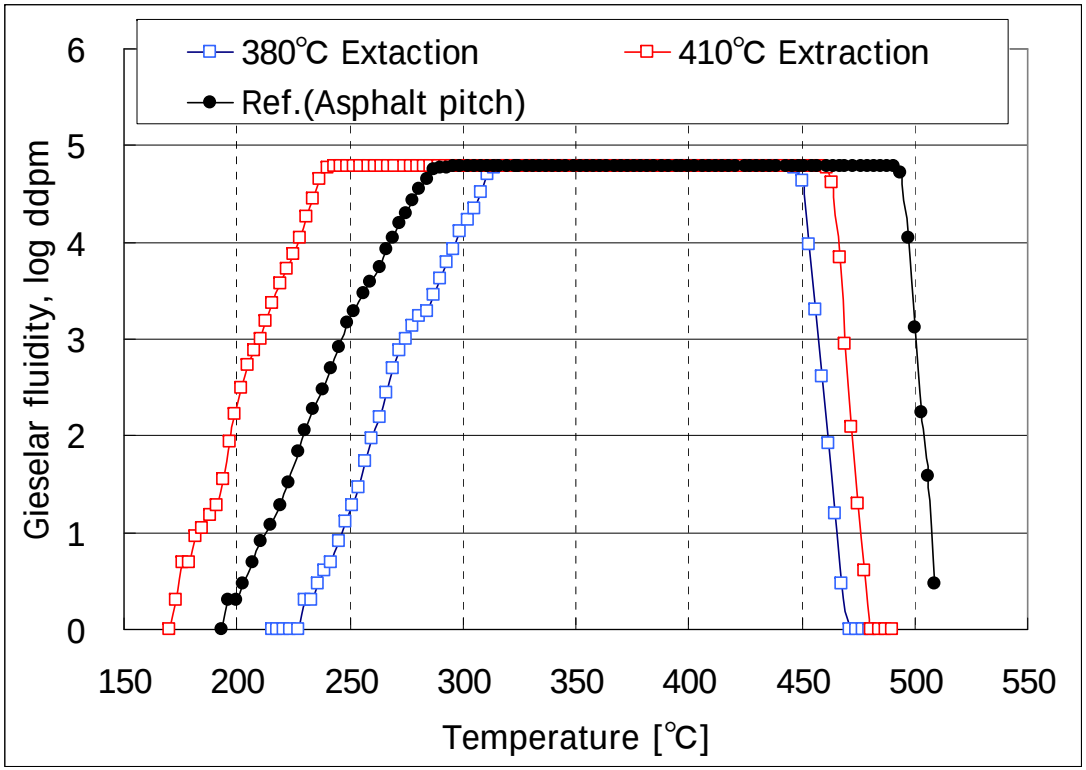
Effects of the extraction conditions on the binder properties

- Softening temperature of the binder can be controlled by the extraction conditions.
- The innovative binder prepared by extracting a bituminous coal at 410 ^{o}C exhibited lower softening temperature and superior fluidity than the ASP binder.

⇒ The enhanced fluidity of the binder may improve the inter-particle adhesion between ore and coal particles under the Ferro-coke carbonization conditions



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Experiments for evaluating the innovative binders

Table Compositions for the feed [wt%]

No.	Coal A	Coal B	Ore A	ASP	HPC1	HPC2	SOP	Remarks
1	26.6	39.9	28.5	2.0			3.0	Ref.
2	26.6	39.9	28.5	1.0	1.0		3.0	ASP/HPC: 1
3	26.6	39.9	28.5	1.0		1.0	3.0	ASP/HPC: 1
4	26.6	39.9	28.5		2.0		3.0	HPC: 2
5	26.6	39.9	28.5			2.0	3.0	HPC: 2

Extraction temperature for the innovative binders: HPC1, 380°C; HPC2, 410°C

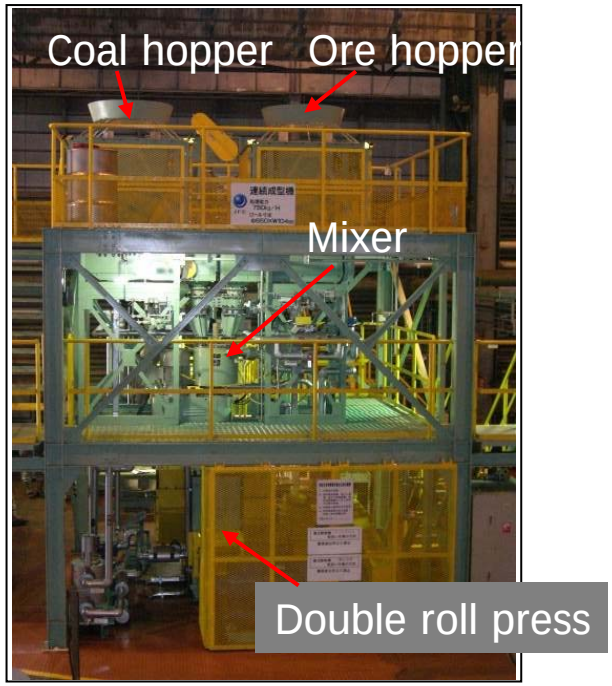

Table Briquetting conditions

Pressure	3-5 ton/cm
Roll diameter	650 mm
Rotation speed	6 rpm
Material temperature	170 ^{o}C
Pocket volume	6 cc (30x25x15 mm)
Coal/ore ratio	7/3 (by weight)
Binder content	SOP, 3%; ASP (or HPC), 2%
Particle size	Coal, <2mm; Ore, <250μm
Feed rate	20 kg/batch

Briquette ejector

Mixer

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Strength of Ferro-coke prepared by the innovative binders

Table Carbonization conditions

Wall temperature:	1000°C
Material temperature:	900°C
Duration:	6 hour

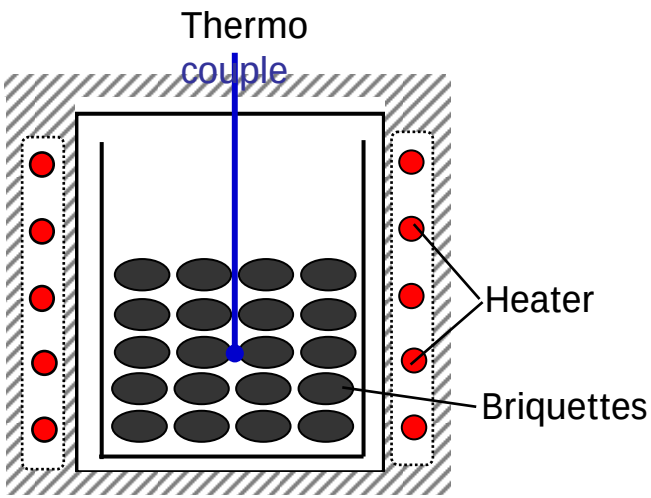

Fig. A schematic for 3kg-scale carbonization apparatus

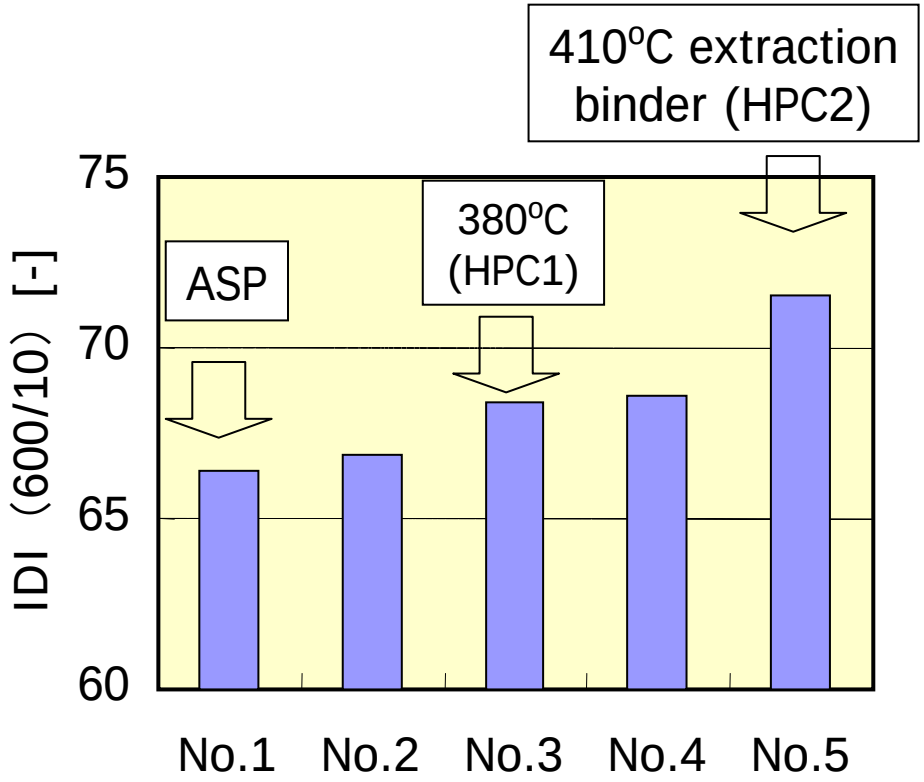

Fig. Drum indices of the Ferro-coke

It was demonstrated that the innovative binder prepared by solvent extraction of coal at 410°C improves the Ferro-coke strength compared to the ASP binder

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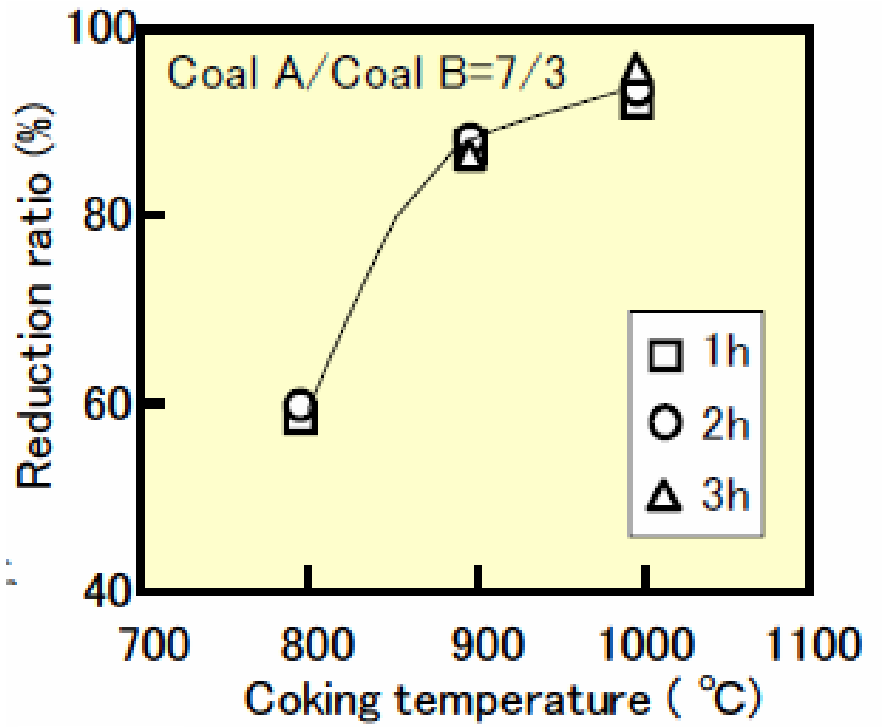
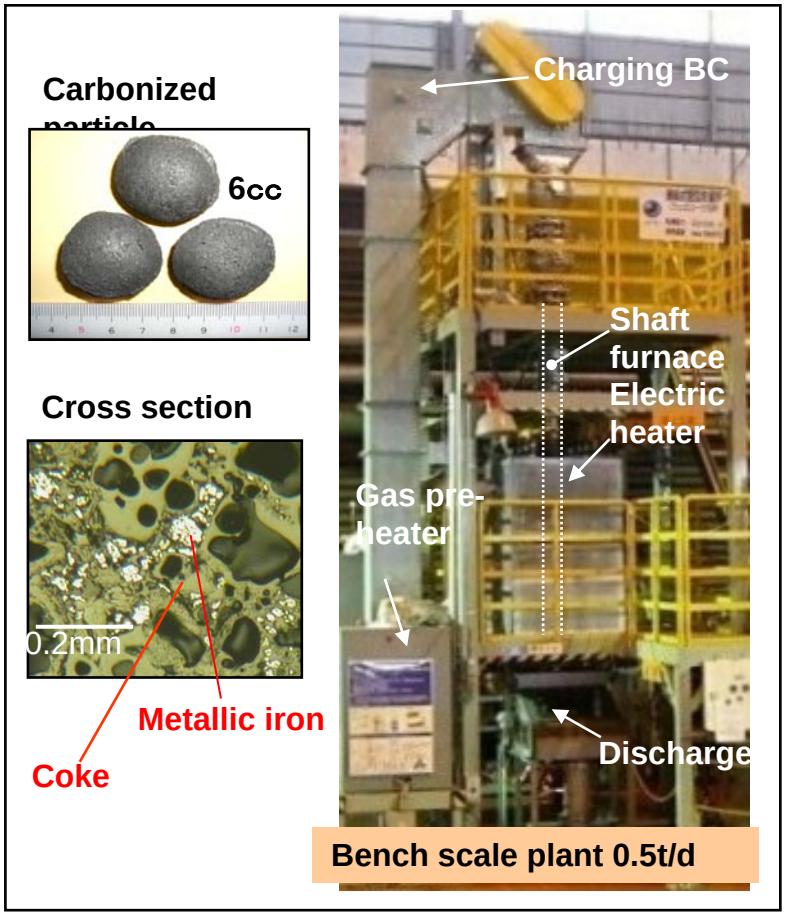
Effect of coking temperature and holding time



Effect of coking temperature on the reduction ratio



Bench scale plant of 0.5 t/d and products.

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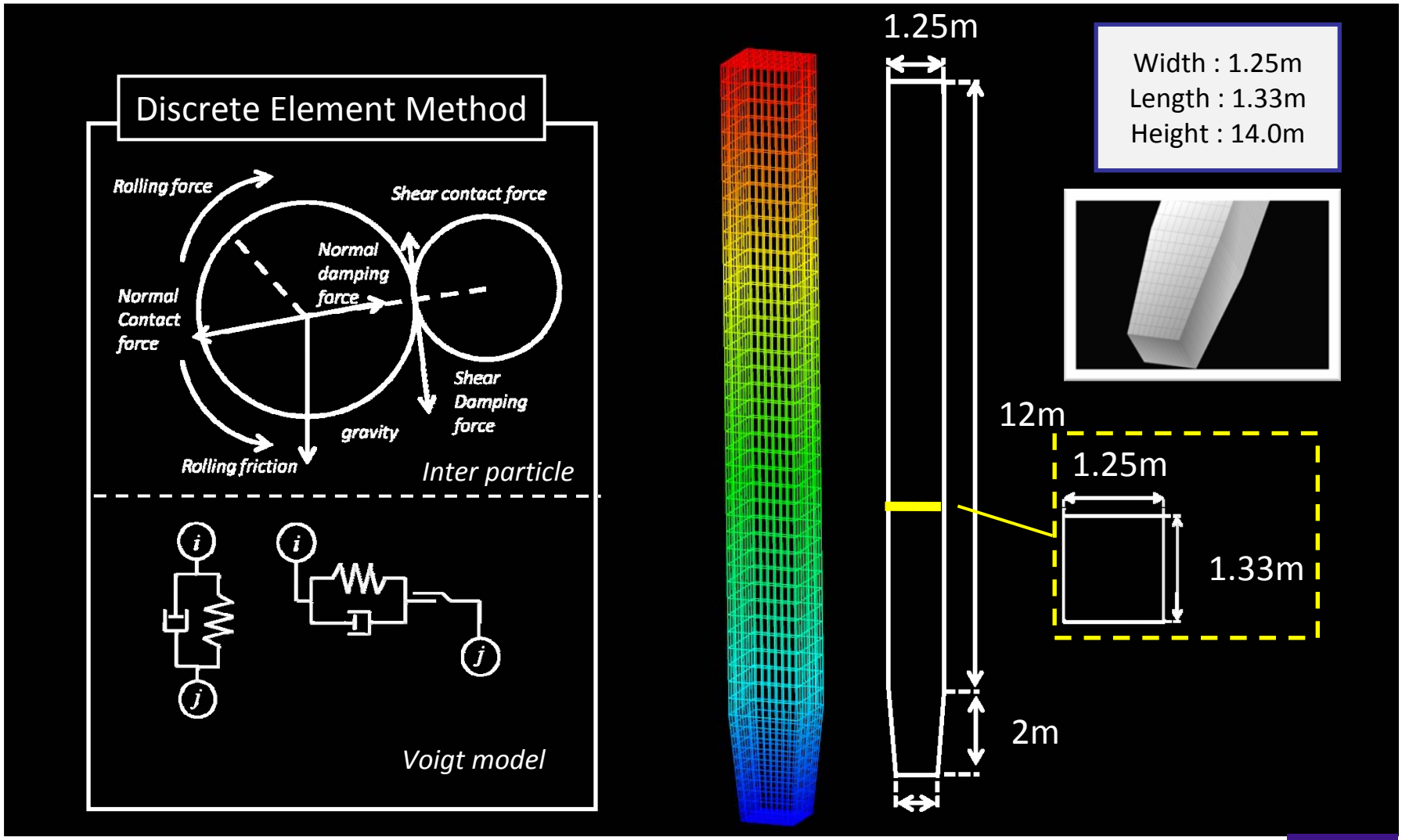
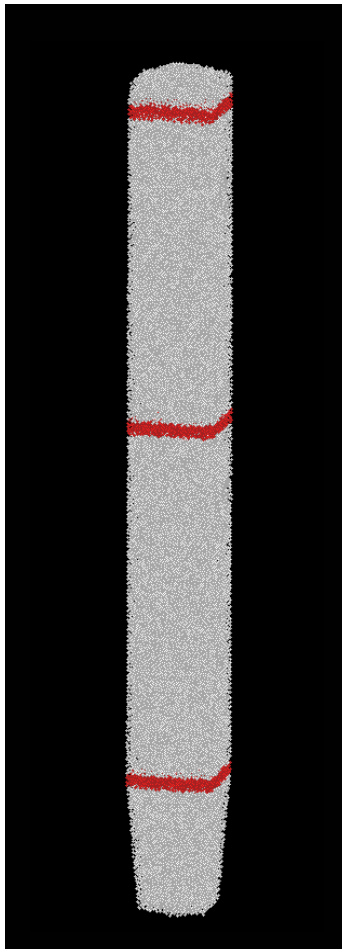
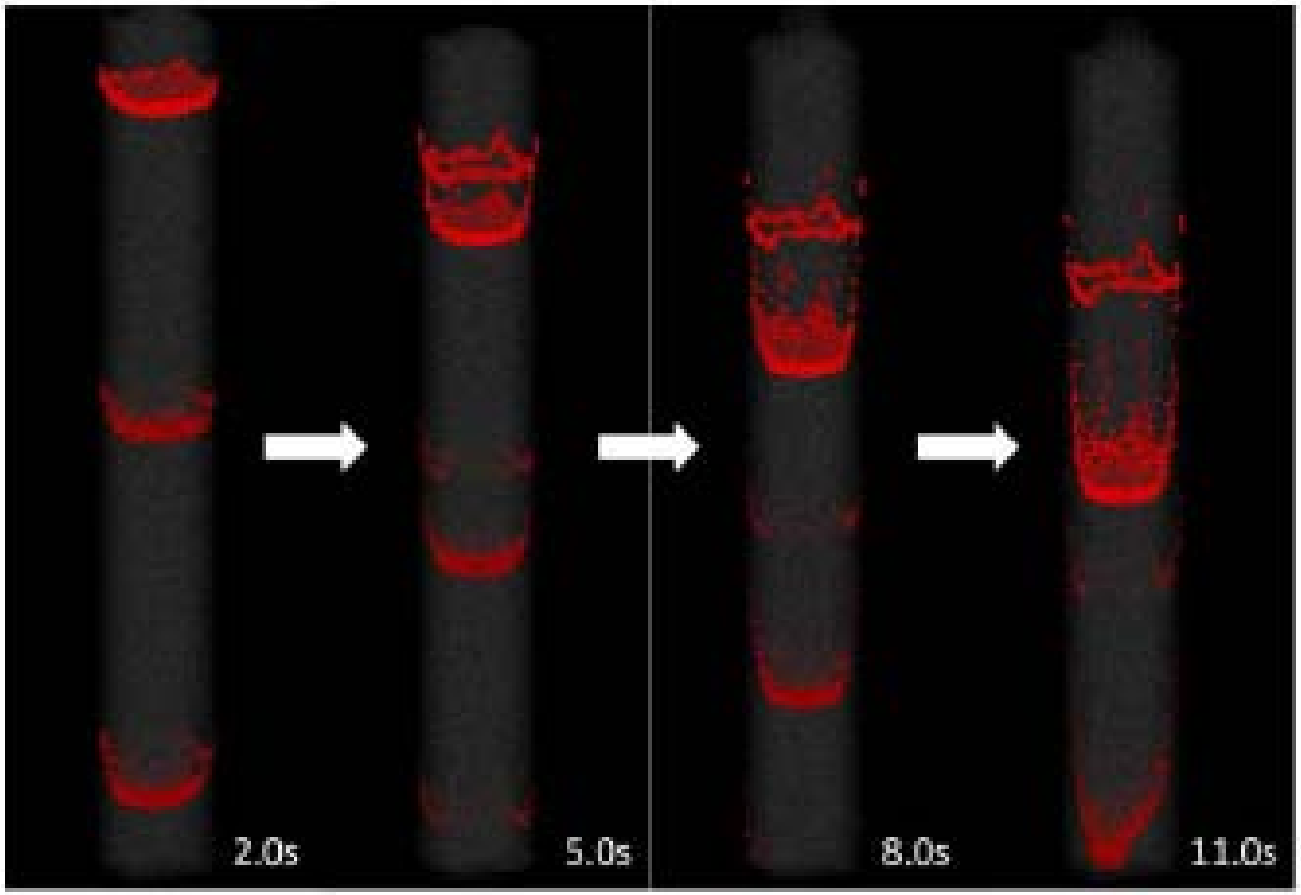
DEM model development of Ferro-coke plant



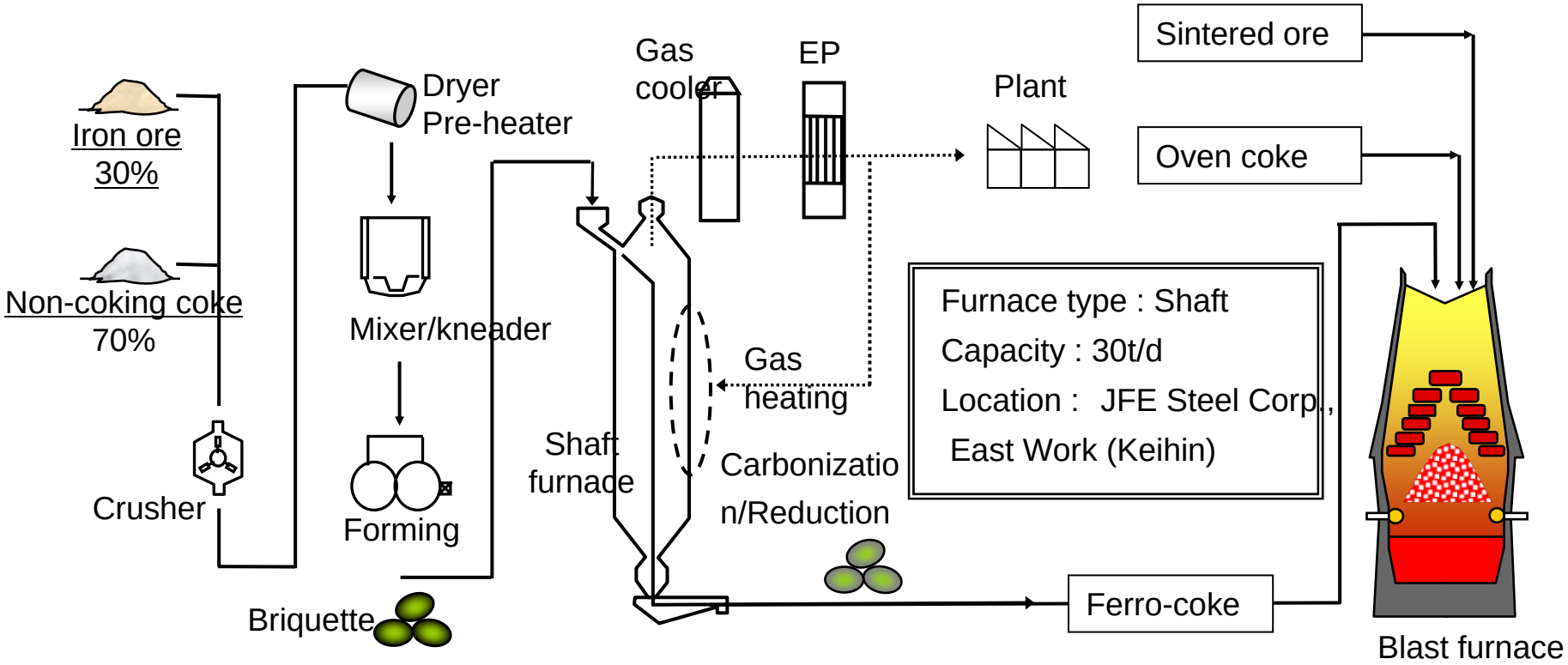
3D images of tracer particle flow



Initial charging



Process flow of a pilot plant of 30t/d



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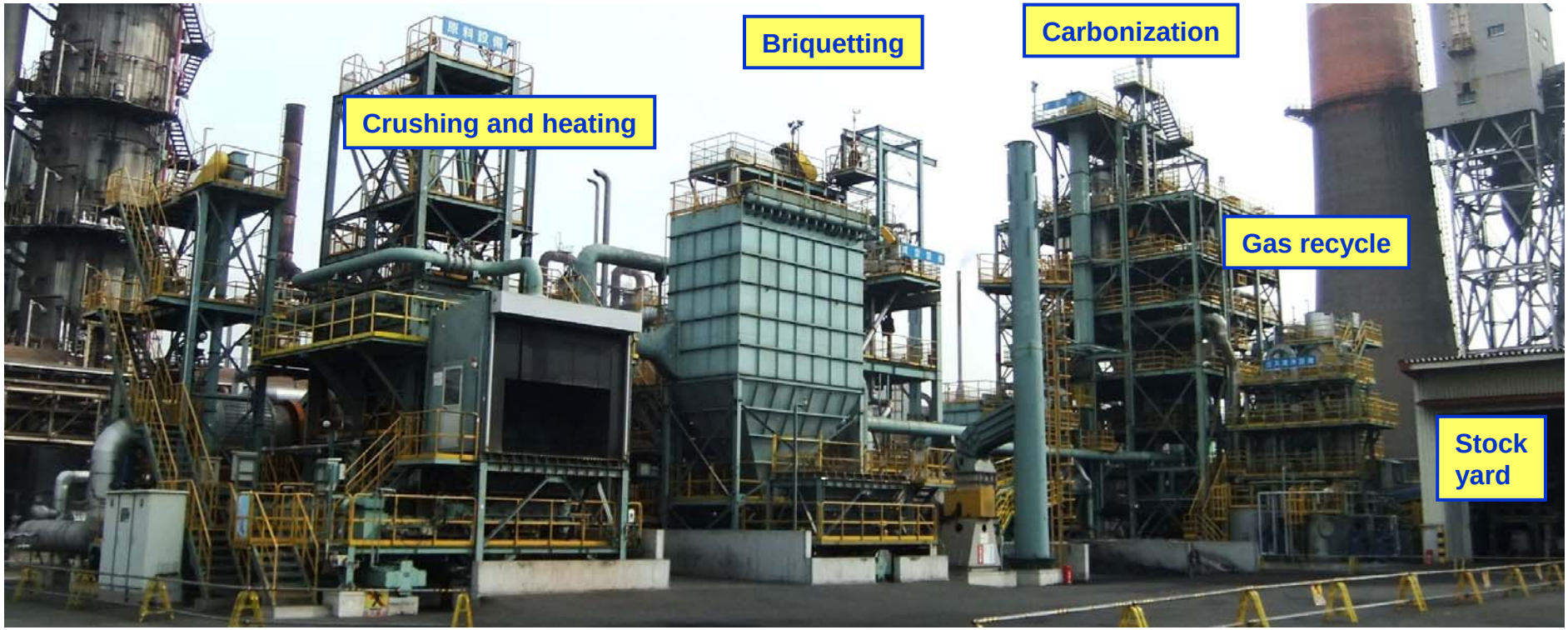
Overview of the 30t/d ferro-coke pilot plant



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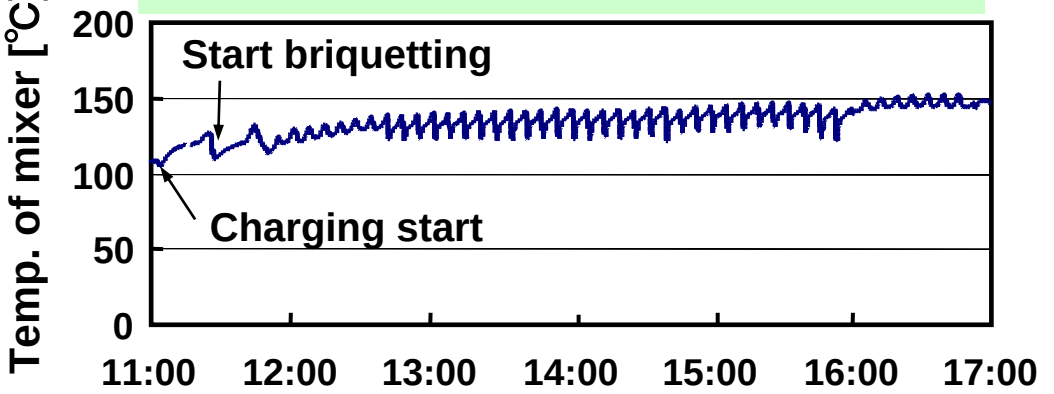
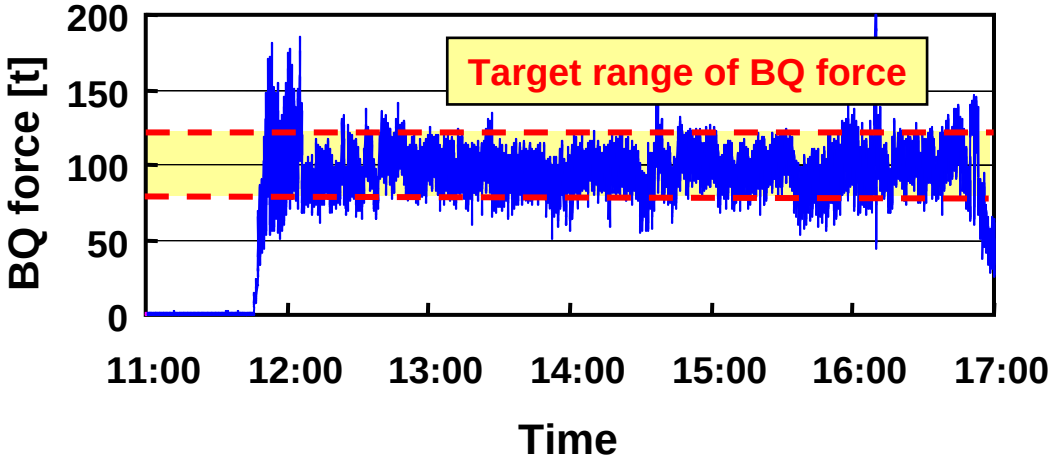
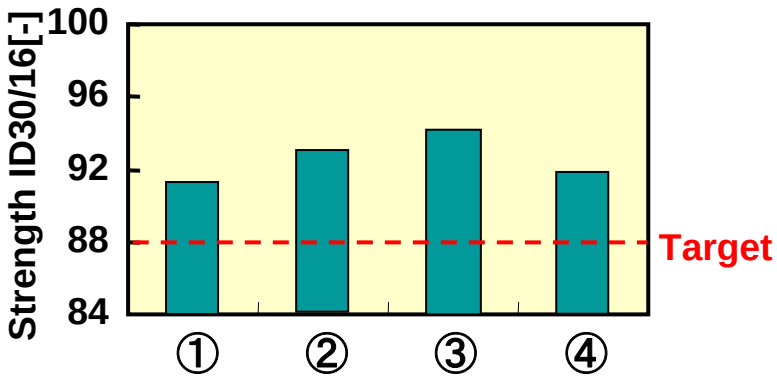
Typical continuous briquetting operation

Continuous operation for 5hr



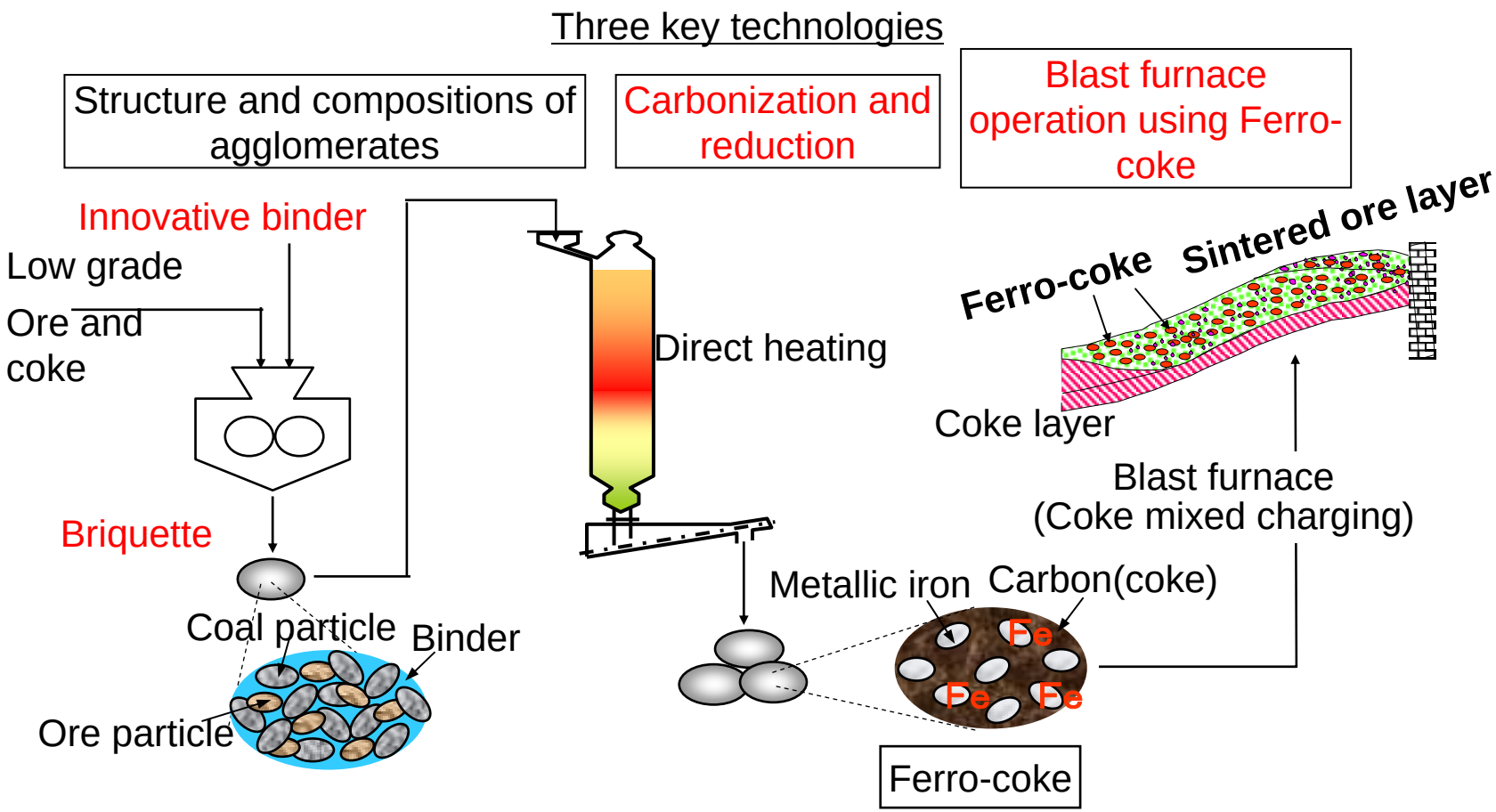




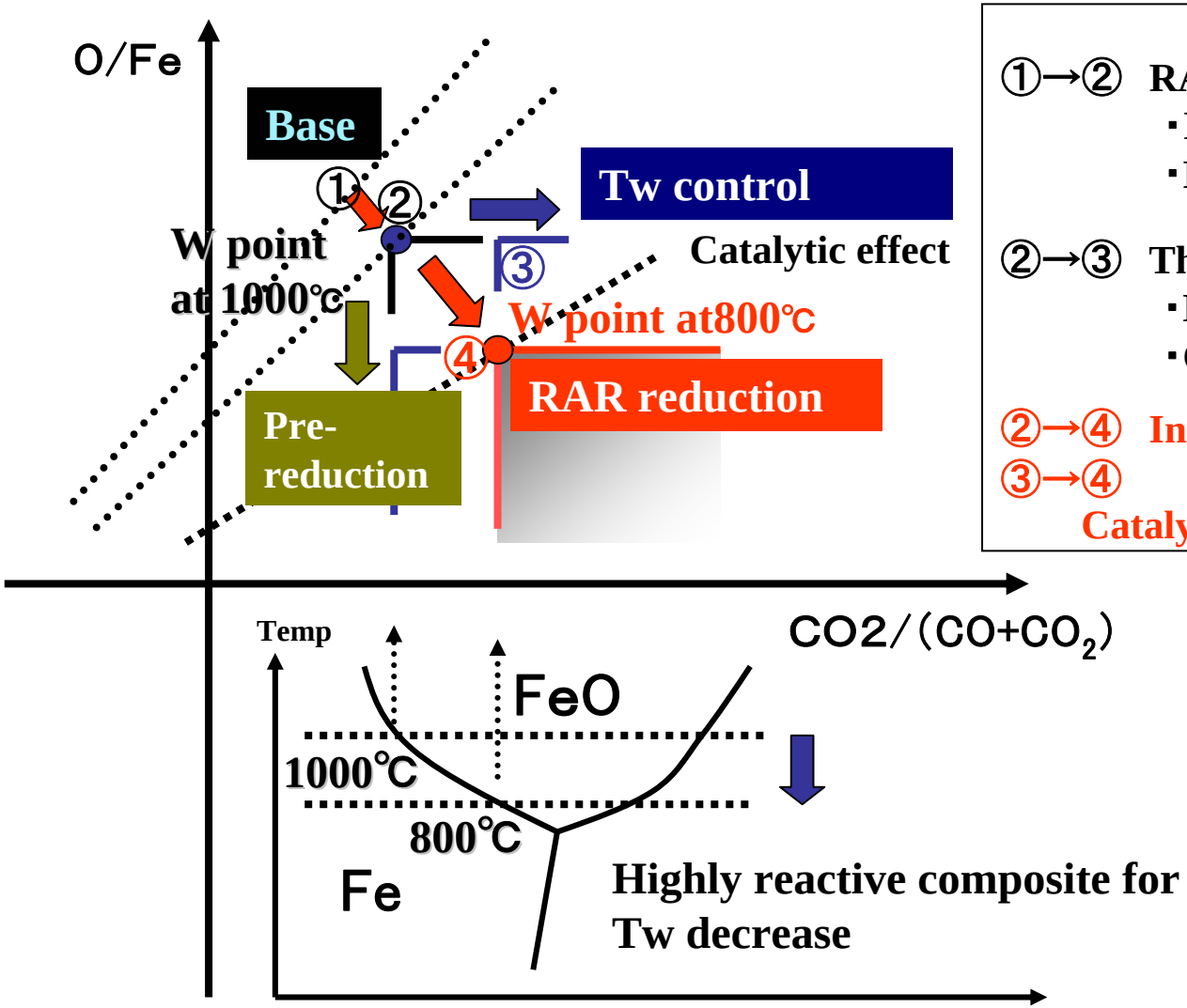
Target DI>88

Briquette for carbonization tests

Development of innovative ironmaking process



Basic concept of low carbon technologies



①→② RAR reduction in short term
- Improve sinter reducibility
- Burden distribution control

②→③ Thermal reserve temp. Tw
- Highly reactive coke
- Carbon contained agglomerates

②→④ Innovative agglomerates

③→④

Catalytic effect for high reactivity

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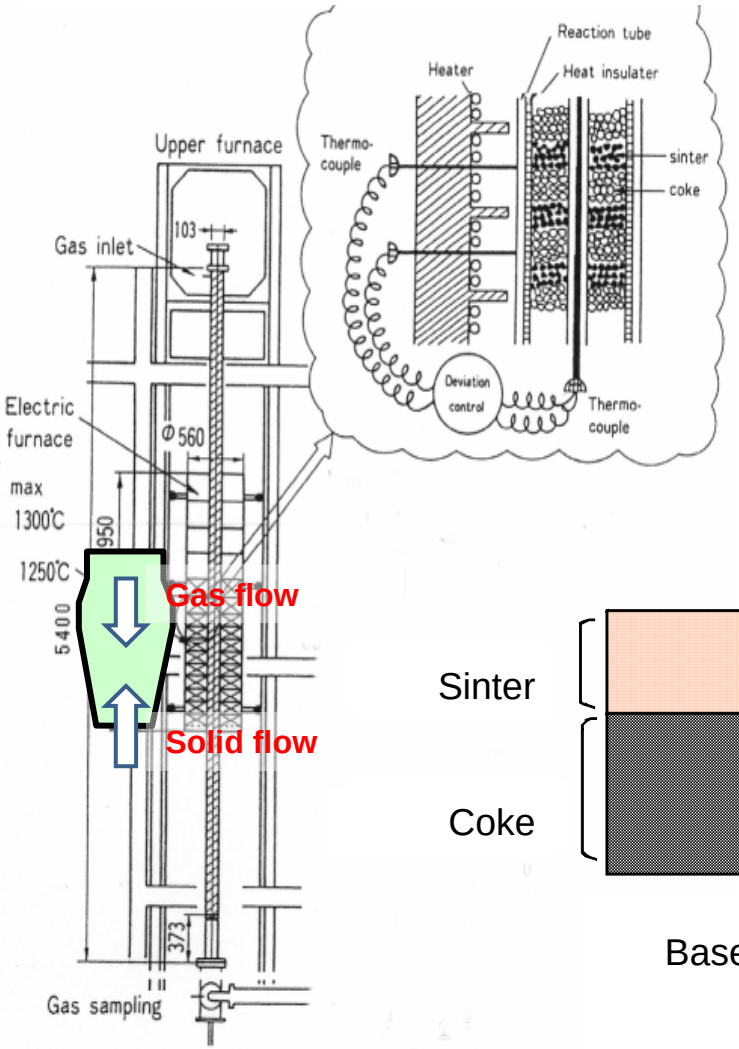
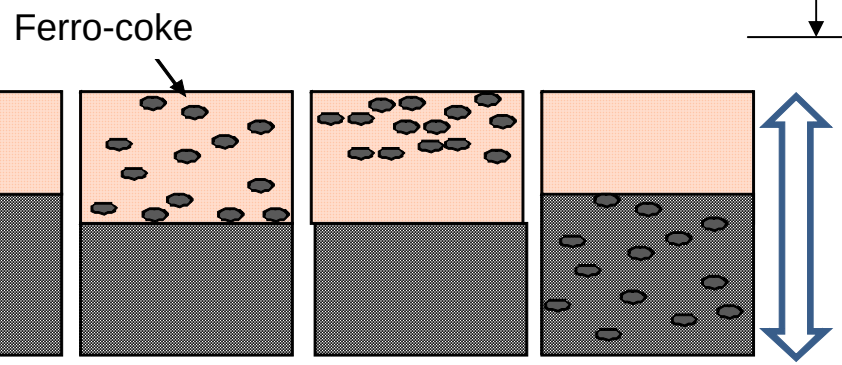
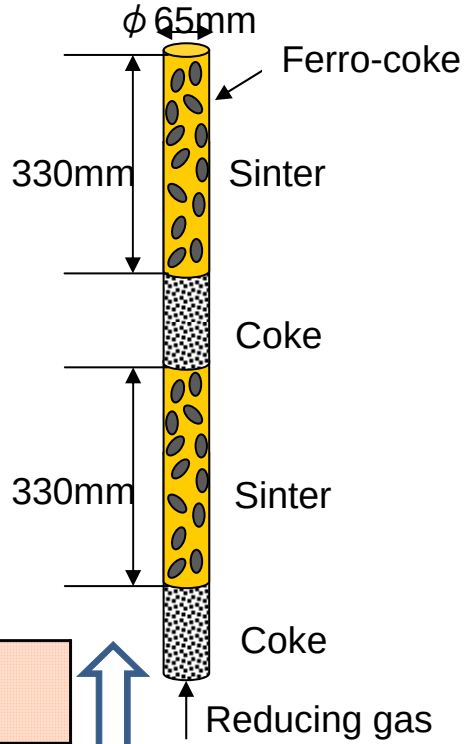
Experimental conditions with BIS and large thickness

Blast furnace Inner reaction simulator



- ✓ 30% of conventional coke was replaced with Ferro-coke.
- ✓ Different mixing conditions with Ferro-coke were tested.
- ✓ Condition with large layer thickness as plant, 330 mm, was tested.





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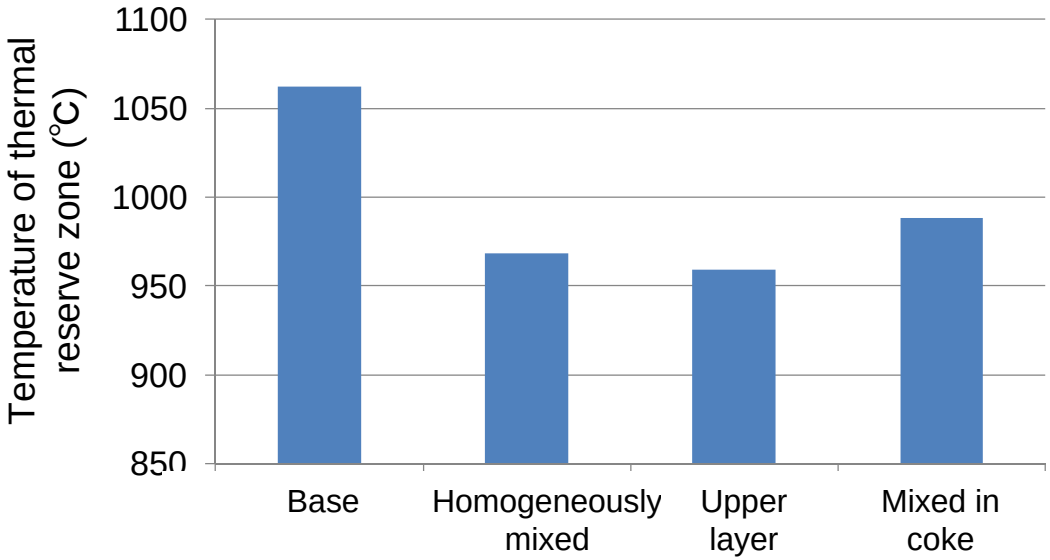

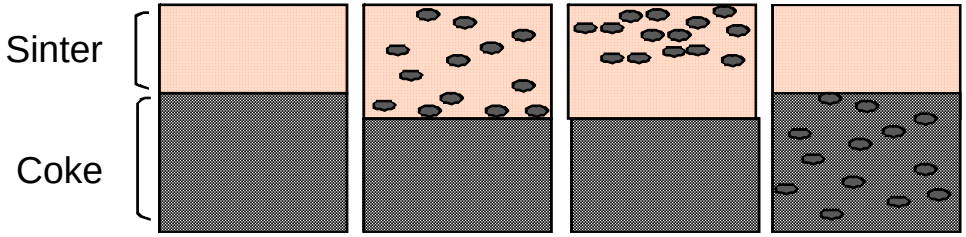

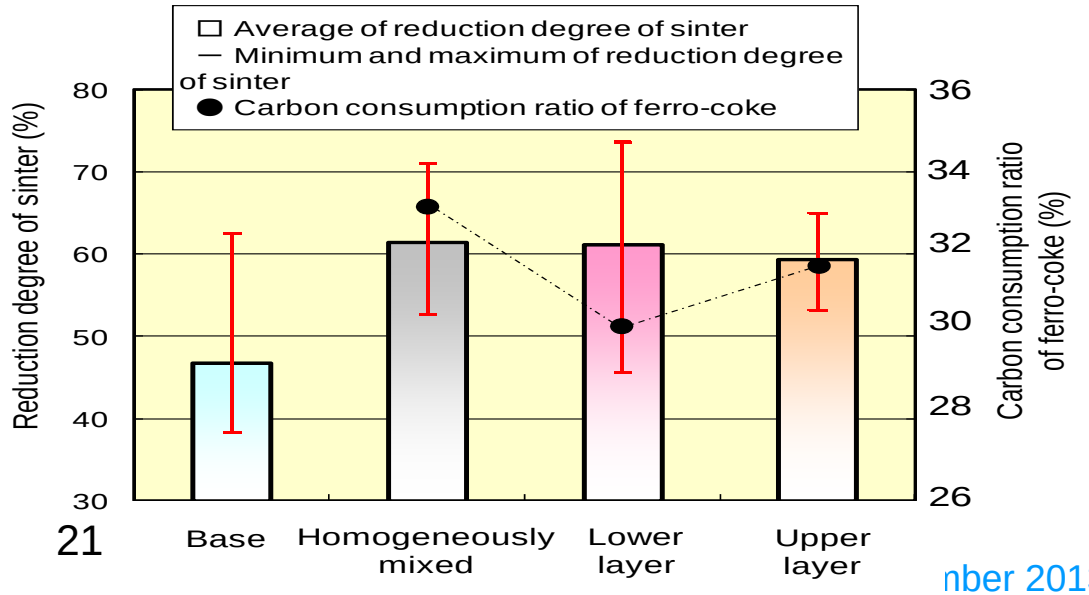

BIS tests

Temperature of thermal reserve zone was lowered by 100℃ with using Ferro-coke.

Proper arrangement of Ferro-coke was homogeneously mixed or segregated in upper layer.

Evaluation with a large layer thickness as plant, 330 mm

✓Both reactivity of sinter and Ferro-coke were large in homogeneously mixed.

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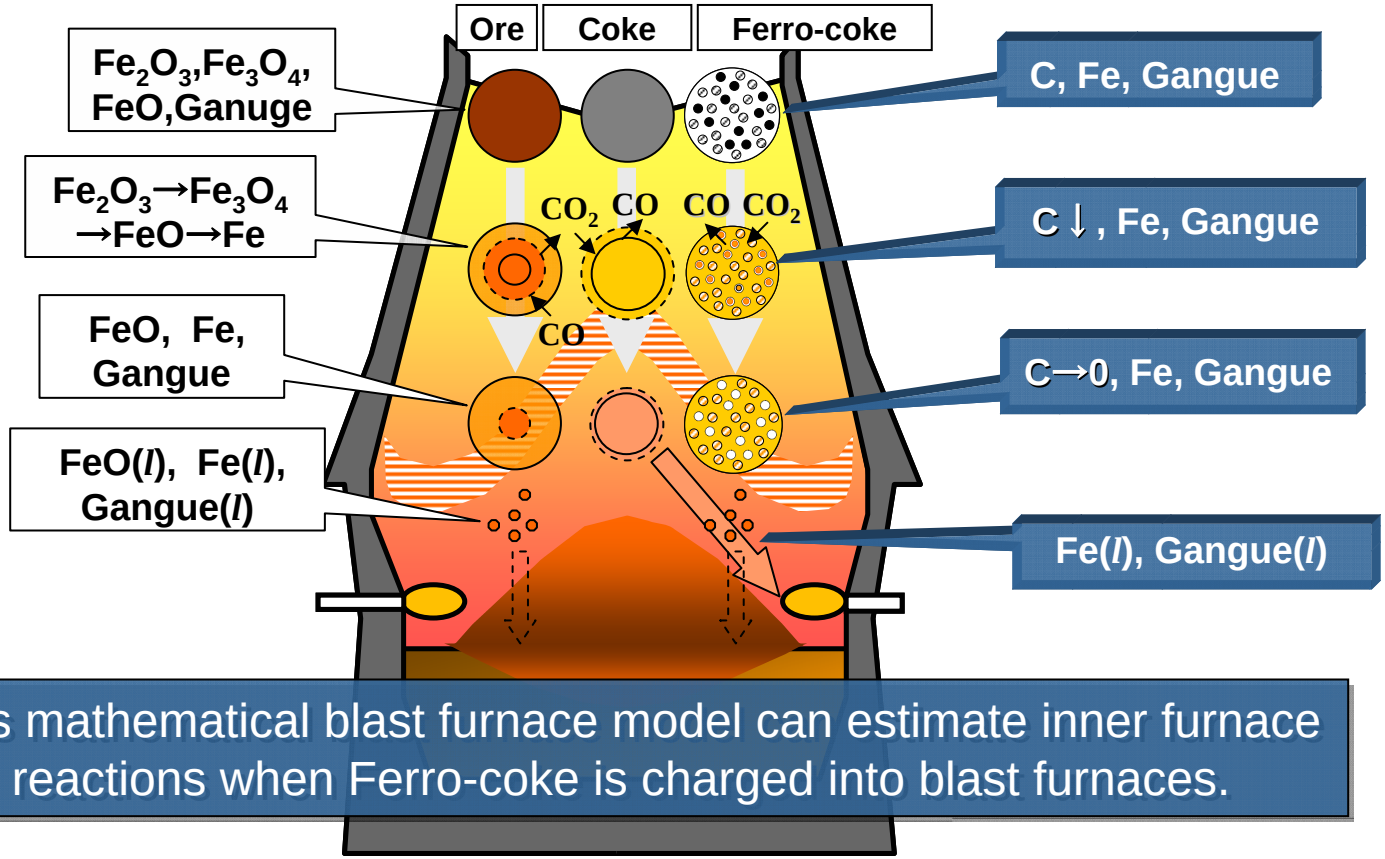
Concept of Mathematical Blast Furnace Model



This mathematical blast furnace model can estimate inner furnace reactions when Ferro-coke is charged into blast furnaces.

Gasification model of Ferro-coke is required to evaluate the effect of Ferro-coke on blast furnace operation.

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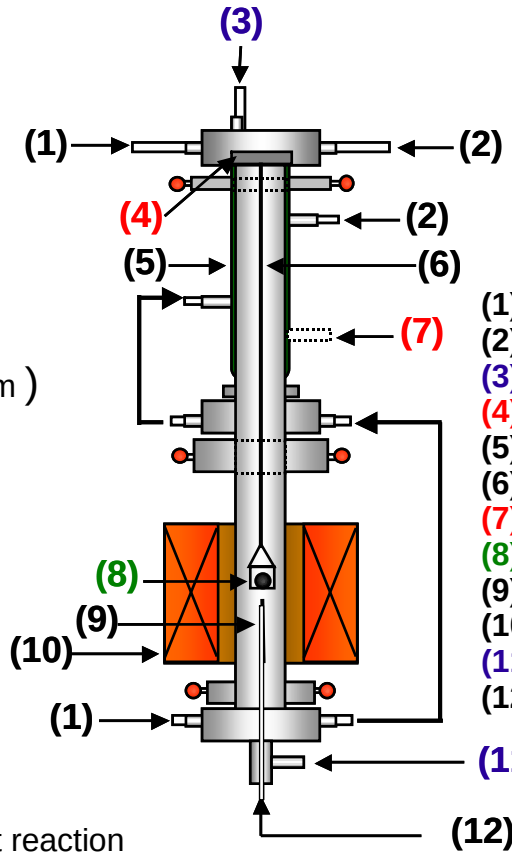
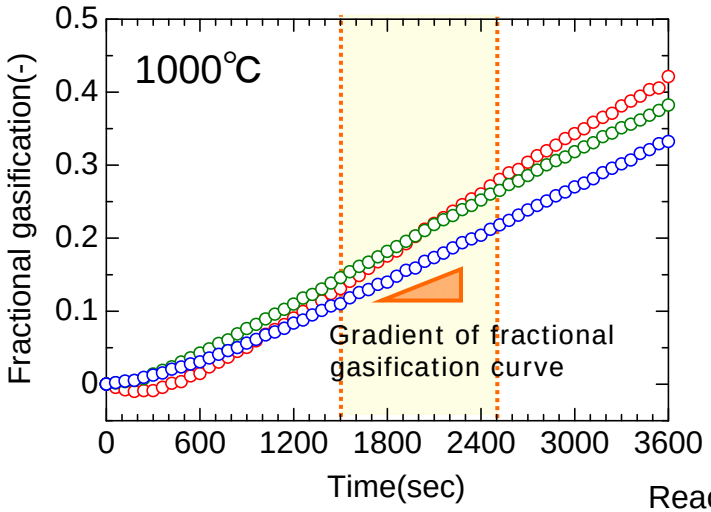
Measurement of gasification rate of Ferro-coke

Ferro coke

Sample (diameter: 11mm)



(1) Cooling water Inlet
(2) Cooling water outlet
(3) Purge gas inlet
(4) Strain gauge
(5) Copper tube
(6) Stainless steel wire
(7) Reaction gas outlet
(8) Sample
(9) Reaction tube
(10) Electric Furnace
(11) Reaction gas inlet
(12) Thermo-couples



An example of fractional gasification curve.

Apparent reaction rate constant *k'*

$$k' = k\left(p_{CO_2} - \frac{p_{CO}^{\ 2}}{K}\right)$$

Reaction rate constant *k*

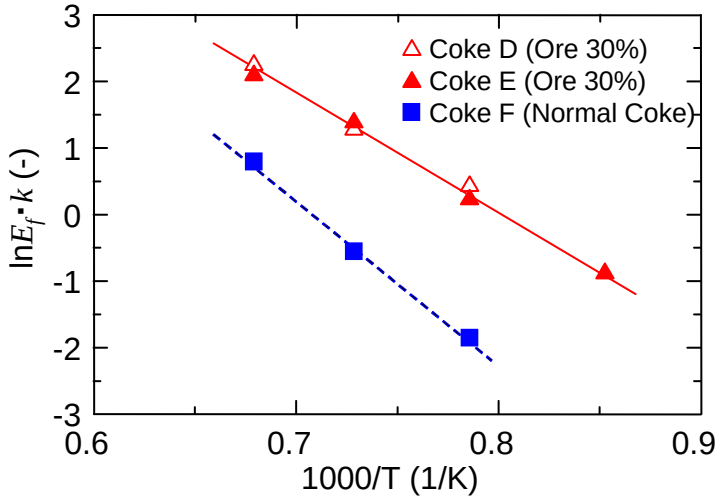
Equilibrium constant

$$K = \exp\left(-\frac{170{,}790 - 174.56T}{RT}\right)$$

Modeling of gasification rate of Ferro-coke

Kyushu Univ.

T.Nakamura *et.al.*: Camp ISIJ, 25(2012),222.



Ore 0% ▪▪▪▪ $E_f \cdot k = 2.208\times10^{7}\, exp(-\frac{181.7\times10^{3}}{RT})$

Ore 10% ▪▪▪▪ $E_f \cdot k = 1.001\times10^{7}\, exp(-\frac{169.1\times10^{3}}{RT})$

Ore 30% ▪▪▪▪ $E_f \cdot k = 4.828\times10^{6}\, exp(-\frac{158.2\times10^{3}}{RT})$

Effective reaction rate constant

NSSMC

Gasification model of Ferro-coke was combined into the mathematical blast furnace model

$$Rate_n = k_a \left(C^{b}_{CO_2} - C^{e}_{CO_2} \right) \cdot \varepsilon_s$$

Over-all reaction rate constant

Bulk Concentration

Equilibrium Concentration

Volume fraction

Particle diameter

Where, $\frac{1}{k_a} = \frac{1}{E_f \cdot k} + \frac{d_p}{6k_f}$

Mass transfer coefficient

Effective reaction rate constant

Gasification model of Ferro-coke made by Kyushu University was combined into the mathematical blast furnace model developed by NSSMC.
The effect of Ferro-coke on blast furnace operation can be evaluated by the model.

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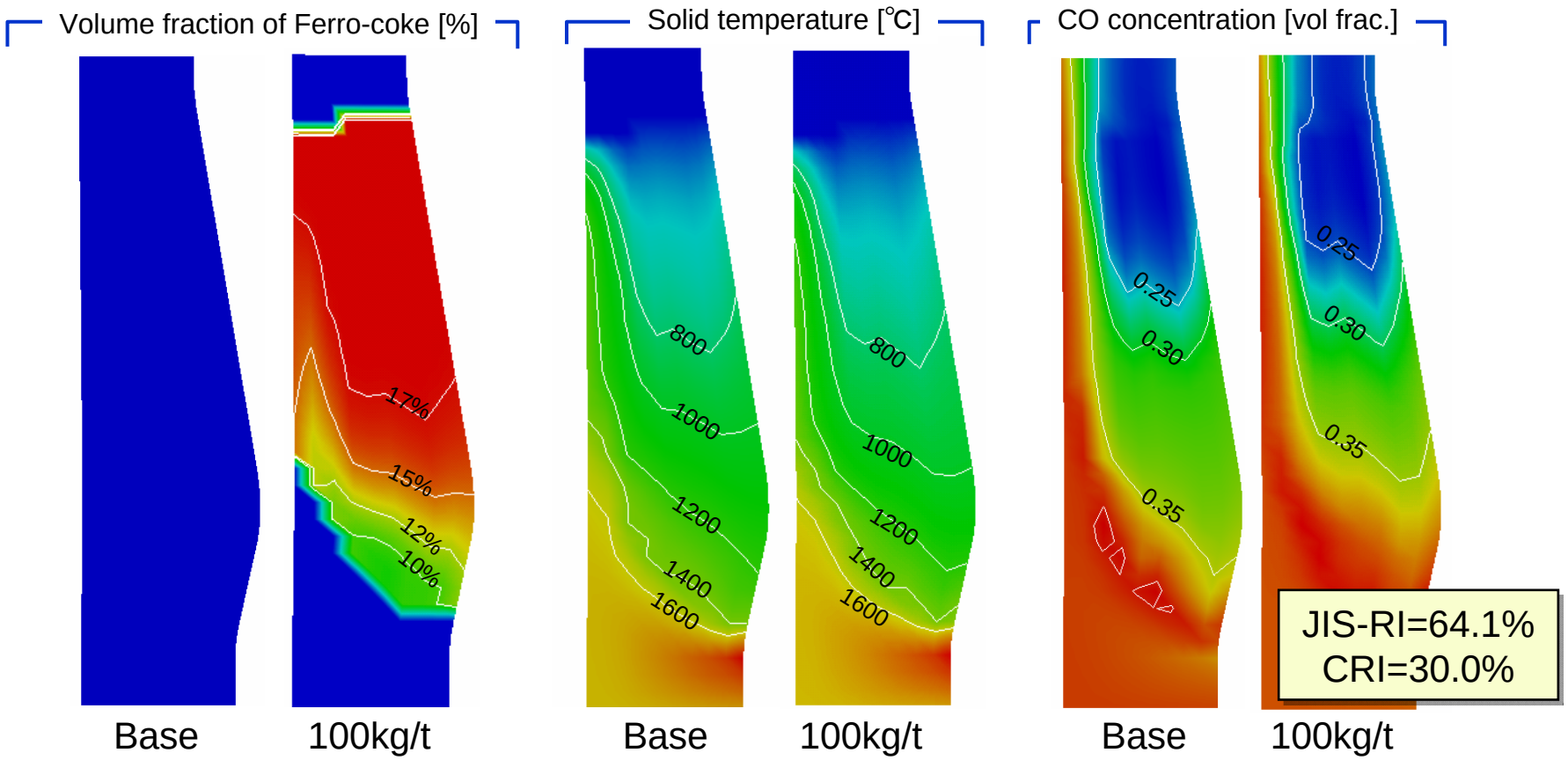
Effect of Ferro-coke on temperature distribution, gas concentration in blast furnace



Variation of inner-furnace state due to the charge of Ferro-coke was estimated.

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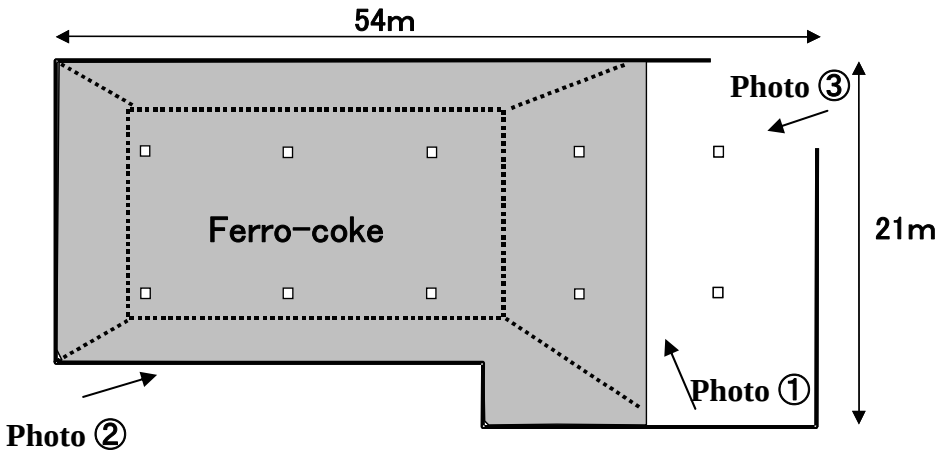
Stock yard of Ferro-coke for blast furnace test



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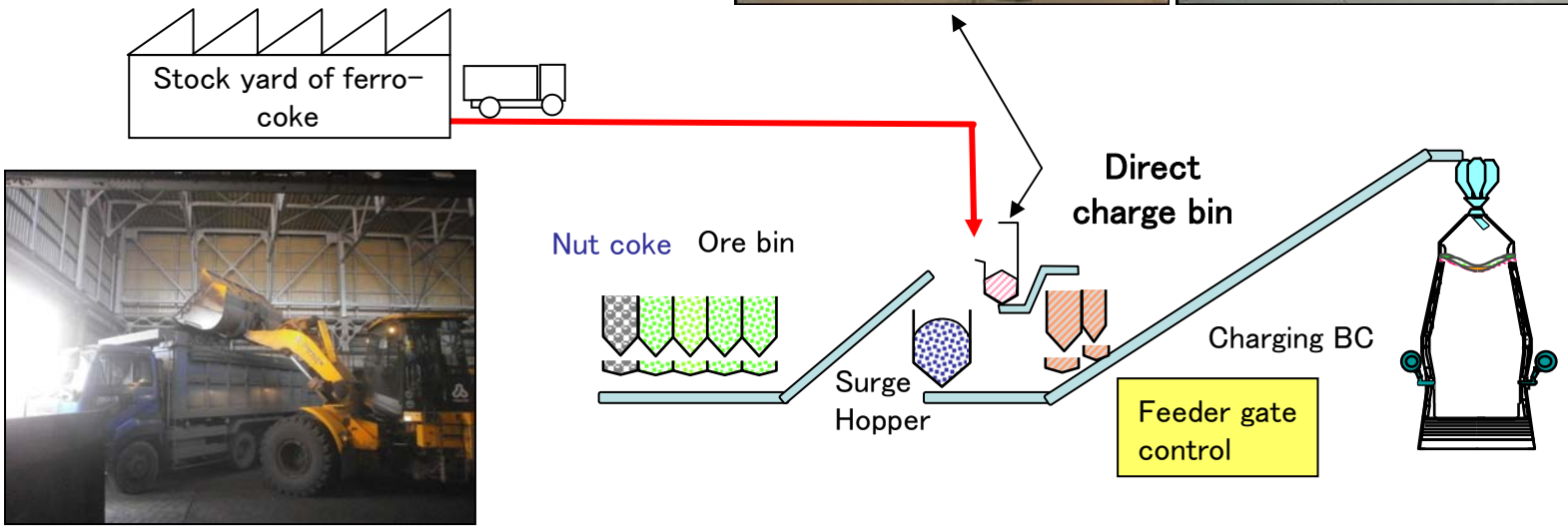
Charging of Ferro-coke to Chiba No.6 blast furnace

Ferro-coke of 2100 ton was transported by truck to the direct charge bin.

Five days charging test was carried out in March 2013.



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Concluding Remarks

The innovative inromaking process development was the final year of four years project in FY2012.

1) Optimization of production conditions of an innovative binder from Hyper coal process and evaluation at the pilot plant.
2) Successive operation of briquetting and carbonization was carried in the end of FY2011 and continuous production trials and charging tests to a blast furnace has successfully completed in FY 2012 to find process feasibility of the production process and technical subjects of blast furnace charging.
3) Development of charging condition for the optimum layer structure has been established at laboratory scale experiments.
4) Evaluation of blast furnace operation with the Ferro-coke at No.6 blast furnace in Chiba Works.