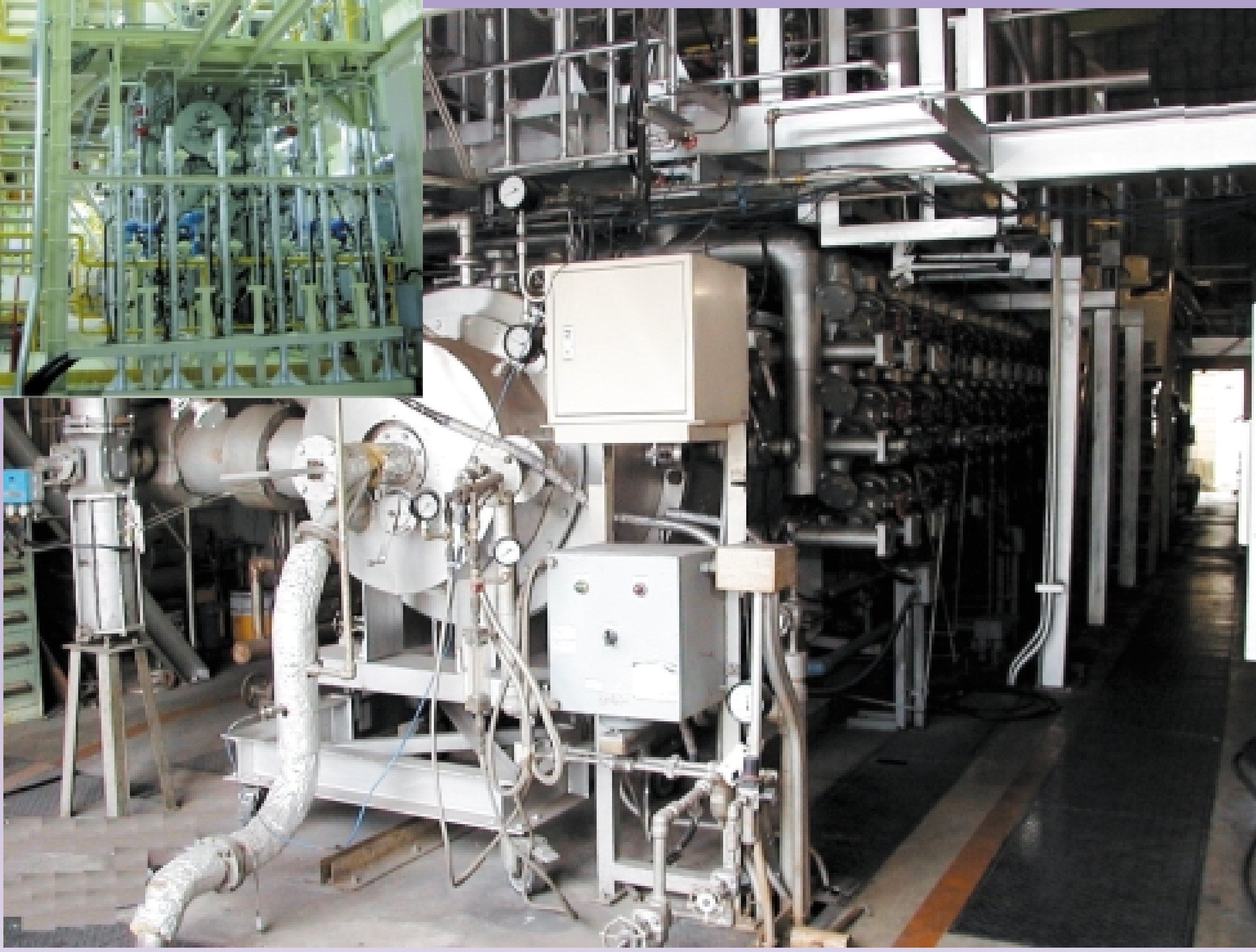
Improvement of Pulverized Coal Combustion Technology for Power Generation

-Enhancing Environmental Protection Technology and Reducing Power Generation Cost -



Central Research Institute of Electric Power Industry

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Editor : Hisao Makino (Dr.) Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

Hiromitsu Matsuda Senior Research Scientist
Chemical Energy Engineering Dept.
Yokosuka Research Laboratory

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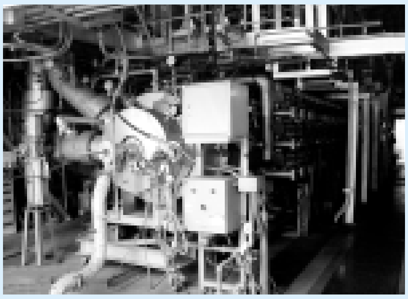
Cover explanation

MARINE furnace
Multi Fuel and Multi-burner Equipment for Advanced Combustion Research for the Development of Ideal No Pollutant Emission Technology (MARINE)



BEACH furnace
Basic Equipment for Advanced Combustion Technology using Horizontal Furnace and Single Burner (BEACH)

Chapter

1

General Features and Properties of Coal

Chapter 1 General Features and Properties of Coal ● Contents

1-1 Reserves of Coal and Distribution of Coal Mine ······ 3
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Hisao Makino (Dr.)
Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

1－1 Reserves of Coal and Distribution of Coal Mine

It is considered that plants, a origin of coal, were buried through earth orogenic movement and were changed into charcoal materials over the years and ultimately became coal. This process, called coalification, shows a tendency that the ratio of carbon in coal increases with the longer period. The calorific value which is the most important characteristics for use of coal as energy depends on coal properties and the coal has been widely used as fuel particularly since the Industrial Revolution. The coal that is currently used in Japan has a very high calorific value of about 7000 kcal/kg (29.5 MJ/kg).

One of the major features of coal is that coal has a much more the estimated amount of deposits than other fossil fuels. **Fig. 1-1-1** shows reserves of various fossil fuels (100 million tons of oil equivalent) (1). In the figure, proved coal reserves represent a technically and economically mining quantity. For reference, proven reserves mean a quantity in which coal is verified though there is no benefit in mining the coal under the current technology levels. On either reserve basis, it is confirmed that coal has extremely greater reserves than other fossil fuels, several times to 10 times in particular principal energy resources, for example oil and naturals gas. The minable years of the fuel, can be calculated by the comparison of proved reserves and the consumption of a fuel for a year will reveal. Coal is estimated to be available for more than 200 years in future and is considered to be important energy that can be supplied in the very long term.

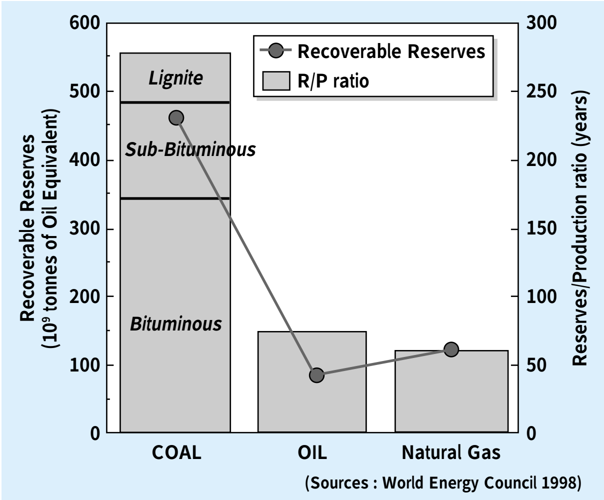

Fig.1-1-1 Recoverable Reserves of Fossil Fuel

Another feature of coal is that coal is produced widely from whole of the world. **Fig. 1-1-2** shows a proved reserve of coal by geographic area (100 million tons of bituminous coal equivalent). Obviously, coal is

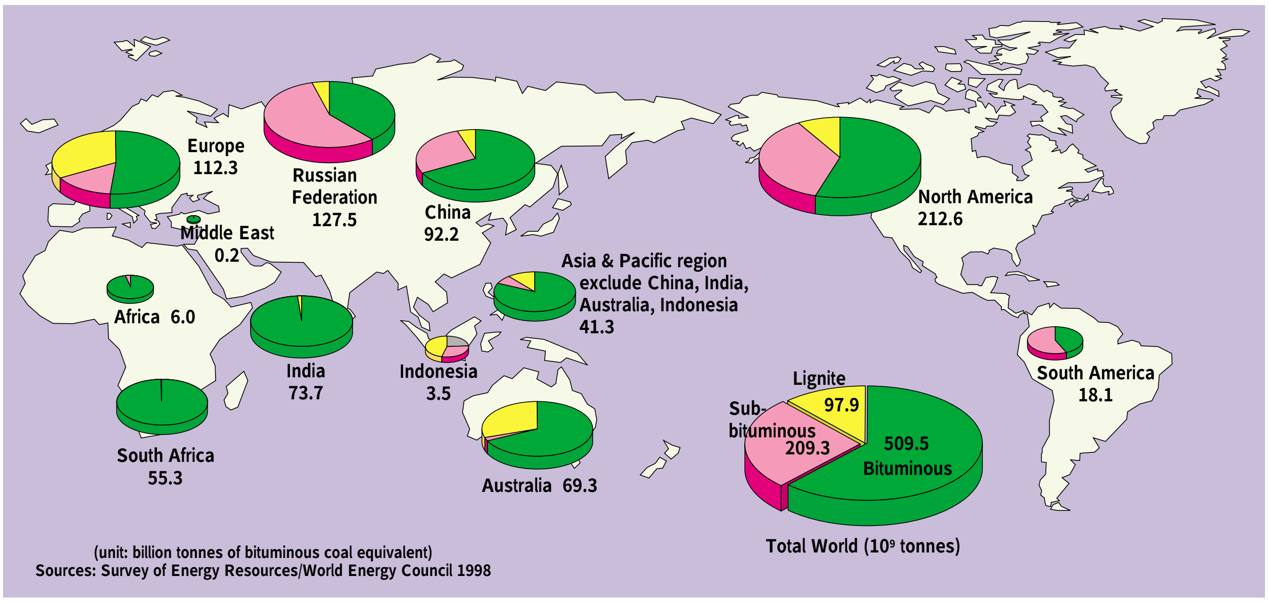

Fig.1-1-2 Proved Recoverable Researves of Coal in the World at End-1996

widely produced in various continents such as America, Asia, Europe, Africa and Australia. This indicates that coal can be expected more stable supply due to a proved reserve and a lot of supply nations.

The worldwide distribution of coal means that coal properties has a wide range too. The plant type varies with the difference of climate and soil characteristics which vary with the location of the world. The difference of the characteristics of plant and soil cause the difference of coal properties. Furthermore, the coal properties are affected from differences of the coalification years of coal, there is a very wide variety of coal kinds. In particular, coal is solid, so it is impossible to easily adjust the coal properties through refinery, for instance, oil processing, and it is basically necessary to develop optimal utilization methods according to the individual coal properties. This is one of the most important issues for coal utilization. Based on this viewpoint, it becomes very important to correctly identify the coal properties and logically classify coal kinds.

1－2 Method of Classification

A coal classification is usually based on the progress of coalification in which plants are changed into coal, and is called a classification on coalification ranks.

Our country employs a classification method that combines two factors as shown in **Table 1-2-1**. The anthracite and the bituminous coal sufficiently carbonized are classified on a fuel ratio (a weight ratio of fixed carbon to volatile matter), while the lignite, the subbituminous coal and the bituminous coal insufficiently carbonized are classified on their calorific values [2]. From this definition, coal with a higher carbonized rank will be higher fuel ratios and have higher calorific values. In the U.S., the American Society for Testing and Material (ASTM) uses a classification on a content ratio of volatile matter shown in **Table 1-2-2** that is based on that higher rank coal reduces volatile matter in coal [3]. Due to that increased volatile matter decreases a fuel ratio, this method is deeply related to that of Japan.

Table 1-2-1 Classification of coal (JIS M1002)

Classification: Class	Classification: Group	Calorific value (Dry ash free basis) kJ/kg (kcal/kg)	Fuel ratio	Agglomerating character
Anthracite (A)	A_1	—	4.0<	non agglomerating
	A_2			
Bituminous (B, C)	B_1	35,160		High agglomerating
	B_2	(8,400)		
	C	33,910≦35,160> (8,100≦8,400>)	—	agglomerating
Sub-bituminous (D, E)	D	32,650≦33,910> (7,800≦8,100>)	—	Low agglomerating
	E	30,560≦32,650> (7,300≦7,800>)	—	non agglomerating
Lignite (F)	F_1	29,470≦30,560> (6,800≦7,300>)	—	non agglomerating
	F_2	24,280≦29,470> (5,800≦6,800>)	—	

Table 1-2-2 Classification of coal (ASTM D388)

Glass / Group	Fixed carbon limits (%) (Dry ash free basis)		Volatile matter limits (%) (Dry ash free basis)		Calorific value limits (Btu/lb) (Moist ash free basis)		Agglomerating character
I . Anthracitic							
1. Meta-anthracite	98			22	—	—	
2. Anthracite	92	98	2	8	—	—	nonagglomerating
3. Semianthracite	86	92	8	14	—	—	
II . Bituminous							
1. low volatile bituminous coal	78	86	14	22	—	—	
2. Medium volatile bituminous coal	69	78	22	31	—	—	commonly
3. High volatile A bituminous coal	—	69	31	—	14,000		agglomerating
4. High volatile B bituminous coal	—	—	—	—	13,000	14,000	
5. High volatile C bituminous coal	—	—	—	—	11,500	13,000	
					10,500	11,500	
III. Subbituminous							agglomerating
1. Subbituminous A coal	—	—	—	—	10,500	11,500	
2. Subbituminous B coal	—	—	—	—	9,500	10,500	
3. Subbituminous C coal	—	—	—	—	8,300	9,500	
IV. Lignitic							nonagglomerating
1. Lignite A	—	—	—	—	6,300	8,300	
2. Lignite B	—	—	—	—	—	6,300	

1−3 Coal Properties

Various analysis methods for evaluation of coal properties are used. The principal methods include proximate and ultimate analyses [(4)~(7)].

In the proximate analysis on coals, the content of moisture, ash and volatile matter of a coal sample dried in the air are measured and the fixed carbon content as a remained part is calculated. Increased moisture content reduces calorific values and also causes the decrease of ignition characteristics. Ash is the incombustible component of coal and consists of minerals in plants and soil mixed in the process of coalification. Increased ash content not only reduces calorific values but also increases coal ash generation after coal utilization, which causes a problem of its disposal. Both of volatile matter and fixed carbon are combustible, and volatile matter is easily devolatized at high temperatures and burns very easily. On the other hand, fixed carbon is consisted of solid carbon and burns slowly, and is easy to remain as unburnt carbon after the combustion. A ratio of fixed carbon to volatile matter content is defined as to a fuel ratio. In general, a higher rank coal has high fixed carbon content while the volatile matter content reduces, which causes the increase of the fuel ratio.

In ultimate analysis on coals, the content of carbon, hydrogen, oxygen, total sulfur, combustible sulfur, nitrogen and phosphorus are measured. Here, carbon is the main component of combustible in all coals, but the proportion of hydrogen becomes higher in coal lower carbonized. Similarly, the content of oxygen becomes higher in a lower rank coal. Total sulfur content means all sulfur contained in coal while combustible sulfur results from the reduction of an amount of sulfur remaining after coal being kept in an electric heated furnace for 2 hours at 815 ± 10 ℃ from total sulfur. These values are also required to identify coal properties and make calculations related in combustion and a ratio of carbon to hydrogen or oxygen to carbon is used as one of indicators on carbonization similar with a fuel ratio. Coal containing more carbon will increase CO_2 emissions deeply related to global warming. Coal containing a higher proportion of sulfur will generate sulfur oxides, so attention should be paid to corrosion of equipment and environmental protection. In addition, due to that coal with a higher content of nitrogen will easily produce nitrogen oxides, considerations should be given to environmental protection.

There are many kinds of coal and the properties of coal are usually classified by coal mine. **Table 1-3-1** shows property examples of coal produced from typical coal mine in various countries. It is found that coal properties are greatly different with coal mine.

Analysis methods to identify coal properties include a maceral analysis on which the area in plants are analyzed, in addition to proximate and ultimate analyses. General properties of coal can be well identified on proximate and ultimate analyses.

Table 1-3-1 Coal properties

Country	Item / Coal	Calorific value [MJ/kg]	Total moisture*1 [%]	Proximate analysis [%]*2				Fuel ratio	Ultmiate analysis [%]*2					
				Moisture	Ash	Volatile	Fixed carbon		Carbon	Hydrogen	Nitrogen	Oxygen	Sulfur	Total sulfur
Australia	Drayton	28.4	9.9	3.4	13.3	34.5	48.8	1.4	71.1	4.9	1.4	8.1	0.8	0.9
	Newlands	28.0	8.4	3.0	15.0	26.6	55.4	2.1	69.1	4.1	1.4	7.0	0.4	0.4
	Hunter Valley	29.6	8.0	3.5	11.2	34.0	51.3	1.5	72.7	4.5	1.6	9.3	0.3	0.6
	Lemington	28.4	9.9	3.7	13.0	32.3	51.0	1.6	71.9	4.5	1.5	8.2	0.4	0.4
	Warkworth	28.9	9.6	3.6	11.8	32.8	51.8	1.6	69.1	4.6	1.5	8.9	0.4	0.4
China	Datong	29.6	10.1	5.1	7.0	28.1	59.8	2.1	78.2	4.5	0.8	8.8	0.6	0.7
	Nan tong	28.4	8.0	4.0	16.0	36.2	43.8	1.2	83.0	5.2	1.6	9.8	0.5	0.8
Canada	Obed Marsh	25.3	8.0	5.0	14.0	37.0	44.0	1.2	64.3	4.6	1.5	14.3	0.3	0.6
	Coal Valley	26.1	11.3	6.4	10.7	33.5	49.3	1.5	69.7	4.7	0.9	13.1	0.1	0.3
Indonesia	Satui	28.8	9.5	5.1	7.9	41.9	45.1	1.1	72.4	5.5	1.2	11.9	0.7	0.8
South Africa	Ermelo	27.8	7.6	3.5	12.9	31.4	52.2	1.7	72.0	4.4	1.7	7.9	0.6	0.8
	Optimum	28.5	8.2	3.8	10.7	32.4	53.1	1.6	72.9	4.9	1.6	9.1	0.5	0.6
USA	Pinacle	27.2	8.3	4.6	13.4	40.9	41.1	1.0	68.2	5.6	1.4	0.3	0.6	0.7
	Plato	25.1	9.8	6.0	9.3	41.8	42.9	1.0	72.8	5.5	1.5	11.2	0.7	0.9

*1 : received basis
*2 : air dryed basis

References

(1) Survey of Energy Resourced 1998 (in Japanese)
(2) JIS M1002
(3) ASTM D388
(4) JIS M8810
(5) JIS M8811
(6) JIS M8812
(7) JIS M8813

Chapter

2

Overview of Coal Utilization Systems

Chapter 2 Overview of Coal Utilization Systems ● Contents

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2-2 Characteristics of Pulverized Coal Combustion Power Plant System 12

Hiromi Shirai (Dr.)
Senior Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

2-1 Various Power Generation System Using Coal

Power generation systems using coal include a steam power generation system on which electric power is generated by steam produced by heat at coal combustion and a combined cycle power generation system on which electric power is generated by steam produced by waste heat after combustion gas is directly introduced to a gas turbine to generate electric power. In addition, coal reaction methods used at these generation systems are fixed bed, fluidized bed and entrained bed methods.

2.1.1 Coal Reaction Methods

Coal combustion or gasification reaction methods include fixed bed, fluidized bed and entrained bed methods as shown in **Fig. 2-1-1**, and a grain size of coal becomes smaller in this order, while the gas flow velocity in equipment becomes higher. In the fixed bed, input block coal statically reacts with air for combustion or gasification. In the fluidized bed, input grain of coal forms a layer of fluid state with air and is burned or gasified within the layer. In the entrained bed, pulverized fine coal flows with air, and is burned or gasified.

Typical example on these combustion methods is explained as follows. As one of the fixed bed combustion methods, a stoker combustion method is most used on which block coal is placed on a conveyor type combustor and burned while being moved. The stoker method has an advantage in its capability to directly use block coal, but requires a lot of excess air and is low boiler efficiency. Furthermore, the method makes the scaling up of a boiler difficult and applies limitations on its scale.

In the fluidized bed combustion method, grain of coal is injected into a layer of lime stone and silica fluidized with airflow and is combusted. This method provides better heat transfer within the fluidized bed, so the size of a boiler can be reduced. Furthermore, due to the combustion at low temperatures of 800～900℃, this methods generate less NOx and can apply in-furnace desulfurization by injecting lime stone into the boiler. The method, however, has some subjects to be solved, such as that attention should be paid to the

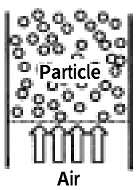
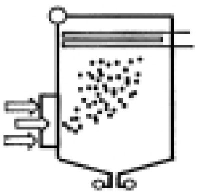
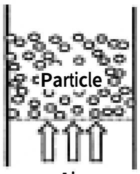
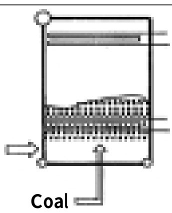
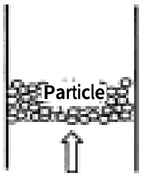
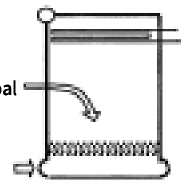
Principle			Outline of boiler		
Entrained Bed	Fine / Fast			Diameter Under 200 mesh ratio 70% Velocity 10～15m/s Temperature 1,400～1,500℃	Pulverized coal Boiler
Fluidized Bed	↑ ↑ Coal particle / Air velocity ↓ ↓			Diameter <10mm Velocity 1.4～10m/s Temperature 800～900℃	Fluidzed bed boiler
Fixed Bed	Coarse / Slow			Diameter <30mm Velocity 0.8～1.5m/s	Stoker boiler

Fig. 2-1-1　Combustion systems and outline

erosion of boiler tube and boiler walls by fluidized particles, that large draft is required and that considerations should be given to reuse of coal ash mixed with gypsum by in-furnace desulfurization.

One of the entrained bed combustion methods is a pulverized coal combustion on which pulverized coal and air is ejected with a burner and fired. As this method use pulverized coal of 30～40 μ m as median diameter, it provides high combustion efficiency and less excess air. Furthermore, As it allows the easy scaling up of a boiler, this pulverized coal combustion method is now mainly used in electric power industries.

In the gasification methods, in principle, the same methods as in the combustion systems are used. Based on the methods, combustible gas such as carbon monoxide (CO) and hydrogen (H_2) is produced with oxgen or air as gasification agent. Currently, the gasification methods mainly developed is an entrained bed gasification that is easy for the scaling up as same as that of combustion.

2-1-2 Power Generation Systems

(1) Steam Power Generation

Fig. 2-1-2 shows the steam power generation system as a typical example using a pulverized coal combustion method. In this method, heat generated by combustion is transferred into steam and use a steam turbine to generate electric power. NOx, dust and SOx generated in combustion of pulverized coal are removed with a De-NOx unit, an electrostatic precipitator and a desulfurization unit located downstream, and clean flue gas is released from a stack. Also in a fluidized bed combustion method, electric power is generated with a steam turbine as done in the pulverized coal combustion method, but the fluidized bed combustion power generation system differs from the pulverized coal combustion power generation system in a burner and a flue gas treatment system, such as no need for desulfurization unit, due to that desulfurization is done with lime stone within a fluidized bed boiler.

(2) Combined Cycle Power Generation System

The combined cycle power generation system is a technology that is being developed to improve the power generation efficiency. Integrated coal gasification combined cycle power generation (IGCC) is a representative generation system on which as shown in **Fig. 2-1-3**, combustible gas generated in a gasifier is burned after being cleaned, and this high temperature and high pressure combustible gas is supplied to a gas turbine. Waste heat of the gas discharged from gas turbine is also used to produce steam to the steam turbine, which increases generation efficiency. Furthermore, integrated coal gasification fuel cell combined power generation (IGFC) is under consideration on which coal gas is used as fuel for a molten carbonate fuel cell (MCFC) and a solid oxide fuel cell (SOFC) to generate electric power, and waste heat generated is also used in a steam turbine to produce electric power.

On the other hand, in fluidized bed combustion power generation system, one at evolved system is

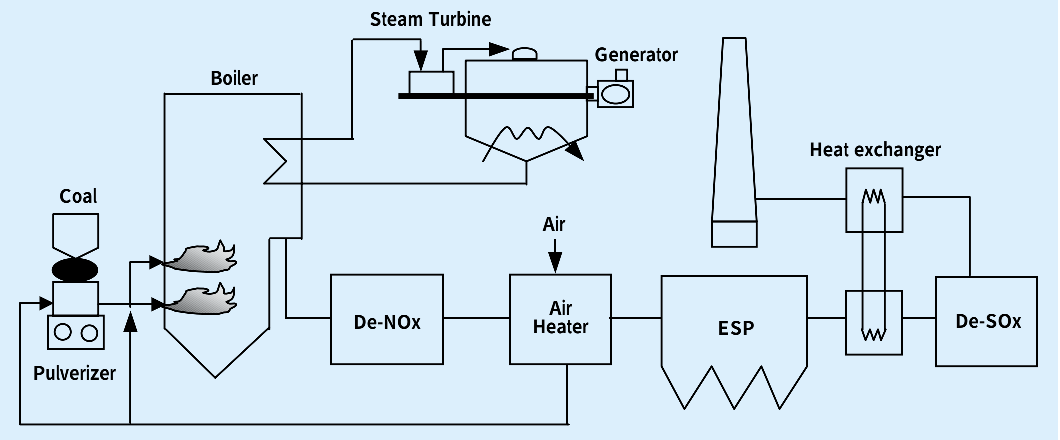


Fig. 2-1-2 Pulverized coal combustion power generation system

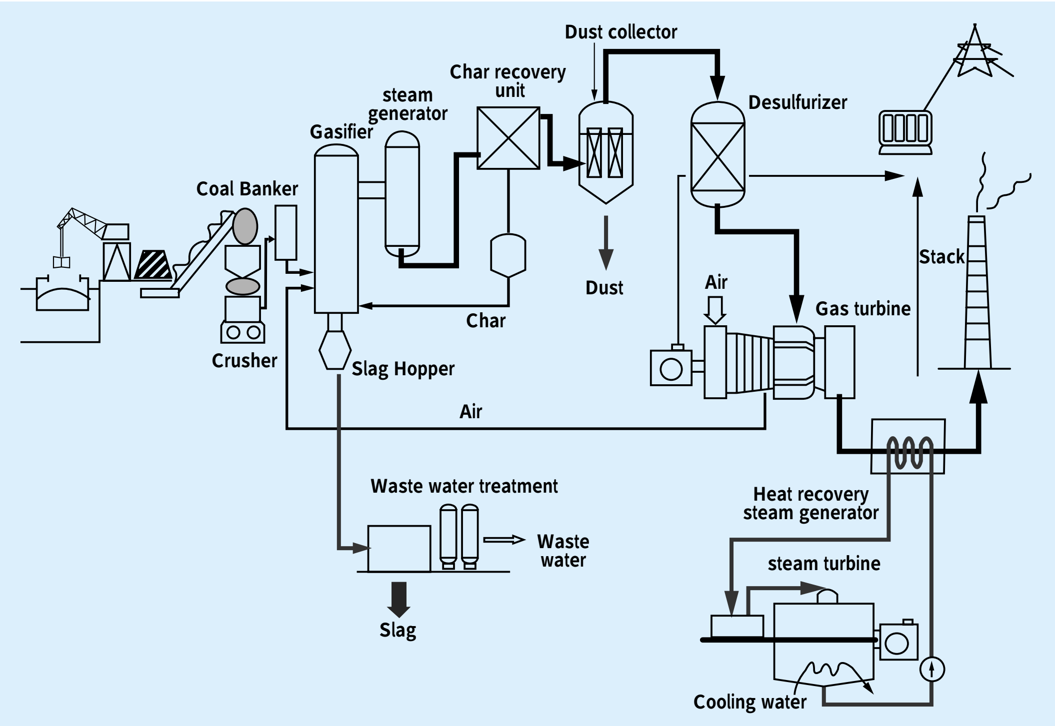


Fig. 2-1-3　Integrated coal gasification combined cycle power generation system

a pressurized fluidized bed combustion combined cycle power generation system (PFBC). In this system, 800℃ or more high temperature flue gas generated at pressurized condition is fed to a gas turbine to generate electric power, and waste heat at an outlet of a gas turbine and combustion heat in a fluidized bed is converted to steam, and the steam is also used in a steam turbine to produce electric power. Furthermore, an advanced pressurized bed combustion combined cycle power generation (A-PFBC), which is a combination of this system and a pressurized fluidized bed gasifire, is being studied.

In electric power industries, a pulverized coal combustion power generation system is mainly employed, and one unit on a fluidized bed combustion power generation system and three units on a pressurized fluidized bed combustion combined cycle power generation system have been operating for electric utilities.

On the other hand, a coal gasification combined cycle power generation system is now being developed toward commercialization, and a demonstration unit (250 MW) is scheduled to commence commercial operation in 2007 in Japan. Coal gasification fuel cell power generation and advanced pressurized fluidized bed combustion combined cycle power generation systems are under development.

Under these circumstances, a pulverized coal combustion power generation system is considered to perform the key part of power generations, and faces an important challenge sophistication of technologies aiming at cost reduction.

2－2 Characteristics of Pulverized Coal Combustion Power Plant System

A pulverized coal combustion power plant system is most used for coal fired power plant. As coal has a lower heat value and contains more ash, sulfur and nitrogen than oil, the system configuration for pulverized coal combustion power plant becomes more complex than that for oil-combustion power plant. **Fig. 2-2-1** shows the details on a power plant system in a pulverized coal combustion power plant. The pulverized coal combustion power plant has coal stock equipment, pulverizer, boiler, flue gas treatment unit and ash treatment unit. The characteristics by equipment are described as follows.

2-2-1 Coal Stock Equipment

Coal that was transported by ship is stored in a coal stock yard or a silo. In order to prevent spontaneous combustion and coal particle dispersion of coal stocked, measures such as periodical watering to coal are taken in the yard. In addition, it is important to prevent spontaneous combustion in a silo where coal is stored. Spontaneous combustion easily occurs in coal rich in volatile matter content, and it is instructed that coal with a risk of spontaneous combustion should be consumed within a specified period. When a temperature in the silo is tend to rise, a coal circulation is done on which coal is exhausted from the bottom of the silo and fed into the top, in order to discharge coal heat.

2-2-2 Pulverizer

In a pulverized coal-combustion system, coal is transfered from coal stock equipment to a coal pulverizer (grinder), and fed to a burner after pulverizing. As a grinder, a vertical type roller mill is mainly used to pulverizes and dries coal, as shown in **Fig. 2-2-2**.

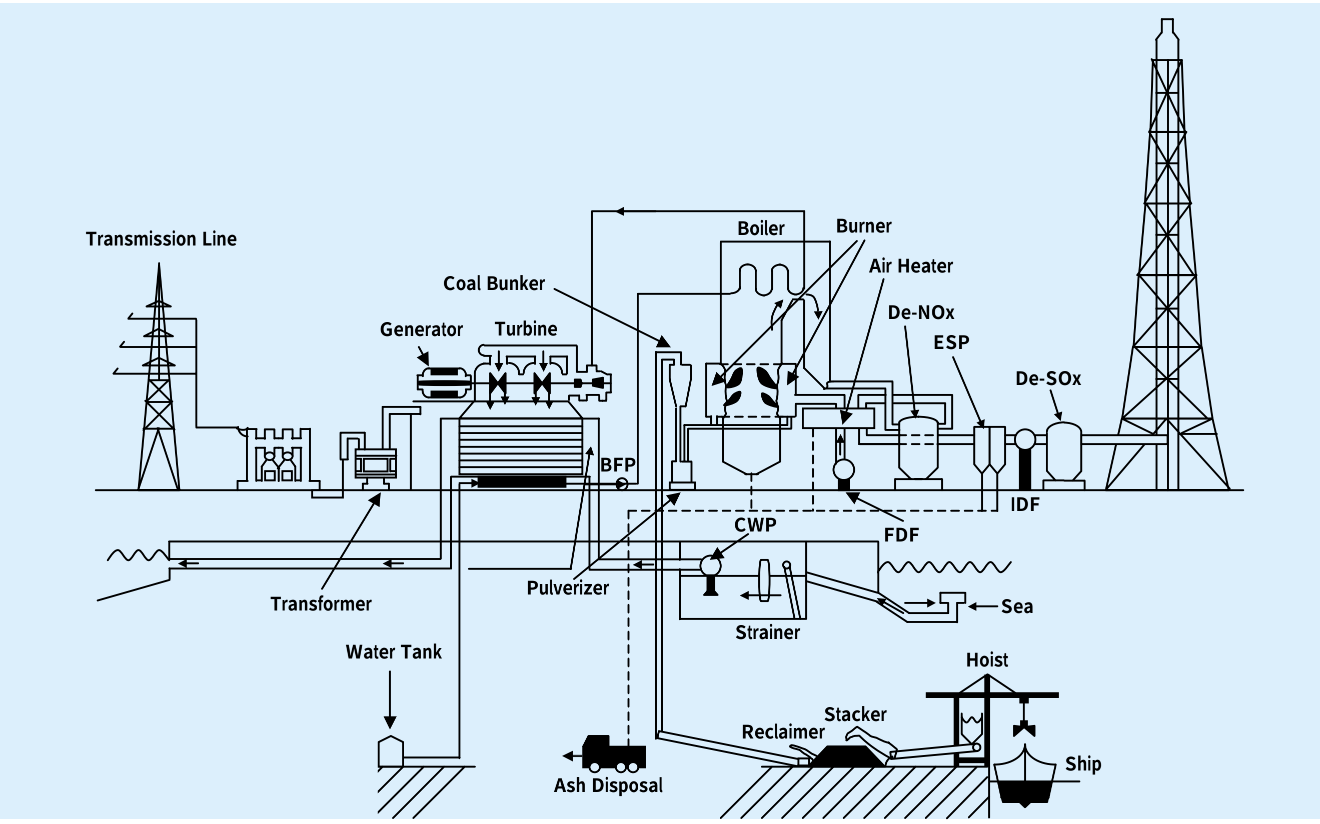


Fig. 2-2-1 Details on a pulverized coal combustion power Plant system

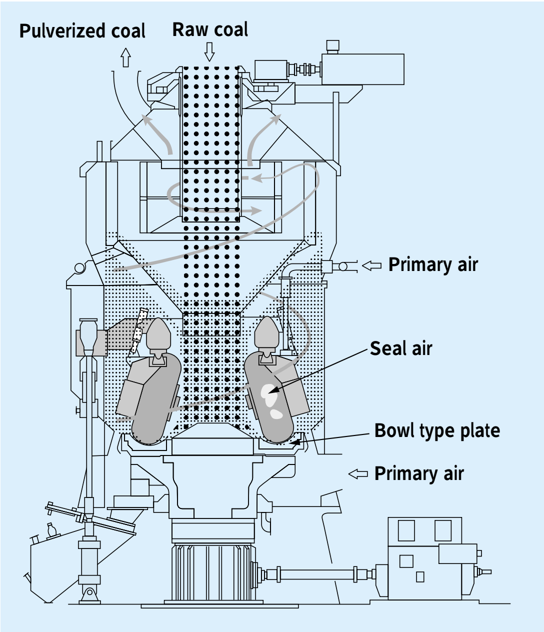


Fig. 2-2-2 Vertical type roller mill

This mill, which consists of a bowl type plate and several rollers, applies a steady pressure to the plate with the rollers and pulverizes coal by rotating the plate. Coal is supplied from the top, dried with about 200 ℃ air and pulverized, and is fed to a burner along with 70～80 ℃ air. A pulverized coal size is adjusted to a rev count of the plate, a roller pressure and a revolution speed of a propeller type rotating classifier installed at the outlet of the mill and reaches penetration mass present of under size of 200 mesh (75 μ m), 75～90 %. The operating condition of this mill is set on coal grindability, and in general, a rev count of the plate and a roller pressure are raised for harder coal.

2-2-3 Boiler

A boiler is a system that transforms heat into steam, and pulverized coal combustion boiler is 1.5 to 2 times as large as an oil-combustion boiler with the same power plant. This is caused by the reason that heat input value per boiler capacity must be reduced in pulverized coal fired boiler because coal has a low combustion reaction rate and the prevent of adhesion ash to a boiler wall and a steam tube.

Pulverized coal is ejected into a boiler from the center of a burner along with carrier primary air and is burned by ejecting secondary and tertiary air. In addition, in order to reduce NOx, a two-staged combustion method is used on which an air injection point is installed downstream from a burner, and also the supplied air to the burner is reduced.

Number of installed burners is decided according to a boiler and a burners capacity. The setting configuration methods of each burners include:

① Burners are placed front and back a boiler (opposed firing).

② Burners are placed at four corners of a boiler (corner firing).

In a boiler, melted ash during coal combustion is attached to a boiler wall and heat-transfer tube, which may reduce heat transfer and increase pressure loss of boiler. This phenomenon is called slugging. In addition, low devolatilization temperature component such as sodium condenses and is attached to a steam superheater, which may cause reduction of heat transfer and increase of pressure loss, and this phenomenon is called fouling. As slugging and fouling are closely related to ash properties, guidelines to prevent these phenomena are defined for each boiler.

2-2-4 Flue Gas Treatment Unit

As a flue gas at an outlet of a boiler contains dust, NOx and SOx, a flue gas treatment unit is installed in order to remove them. A De-NOx unit uses mainly a selective catalytic reduction method (SCR method) on which NOx is reacted with ammonia on a catalyst at about 350 ℃ and decomposed into nitrogen and vaporized moisture. After De-NOx, an electro static precipitator removes fly ash, and a desulfurization unit removes SOx after cooling it. A desulfurization unit generally uses a lime stone-gypsum method on which lime stone slurry is utilized to absorb SOx and recover it as gypsum.

2-2-5 Wastewater Treatment Unit

Wastewater from power plants include domestic wastewater, oil contained wastewater, general wastewater and wastewater at desulfurizer. As these wastewater differs in contents such as suspended solid (SS) including gypsum and fly ash, oil and heavy metal, wastewater is treated through a complicated treatment system. These water are separately treated, and finely fed to filter and absorber.

In a large-scale treatment system for general wastewater and wastewater at desulfurizer, firstly, suspended solid and heavy metal are settled in a coagulating sedimentation tank. After their sedimentation, fine particles are removed through a filter and substances involving chemical oxygen demand (COD) are removed through an absorber, using activated charcoal, and then discharged. In addition, in order to remove fluorine, the salt of Aluminum or Calcium and fluoride are added in the tank.

Chapter 3

Developments and Research Subject of Pulverized Coal Fired Power Plant

Chapter 3 Developments and Research Subject of Pulverize Coal Fired Power Plant ● Contents

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3-2 Subjects Toward the Development of Advanced Pulverized Coal Fired Power Plants 19

Mikio Sato (Dr.)
Senior Research Scientist
Research Coordinator
Yokosuka Research Laboratory

Hisao Makino (Dr.)
Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

3－1 Developments of Pulverized Coal Fired Power Plant

Power plants in Japan had re-started as a domestic coal fired boiler after the second world war, and had promoted the scaling up of an larger capacity oil fired boiler since the late 1950s. After the oil crisis in 1973, LNG-fired and overseas coal fired power plants with large capacity have been main power generation system. **Table 3-1-1** shows developments of pulverized coal fired thermal plants in our country and related situation.

Looking back the postwar recovery of coal fired power generation, a system for one boiler drum per one unit was first employed in the Onoda Thermal Power Plant Unit 5 (160 t/h, 6.7 MPa, 490 ℃), the Chugoku Electric Power Co., Inc., in 1953. The Onoda No.5 and No.6 units, in which domestic coal was used by blending, became a model for advanced domestic low rank coal fired thermal power plants. In the late 1960s, the main fuel for new thermal power plants was shifted from coal to oil which is economically efficient.

Table. 3-1-1 Developments of pulverized coal fired power plants and related other information

FY	Development of Coal fired power plant	Related information
1953	Chugoku EPC's Onoda No.5 unit first employed one boiler drum per one unit system	
1962		A total output of thermal power generation exceeded that of hydro power generation
1963	EPDC's Wakamatsu No.1 and 2 units were built in order to utilize low rank coal yielded from the Chikuho coal mine	"Low concerning regulation of dust emissions" was established
1966		Electrostatic precipitator was introduced
1968		"Air pollution Control Low" was established
1973		Oil crisis
		Flue gas desulphurization equipment using a lime stone-gypsum process was introduced
		"NOx emission control low" was established
1977		Denitrification equipment with a selective catalytic reduction process was introduced
1979		The IEA's resolution for banning oil fired power plants
1981	EPDC's Matsushima No.1 and 2 units (538/538℃) which introduced the first overseas coal fired super critical pressure power plant in our country, started to operate	
1985	Hokaido EPC's Tomato-Atsuma No.2 unit (538/566℃) first employed the overseas coal fired variable pressure operation system	
1990	EPDC's Matsuura No.1 unit (538/566℃) first employed the 1000MW coal fired power plant	
1991	Hokuriku EPC's Tsuruga No.1 unit employed 566℃ main steam temperature	
1992		United Nations/Conference on Environmental Development (Rio Summit) was hold
1993	Chubu EPC's Hekinan No.3 unit first employed 593℃ reheater steam temperature	
1995		COP1 was hold in Bonn
1997		COP3 was hold in Kyoto
1998	Chugoku EPC's Misumi No.1 unit and Tohoku EPC's Haramachi No.2 unit employed 600/600℃ steam temperature	
2000	EPDC's Tachibanawan No.1 and 2 unit employed 600/610℃ steam temperature	
2002	EPDC's Isogo No.1 unit employed 600/610℃ steam temperature with full variable pressure operation system	

During these years, a total output of thermal power generation exceeded that of hydro power generation in 1962, which caused an energy supply system of higher thermal and lower hydro power. Oil fired thermal power plants was introduced while low rank coal fired power plants were constructed. For instance, the Electric Power Development Company (EPDC) 's Wakamatsu No.1 and No.2 units (75 MW each) were built in 1963 in order to utilize low rank coal from the Chikuho yard.

Coal fired power plants, which were the main of power generation systems during the initial foundation period of electric industries, were economically vulnerable to tough competition, and was forced to hand their power mainstay to oil fired thermal plants. In addition, due to that coal fired power plant exhausts a great amount of environmental pollutants such as dust, SOx and NOx, it became difficult to construct new coal fired power plants.

In the development trend of protection technologies for these pollutants matter, an electrostatic precipitator with very high collection efficiency was introduced in 1966, under the "Law concerning regulation of dust emissions" established in 1963. Due to that the "Air Pollution Control Law" was established in 1968, in order to prevent the influence of SOx emissions, low sulfur fuel, high height chimneys and concentric stacks were used to control environmental impacts, and in 1973, a high-efficiency flue gas desulfuriation eguipment using a lime stone-gypsum process was introduced. In order to control NOx emissions, emission regulations were established in 1973, which promoted the improvement of a low NOx combustion technology and the use of a low NOx burner. In 1977, a denitrification equipment on a selective catalytic reduction process started to be introduced.

With the progression of protection technologies for these environmental pollutants, however, oil crisis in 1973, soaring oil prices in the wake of the oil crisis and the IEA's resolution for banning oil fired power plants in 1979, in principle, eliminated construction of new oil fired power plants and resulted in launching a policy for energy diversification. Fuel such as LNG and LPG was increasingly used while the construction of large-scale power plants using overseas coal such as Australian coal, Chinese coal and South African coal was planned. Furthermore, with the advancement of technical development for reduction of environmental pollutants, NOx and SOx emissions could be controlled, and the improvement of technologies to construct power plants more costly was progressed. For this reason, coal fired power plants were focused again, with the enhancing of movement away from oil energy.

In 1981, EPDC's Matsushima No. 1 and 2 units (each for 500 MW), which introduced the first overseas coal fired super critical condition in our country, started to operate, and afterwards, an era of large capacity and overseas coal fired power plants started in earnest. A variable pressure operation system was first employed in the Tomatoh-Atsuma No. 2 unit (600 MW) (1985, 538/566℃), Hokaaido Electric Power Co., Inc. After that, high temperature and high pressure of steam conditions started in the Tsuruga No. 1 unit (500 MW) (1991, 566/566℃), Hokuriku Electric Power Co., Inc., while a reheating steam temperature reached 593℃ in the Hekinan No. 3 unit (700 MW) (1993, 538/593℃), Chubu Electric Power Co., Inc. Further-more, the Chugoku Electric Power Co., Inc.'s Misumi No. 1 unit (1,000 MW) (1998, 600/600℃) and Tohoku Electric Power Co., Inc.'s Haramachi No. 2 unit (1,000 MW) (1998, 600/600℃) entered into an era of 600℃ of a main steam temperature and a reheating steam temperature. Following that, EPDC's Tachibanawan No. 1 and No. 2 units (each for 1,050 MW) employed 600/610℃ in 2000, and a pure transformation system was used in EPDC's Isogo New No.1 unit that commenced commercial operation in 2002 and employed a main steam temperature of 600℃ and a reheating steam temperature of 610℃.

As described above, pulverized coal fired power plants in Japan experienced the recovery period after the world war Ⅱ, transition to an energy mix of more thermal and lower hydro power, the oil crisis and the establishment of the "Air Pollution Control Law", and are currently at the top international level, accomplishing high power generation efficiency based on high temperature and high pressure steam conditions and providing environmental protection methods against dust, SOx and NOx.

3－2 Subjects Toward the Development of Advanced Pulverized Coal Fired Power Plants

As mentioned previously, technologies for pulverized coal fired power plant are highly reliable and established. The issues toward their upgrades will require "new advanced measuring technologies," and "numerical simulation of pulverized coal combustion," along with "diversification of coal class," "improvement of thermal efficiency," "enhancement of environmental protection technology," "improvement of operation technology for the load change."

In order to diversify coal rank, coal, which greatly differs in their properties, must be used, due to that coal supply in our country depends on import from various countries. From this viewpoint, it is important to establish a method on which the applicability of various kinds coal to existing power plants can be correctly evaluated in advance. In particular, in order to expand more energy resources and reduce fuel costs, it is required to enable to use coal with a wide range of properties such as low rank coal with low calorific value and high moisture content and high fuel ratio coal, which was less used in the past.

The greatest challenge for improvement of thermal efficiency is the improvement of steam conditions (high temperature and high pressure) as the conventional technology advancement. In our country, power generation efficiency is already reached to the highest worldwide level of steam conditions, and the advancement of high temperature materials is one of the most important issues in order to achieve higher generation efficiency in the future. In addition, reduction of power consumption of various auxiliaries equipment such as a fan and a mill is effective in enhancing the efficiency.

In order to improve the environmental protection, it will become more important to reduce nitrogen oxides (NOx), sulfur oxides (SOx) and particulate matters (coal ash). As shown in **Fig. 3-2-1**, in our county, technologies for environmental protections, which could attain the lowest emission level of environmental pollutants in the world, was already established, through air pollution problem after 1960s, but the requirement for environmental protection is becoming increasingly stringent. Based on these circumstances, it will become important in the future to improve conventional environmental protection technologies such as desulfurization, denitrification and dust collection. In particular, it is likely to become increasingly more important to develop and improve low NOx combustion technologies in consideration for cost reduction. In addition, recently, disposal of coal ash has become an important issue, and technologies to reduce unburned carbon concentration in fly ash, which control coal ash properties for utilizing easily are useful for cost reduction and, are energetically being developed.

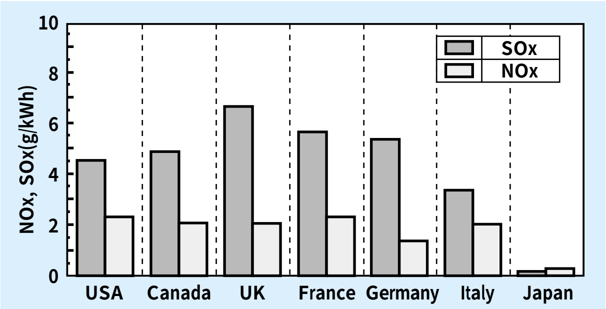

Fig. 3-2-1 Emissions of NOx and SOx from coal fired power plants in the world

These years, pulverized coal fired power plants are also increasingly required to control load variations for the demand of power supply, and attention is being given to their improvement of operation technology for load change. A pulverized coal fired burner becomes worse in stable combustion at low load, so it has become important to also develop technologies for improving the combustion stability. In addition, it has become important to make this technology combined with low NOx combustion technology in terms of environmental protection.

On the other hand, a coal combustion flame was difficult to control and strictly investigate due to being subject to extremely high temperature turbulent flow, and combustion equipment have been often designed and operated depending on an empirically engineering method. However, as it became necessary to develop various advanced technologies including development of advanced low NOx and low load combustion and use of extremely various coal kinds, it become desirable to apply new efficiency methods because traditional methods required a longer period to develop these technologies. As one of the methods, attention is given to an advance measuring technology using laser beam and a combustion status analysis technology based on numerical simulations that can quantitatively elucidate the combustion field and reflect the results in the development of more advanced combustion technologies. In the future, a method is also likely to become important, that can apply these technologies to an actual combustion flame and also that can improve their accuracy and lead to the improvement and modification of combustion technologies.

In this way, the investigations including many technical development subjects for more advanced pulverized coal fired power plants toward future are required from a very wide range of viewpoints.

Chapter 4

Adaptability Evaluation on Fuel for Pulverized Coal Fired Power Plants

Chapter 4 Adaptability Evaluation on Fuel for Pulverized Coal Fired Power Plants ● Contents

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Hisao Makino (Dr.)
Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

Hiromitsu Matsuda
Senior Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

4-1 Research Background

Currently, pulverized coal fired power plants use various imported coals from many countries. Australia coal represents 50 % or more of the total while Chinese, American and Indonesian coal represent 10 %, respectively. These countries have a lot of coalfields, and their coal properties greatly vary with individual coalfields. In addition, as new coalfields are being developed year by year, it is important to properly introduce various types of coal in terms of increased energy resources and reduced fuel costs.

In introducing new coal to Japan, we have to concern that its properties can be sufficiently applied to each power plant within an adjustable range of its operating conditions. Conventionally, when the power plants are designed, coal properties within an applicable range have been defined (the coal is called design coal), and coal those properties are in this range has been basically used. When using coal beyond the property range of design coal, the coal was introduced after preliminary verifying its characteristics through a combustion test in which the coal is burned in a test furnace modeled on an actual boiler. For this reason, preliminary evaluation required a lot of cost and time.

In order to develop a method to determine the possibility, applicability of various new coal types to an actual unit in a simple and correct, CRIEPI started to develop a method for estimating various coal characteristics when coal is used, based on only information concerning analysis values of coal properties and operating conditions in power plants.

In developing this technology, utilizing pulverized coal combustion test furnace (nicknamed "BEACH" furnace) in CRIEPI that can burn about 100 kg of coal per hour, the "Evaluation method for the adaptability of coal for power generation," which estimates emission features of NOx and unburned carbon in fly ash in this test furnace based on coal properties and combustion conditions, was established at first.

In conducting the evaluation of the influence of on coal properties of this method, various types of coal were burned under same combustion conditions to clarify a relation between emission characteristics and coal properties. On the other hand, in order to conduct the evaluation on the effects of burning conditions, combustion conditions on several coal types were changed to estimate emission characteristics of NOx and unburned carbon in fly ash.

Next, based on the impact evaluation method for coal properties and combustion conditions obtained from the "Evaluation method for the adaptability of coal for power generation," data collected from various actual power plants were evaluated, and a "Technology of extending applicable coals" was developed on which emissions of NOx and unburned carbon in fly ash are estimated from properties of available coal and combustion conditions.

4-2 Evaluation Method for the Adaptability of Coal for Power Generation

In determining whether to introduce various types of coal into actual units, the most important evaluation factors are emission characteristics of NOx and unburned carbon in fly ash. CRIEPI developed a evaluation method for the adaptability of coal for power generation to estimate emission characteristics of NOx and unburned carbon in fly ash when various types of coal are burned, using a coal combustion test furnace [1][2].

4-2-1 Impact Evaluation on Coal Properties

(1) Emission Characteristics of NOx

Concentrations of NOx generated from various types of coal under certain combustion conditions have a tendency for nitrogen compounds content (N content ratio) in test coal as shown in **Fig. 4-2-1**. With increased N content in fuel, NOx concentrations increase, which does not lead to a clear correlation between the content and concentrations. This is ascribable to that a rate on which N contained in fuel is converted to NOx (NOx conversion ratio) greatly varies with coal types. Hence, bases on a NOx conversion ratio (CR) defined in the following expression, the ease of the NOx generation from various types of coal can be clarified.

$$CR = NOx\ (\text{actual measured value}) / NOx\ (\text{calculated value}) \qquad (4\text{-}1)$$

Where,

NOx (actual measured value) : Actual measured NOx concentration (ppm)

NOx (calculated value) : NOx concentration (ppm) when N content in coal cnverts into 100 % NOx

Fig 4-2-2 shows a relation between conversion ratios and coal properties. In this figure a lower fuel ratio (FR) decrease a conversion ratio. Coal types with low FR contain a high proportion of well combustible volatiles, so the coal is significantly burned near a burner while a reducing atmosphere is immediately formed. As this reducing flame decomposes NOx, NOx concentrations can be considered to decrease. In addition, when a FR is common in various coal types, there is a trend that the lower fuel nitrogen content (FN) is, the higher the conversion ratio is. This is due to that higher FN increases NOx concentrations and accordingly conversion of N content to NOx is restricted.

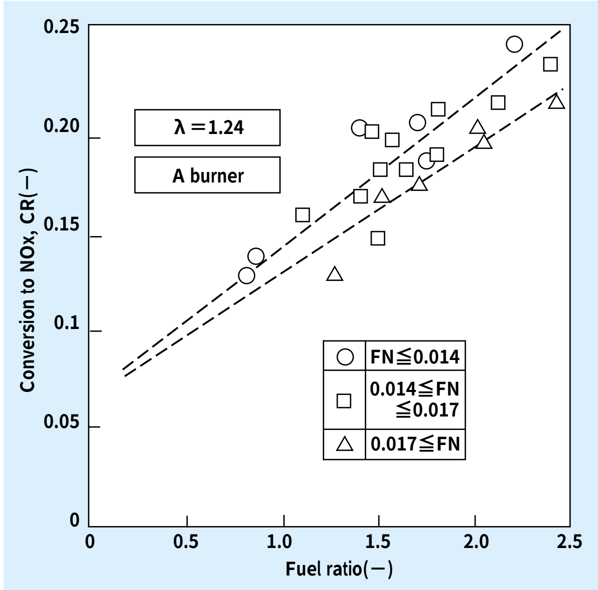


Fig. 4-2-2 Influence of fuel ration of coals on conversion to NOx of fuel nitrogen

Considering these relations, a NOx conversion ratio has a much better linear relationship on the ratio of FR to FN, providing a tendency shown in **Fig. 4-2-3**. When empirical formulas showing the relationship in the figure are calculated on a least square method, the following estimation expression for a NOx conversion ratio is determined for each burner.

$$CR = a_1 \cdot FR/FN + a_2 \qquad (4\text{-}2)$$

$$a_1 = 1.09 \times 10^{-3},\ a_2 = 6.77 \times 10^{-3}\ (\text{A burner})$$

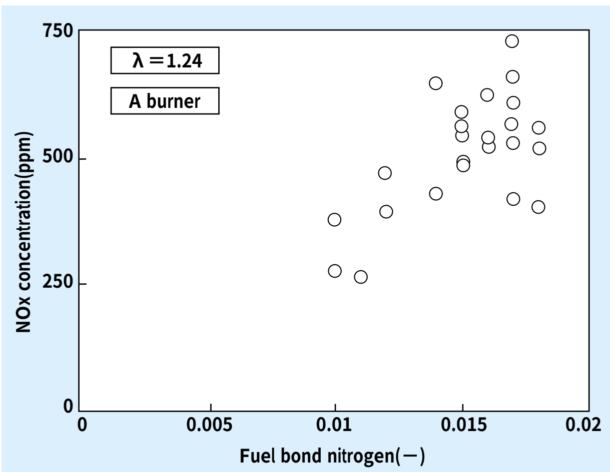


Fig. 4-2-1 Influence of fuel bond nitrogen on NOx concentration

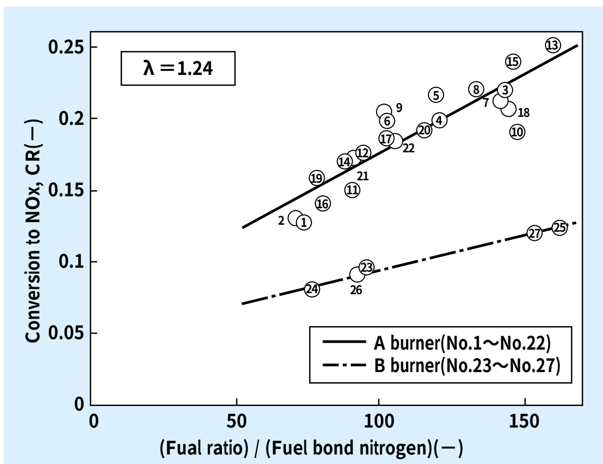


Fig. 4-2-3 Influence of (Fuel ratio) / (Fuel bond nitrogen) on conversion to NOx

$a_1 = 4.89 \times 10^{-4}$、$a_2 = 4.57 \times 10^{-2}$ (B burner)

Using the above expression, it will become possible to easily predict NOx concentrations in flue gas from the following expression.

$$NOx = \frac{1.60 \times 10^{-4}}{V_{dry}} (a_1 \cdot FR + a_2 \cdot FN) \quad (4\text{-}3)$$

Where,

V_{dry}: Flue gas corresponding to excess air ratio (m^3N/kg)

Fig. 4-2-4 compares estimated values for NOx concentrations determined from Expression (4-3) with actual measured concentrations and shows the very good agreement between the estimated and measured values. From this figure, it becomes clear that NOx emissions can be accurately predicted from coal properties under certain combustion conditions.

(2) Emission Characteristics of Unburned Carbon in Fly Ash

An in-ash unburned carbon concentration (Uc) in ash represents a weight ratio of combustible matter remaining in coal ash generated at coal combustion. As this concentration is affected by an ash content in coal and as well as coal combustibility, it is difficult to make direct evaluation on the combustibility from the concentration value. So, first, an unburned fraction (Uc*) of combustible matter in coal is calculated from the following expression, and the result is often used as an evaluation factor for coal combustibility.

$$Uc^* = \frac{A \cdot Uc}{(1 - A) \cdot (1 - Uc)} \quad (4\text{-}4)$$

Where,

A : Ash content ratio in coal

Uc: Unburned carbon in fly ash

Uc*: Unburned fraction

Fig. 4-2-5 shows a relationship between a fuel ratio, an indicator for coal combustibility and an unburnd fraction. The relationship slightly varies with coal types, but a liner relationship between the two establishes itself. When the relationship in Fig. 4-2-5 is determined on a least square method, the following expression of (4-5) is obtained.

$$Uc^* = b_1 \cdot FR + b_2 \quad (4\text{-}5)$$

Where,

$b_1 = 2.50 \times 10^{-3}$, $b_2 = 2.20 \times 10^{-4}$ (A burner)

$b_1 = 2.95 \times 10^{-2}$, $b_2 = 2.29 \times 10^{-2}$ (B burner)

On the base of the above relationship in Expression (4-5), if coal properties can be determined unburned fraction can be estimated. Furthermore,

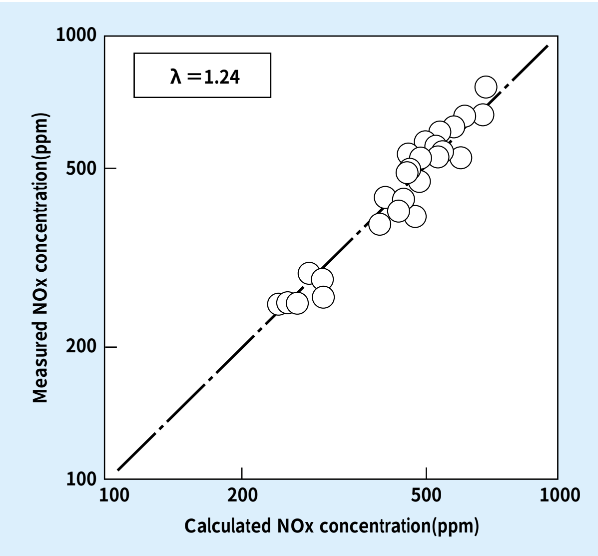


Fig. 4-2-4 Calculated and measured NOx concentration

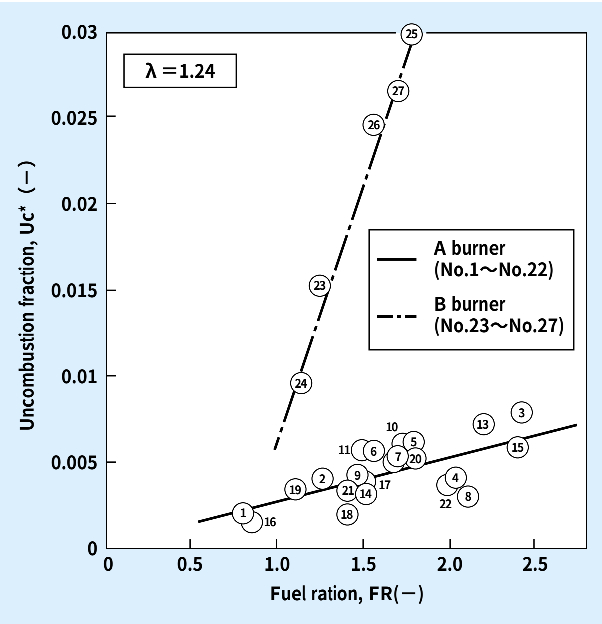


Fig. 4-2-5 Relation of Fuel Ratio and Unburnd fraction of coals

using an ash content ratio and the expressions of (4-4) and (4-5), it becomes possible to determine unburned carbon concentrations in ash. A relation between calculated unburned carbon concentrations in ash and actual measures values is shown in **Fig. 4-2-6**. This relation represents slightly greater dispersion than that for NOx concentrations. It is considered that this is due to the existence of affecting factors such as a size distribution and fine structure of coal, which are not included in coal properties used for consideration by CRIEPI. It will now become important to examine these effects in detail and enhance the accuracy of data.

(3) Emission Characteristics at Blended Coal Combustion

By using blended coals, which have different properties, there is a possibility of improving each coal type's problems. For instance, when two types of coal with different NOx concentrations are blended on a different blend ratio and burned, a relationship between nitrogen content in coal determined from their blend ratio and a ratio of N conversion to NOx is shown in **Fig. 4-2-7**. The ratio of nitrogen content continuously change by blending, so the effect of the N content on a NOx conversion ratios become clearer than that when a lot of coal is burned individually. For instance, focusing on Ipswich coal and Bloomfield coal, each fuel ratio represents 1.7 and 1.6, respectively, almost the same value, and only a N content ration is

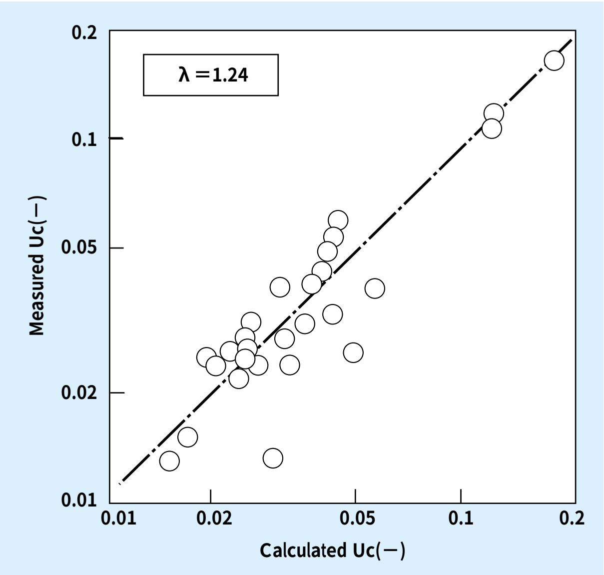


Fig. 4-2-6 Measured and calculated fraction of carbon content in fly ash

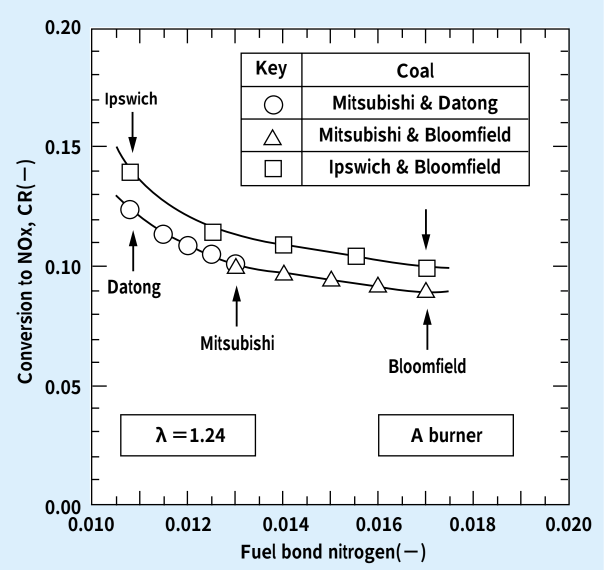


Fig. 4-2-7 Influence of fuel bond nitrogen on conversion to NOx for the blended coal combustion

considered to affect a conversion ratio. Also under these conditions, a trend is clearly demonstrated that a NOx conversion ratio decreases according to the increase of a N content ratio, as a trend indicated when non-blended coal is burned.

Therefore, when identifying a relationship between a fuel ratio/N content ratio in fuel and a conversion ratio on blended coal properties also at its combustion, as in Fig. 4-2-3, the relationship is shown in **Fig. 4-2-8**. Also when blended coal is burned, a better liner relationship between a fuel ratio/N content ratio in fuel and a NOx conversion ratio is shown as at combustion of non-blended coal. Also under this condition, it becomes clear that NOx concentrations can be estimated from coal properties.

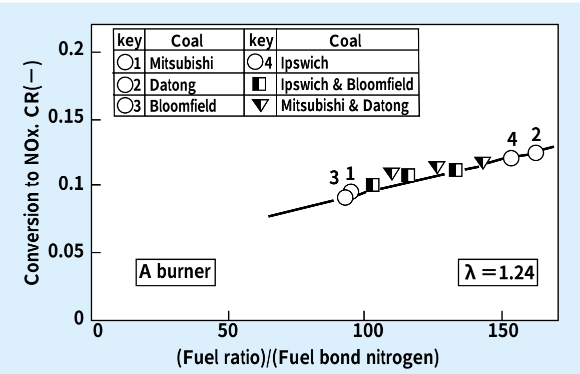


Fig. 4-2-8 Influence of (Fuel ratio)/(Fuel bond nitrogen) on conversion to NOx for the blend coal combustion

On the other hand, unburned carbon concentrations in fly ash at blended coal combustion were examined based on the following process. Supposing that a combustion process for blended coal is the same as that at combustion of non-blended coal due to combustion conditions such as a furnace thermal load and an excess air ratio are the same, coal ash emitted at blended coal combustion is made up of blended coal ash generated at blended coal combustion according to a blended coal ratio. In this case, for instance, unburned carbon in fly ash when n-type coal is mix burned on a blended coal ratio Xi (weight ratio) is shown from the following expression.

$$Uc = \sum_{i=1}^{n}\left(X_i \cdot A_i \frac{Uc_i}{1-Uc_i}\right) / \sum_{i=1}^{n}\left(\frac{Xi \cdot Ai}{1-Uc_i}\right) \quad (4\text{-}6)$$

Where,

Uc: Unburned carbon in fly ash at blended coal combustion

Xi: Coal (i) blending ratio (weight ratio)

Uci: Unburned carbon in fly ash at non-blended coal combustion

Ai: Ash content in coal

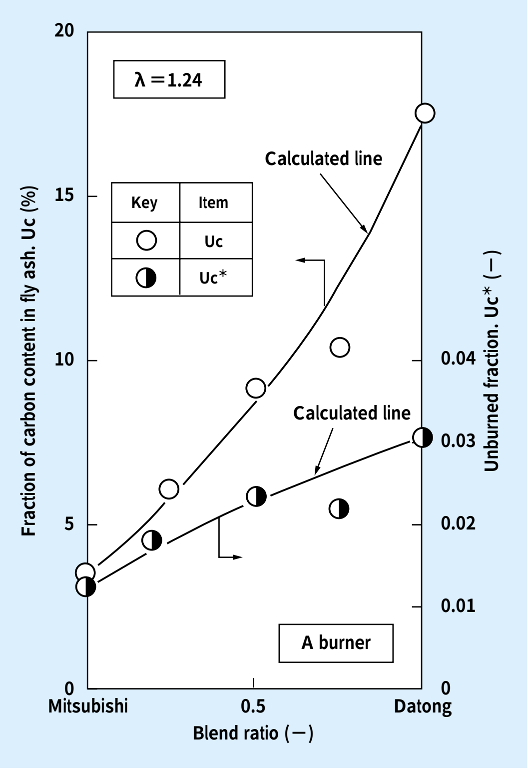


Fig. 4-2-9 Influence of coal blend ratio on fraction of carbon content in fly ash and unburned fraction

Fig. 4-2-9 shows unburned carbon concentrations in ash and unburned fraction when Mitsubishi coal and Daido coal are blended and burned with an estimation line determined from each coal type's unburned carbon concentration in ash at non-blended coal combustion with the use of Expression (4-6). The estimation line slightly varies, but well indicates a trend of actual measurements.

Based on these results, it became clear that a evaluation method for the adaptability of coal for power generation could be used for estimating unburned carbon concentrations in ash at blended coal combustion, and it is possible to estimate emission characteristics of NOx and unburned carbon in fly ash when various types of coal are used under the same combustion conditions in CRIEPI's coal combustion test furnace.

4-2-2 Impact Evaluation on Combustion Conditions

In an actual furnace, the amount of NOx and unburned carbon in fly ash is adjusted by regulating an air ratio (ratio of actual air input to air rate theoretically necessary for burning coal charged into a furnace) and a two stage combustion ratio (ratio of all inputs of air rate divided in the two stage combustion method on which rapid formation of NOx is restrained by separately charging combustion air into a burner instead of all the air). In making adaptability evaluations on power generation coal, it becomes also important to evaluate the effects of these combustion conditions.

Fig. 4-2-10 shows the concentrations of NOx and unburned carbon in fly ash when a two stage combustion ratio is varied. With the increase of the two stage combustion ratio, NOx concentrations can be reduced while unburned carbon concentrations in ash rise. These considerations were given to various coal types. Determining a relationship between a NOx conversion ratio for each coal type on a certain condition of the two stage combustion (charging position: 2.99 m from a burner, charge ratio: 20 % and 30 %) and a NOx conversion ration at the base combustion (a condition when the effect of coal types described in the section of 4-2-1 is considered), a better linear relationship as shown in **Fig. 4-2-11** can be

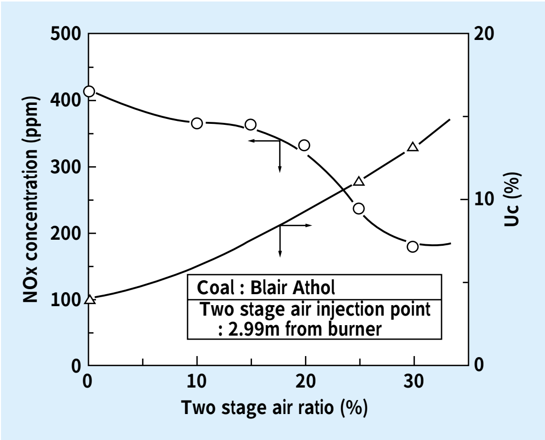


Fig. 4-2-10 Relation between the two stage air ratio and NOx, Uc

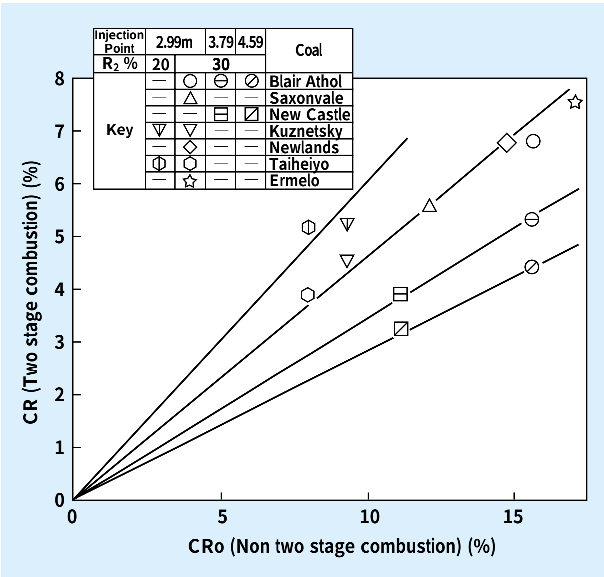


Fig. 4-2-11 Correlations between CRo and CR

obtained. In addition, a relation between unburned fraction at base and two stage combustions (charge position: 2.99 m from a burner, charge ratio: 30 %), as shown in **Fig. 4-2-12**, represents a linear pattern, as seen in a case for NOx conversion ratios. This implies that a testing coal with high NOx conversion ratio or high unburned fraction at the base combustion condition will also have a relatively higher value at two stage combustion.

This clarifies that a reduced rate of a NOx conversion ratio from the ratio at the base combustion on a certain condition of the two stage combustion and an increase rate of an unburned fraction from the ratio at the base combustion are

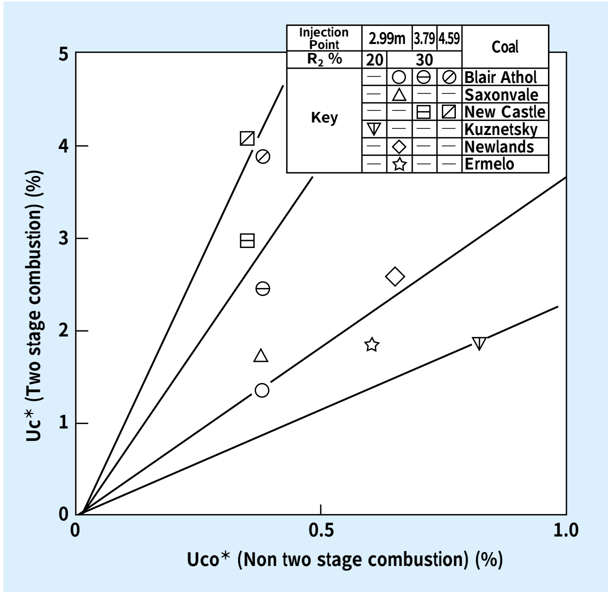


Fig. 4-2-12 Correlations between Uco* and Uc*

almost same in all coal types, although the rate of NOx and unburned carbon in fly ash greatly varies with the two stage combustion conditions as shown in Fig. 4-2-10. Using these relations, a relation between a reduced rate of a NOx conversion ratio under various conditions of the two stage combustion and a reciprocal of an increase rate of an unburned fraction can be represented a straight line under any combustion condition as shown in **Fig. 4-2-13.** In addition, in the range from 3% to 6% of excess oxygen concentration by increasing of air ratio it is obvious

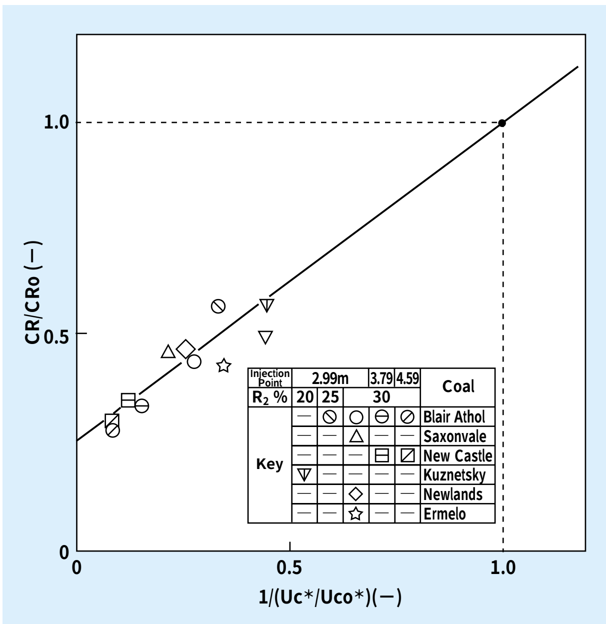


Fig. 4-2-13 Correlations between 1/(Uc*/Uco*) and CR/CRo

that the reduced rate of NOx conversion ratio and the reciprocal of the increase rate of unburned fraction vary on the same straight line as under the two stage combustion condition. Based on the above results, it became clear that the reduced rate and accordingly the increase rate of an unburned fraction represented a certain relation independently of coal properties. Quantifying this relation based on Fig. 4-2-13, the following expression is determined.

$$\frac{\text{CR (at conditioned change)}}{\text{CRo (a each base combustion)}} = 0.77 \times \frac{\text{Uco (at basecombustion)}}{\text{Uc (at conditioned change)}} \tag{4-7}$$

By providing a NOx conversion ratio and an unburned fraction each test coal at the base combustion, a function of the relation between the conversion and unburned fraction at the change of combustion conditions can be determined. If coal properties such as N content in fuel and ash content are identified through the use of this relation, it will be possible to estimate emission characteristics of NOx and unburned carbon in fly ash at the change of combustion conditions of each coal type in a coal combustion test furnace, as shown in **Fig. 4-2-14**.

In the figure. measurd values are indicated for comparison, but there is a very good agreement between measured values and estimated results. Measured values for NOx conversion and unburned fraction at the standard combustion were used to examine the relation here, however, if a method to estimate emission characteristics of NOx and unburned carbon in fly ash at the standard combustion based on coal properties, as clarified in the section of 4-2-1, is used, it will become possible to determine the relation in Fig. 4-2-14 only from of coal properties the analysis values of without doing combustion tests.

In above research, the effects of combustion conditions were discussed using only one type of burner. However, there are many types of pulverized coal firing burners, and emission characteristics of NOx and unburned carbon concentration in fly ash vary with their types. **Fig. 4-2-15** shows the results after a relation between a reduction ratio of a NOx conversion and an increase ratio of an unburned fraction was investigated for three burner types. As shown in the figure, the same linear relation as shown in Fig. 4-2-13 was obtained for any of these three types, but a gradient of the relations slightly is different from the burners. Using the relation determined in Fig. 4-2-15 and NOx and unburned fraction actually measured at the standard combustion, it will be possible to determine emission characteristics of NOx and unburned carbon concentration in fly ash at any combustion conditions for three types of burners, as determined in Fig. 4-2-14 for re type burner. **Fig. 4-2-16** shows the comparison of emission characteristics obtained by this method and actual

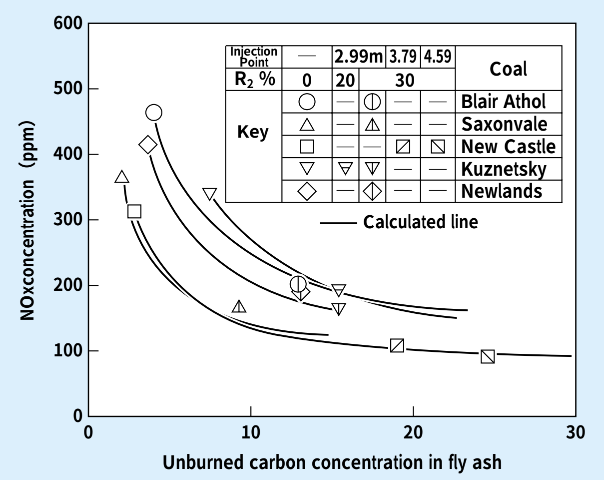


Fig. 4-2-14 Comparison between experimental and predicted values of NOx and inaburned carbon concentration in fly ash

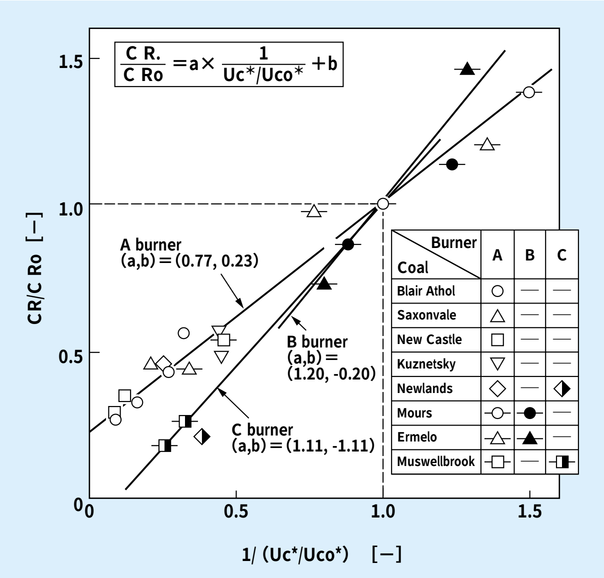


Fig. 4-2-15 Correlations between 1/ (Uc*/Uco*) and CR/CRo on each burner type

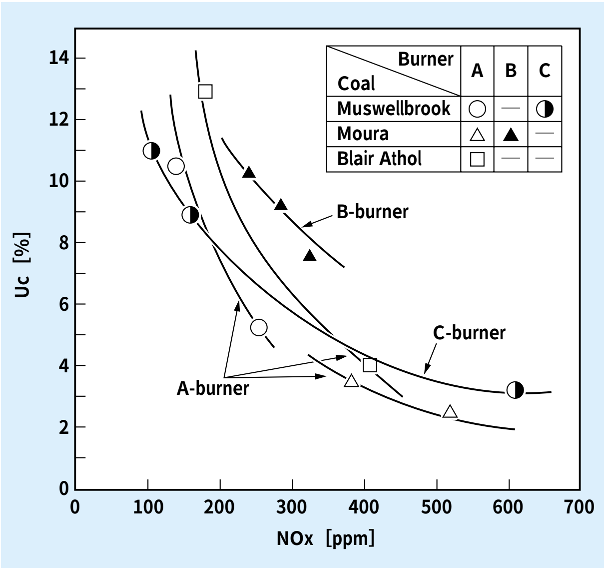


Fig. 4-2-16 Experimental and predicted values of NOx, Uc on each burner type

measured values at some combustion conditions. As found in the figure, there is a good agreement between estimated and measured values when any coals type is fired using three types of burners.

Based on the method described in this section, it is possible to accurately estimate the emission characteristics of NOx and unburned carbon concentration in fly ash when various kinds of coal are fired in a pulverized coal combustion test facility of CRIEPI, if specific relations between coal properties and NOx conversion or unburned fraction, and other specific relation between a reduction ratio of a NOx conversion and an increase ratio of an unburned fraction are decided for each burner.

4－3 Technology of Extending Applicable Coals

In order to use the coal with a wide variety of properties that has never been used in the past, CRIEPI developed a "coal adaptability evaluation system" on which the adaptability of new coal types to each power plant can be evaluated from coal properties and operating conditions, based on the evaluation method for the adaptability of coal for power generation in the foregoing section [(3)]. In addition, in the development of the system, a "search system for coal operating instance in the utility boiler" was prepared by constructing a database on properties of various coal types collected from each power plant and operation characteristics for any coal used in the power plant. The utilization of coal in utility boiler requires the complicated operation conditions, for example coal blending and partial load. So, in the process of this development, firstly, the system for non-blended coal combustion on full load were constructed, and the system will be expanded by establishing system on blended coal combustion and then partial load combustion [(4)].

4-3-1 Construction of Database on Coal Used in Utility Boiler

(1) Overview of this Database

The "Search system for coal operating instance" developed by this research is intended to assist the estimation of the characteristics of coal not used in the past and judge the acceptability of the coal, referring to operating data for each coal type in other power plants, based on a database on coal operating performance in each power plant. As shown in **Fig. 4-3-1**, the database consists of three databases on "power plant units," "coal properties" and "operation performance for coals."

① Database on power plant units

This is a database on about 220 items of equipment specifications for coal stock yards, coal pulverizers, boilers, denitrification units, desulfurization, dust separators, waste water treatment equipment and fly ash treatment equipment of 37 coal fired power plant units in Japan.

② Database on coal properties

This database summarized about 50 items focusing on general analysis such proximate and ultimate

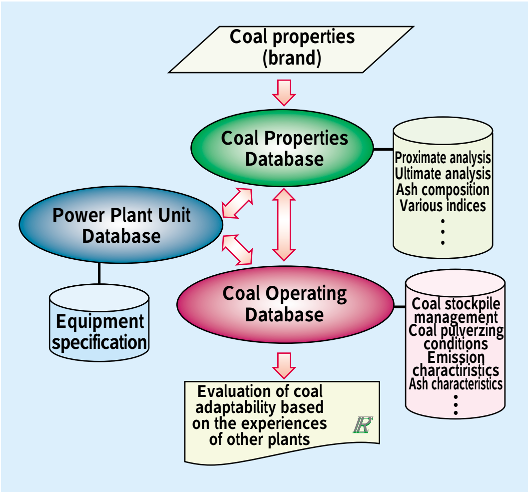


Fig. 4-3-1 Coal operating instance search system

analysis on coal used in each power plant mainly after 1995 and design coal for new power plants in Japan. In addition, the system displays an ash alkali ratio, a fouling index, a slugging index and an ignitability index that are calculated from analyzed coal properties. Furthermore, a database on considerations which has to be paid attention for using coal such as temperature increase in coal stock pile and adhesion characteristics of fly ash was constructed. Since coal properties vary with mining locations even though they have a same name, data on the properties were collected for each (lot ship) as far as possible. Currently, this database consists of about 170 coal name and about 2000 lots

③ Database on operation performance for coals

This database includes data on operating conditions of boilers and emission characteristics of gas component at coal combustion in each plant after 1995. It contains data on coal utilization performance of about 800 cases at non-blended and full load combustion and about 450 cases at blended coal combustion.

(2) System for Using Computer

A main display on "a search system for coal operating instance" was shown in **Fig. 4-3-2**. This system features data search, selecting , sorting and conversion to a file for creating tables. In addition, three databases are linked each other. For instance, linking a coal properties DB to on operation performance for coals DB provides coal properties and operation characteristics of coal at both of non-blended and blended coal combustion.

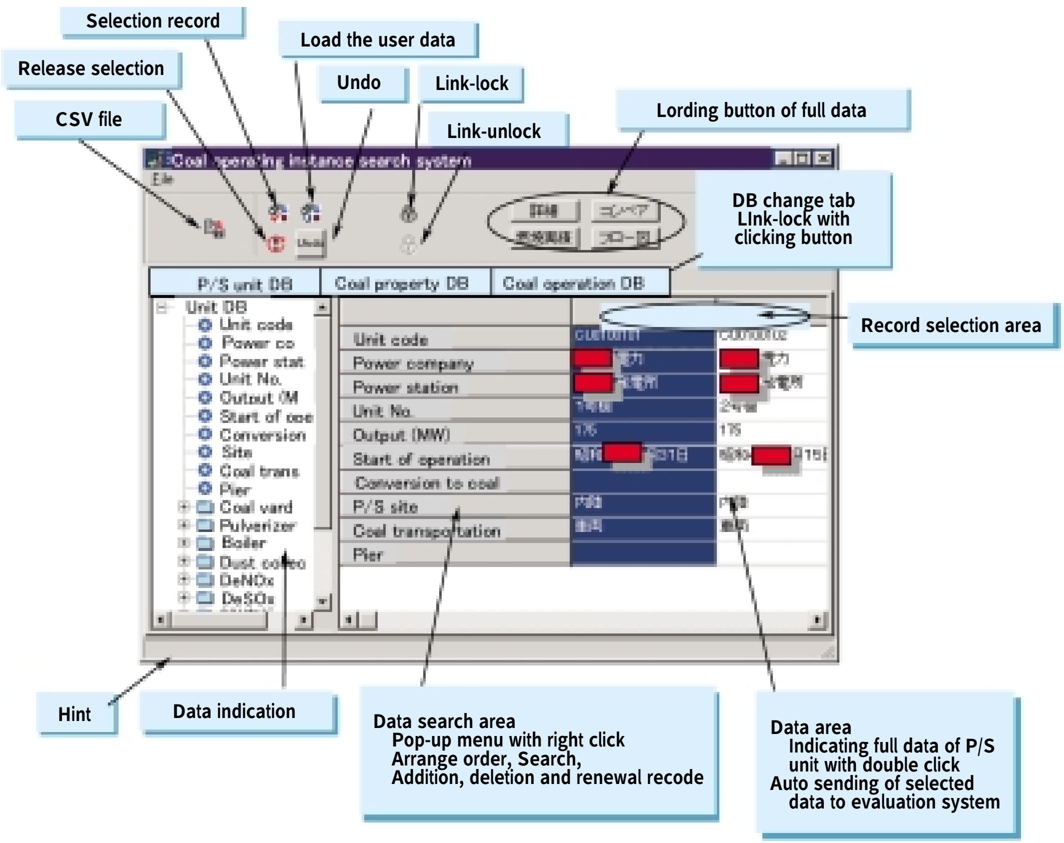


Fig. 4-3-2 Main form of coal operating instance search system

Furthermore, this system was distributed to electric power companies in Japan in a form of CD ROM in 2000, and the trial use started. However, considering users' convenience, they can add the new data continuously obtained in each power plant to the system and analyze a combination of the data and existing DBs, and the system provides a feature on which the properties can be input directly from DBs when the coal focused in "Suitability evaluation on coal types" are contained in the "Search system for coal operating instance."

4-3-2 Suitability evaluation on coal types

The coal adaptability evaluation system is a system on which adaptability of each coal for each power plant can be determined by estimating characteristics during operations of boilers from coal properties and operation conditions, based on the above three DBs. In addition, a criterion of adaptability judgment included four items of "NOx and unburned carbon emission characteristics," "coal ash properties," "grindability" and "Characteristics of spontaneous combustion" which are focused as an important estimation item in many power plants based on the results of a questionnaire survey to electric power companies. This system was prepared based on data collected during non-blended and blended coal combustion at full load.

(1) Emission Characteristics of NOx and Unburned Carbon Concentration in Fly Ash

A method, which allows us to predict the emission amount of NOx and unburned carbon concentration in fly ash from coal properties and combustion conditions was established for these evaluation items. In addition, a technology, which enables us to evaluate coal adaptability and estimate the best combustion condition on which their emissions can be reduced for each coal was developed. In this development, based on data from utility boilers and laboratory data from a coal combustion test furnace, a correlation between influential factors such as boiler/burner types, combustion conditions and coal properties and NOx emissions unburned carbon concentrations in fly ash was identified to develop a predictive expression

In order to develop a predictive expression for evaluating NOx emission characteristics, firstly, factors (influential factors), which have a correlation with a ratio of conversion from nitrogen content in coal to NOx (NOx conversion ratio (CR)), were picked up from data collected in utility boiler and data obtained from experiments in a pulverized coal combustion test furnace of CRIEPI (5) (6). Next, experiments with defined coal properties and combustion conditions were conducted so that effects of the individual factors were identified, in order to determine a basic function form from the relation of each factors. Since these conditions vary simultaneously in utility boiler, the effects of individual factors on NOx conversion ratio will have been combined. By systematically summarizing the factors, a predictive expression per unit was developed. When a two staged combustion ratio cannot be obtained in some boilers, the degree of damper opening is added to the expression. A development flow of an evaluation expression is shown in **Fig. 4-3-3**.

Based on the evaluation expression obtained in this way, a relation between a predicted value when a NOx conversion ratio is calculated for non-blended and blended coal combustion at full loads, and an measured value was shown in **Fig. 4-3-4**. In this figure, (1) is a case in which a NOx conversion ratio is estimated during non-blended and blended coal combustion based on an evaluation expression derived only from data obtained during non-blended coal combustion, and (2) is a case in which NOx conversion ratio is estimated during the combustion using a more accurate evaluation expression by re-deriving an evaluation equation including data obtained during blended coal combustion. Adding data obtained during blended coal combustion and the improvement of an evaluation expression based on more coal properties and combustion conditions enabled more accurate evaluation.

Formation characteristics of unburned carbon in fly ash were investigated using an unburned fraction (Uc*) of combustibles in coal shown in equation 4-4 of the foregoing section as an evaluation factor. The evaluation equation was prepared using coal properties and combustion conditions as influential factors similar with the investigation for NOx formation characteristics.

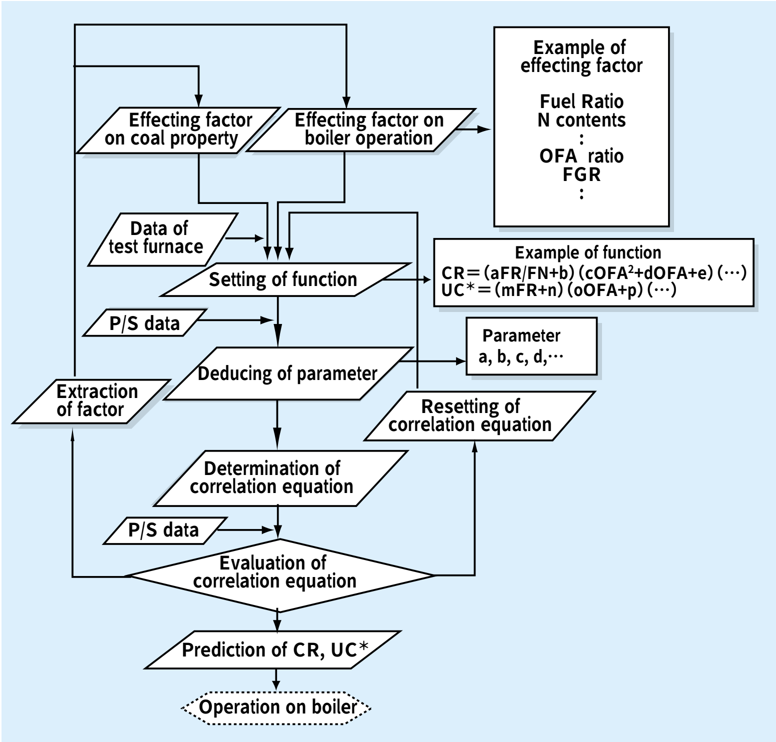
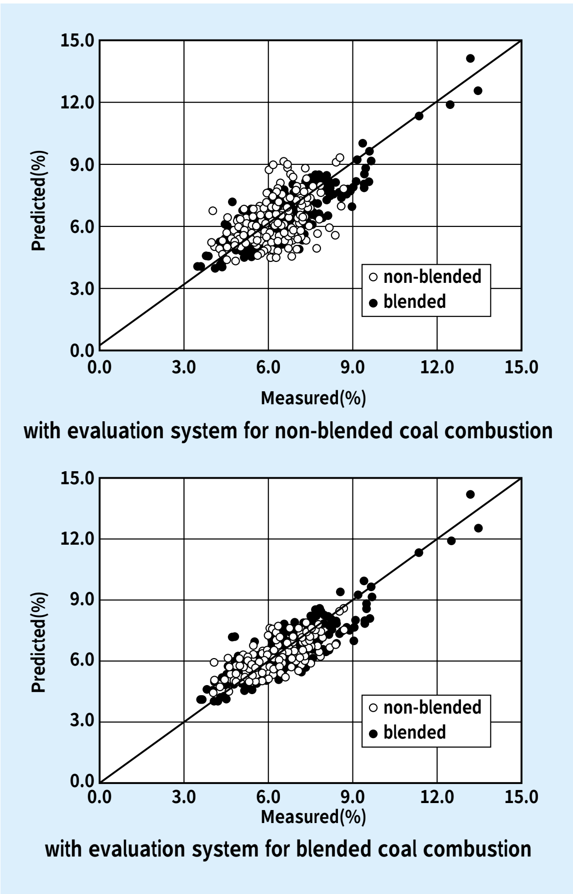


Fig. 4-3-3 Flow of deducing prediction equation on NOx(CR) unburned matter(Uc*)



with evaluation system for non-blended coal combustion

with evaluation system for blended coal combustion

Fig. 4-3-4 Relation between predicted value and measured value for conversion to NOx

A relation between predicted and measured values of an unburned fraction during non-blended combustion is shown in **Fig. 4-3-5**. It became clear that the unburned fraction could be accurately predicted on non-blended combustion, although the fraction varies with boiler types.

On the other hand, during blended coal combustion the measured values are larger than estimated values, as shown in **Fig. 4-3-6** (1), the accuracy of prediction is decreased. This was considered to be due to that coal with relatively high moisture content such as sub-bituminous coal is often blended with other coal

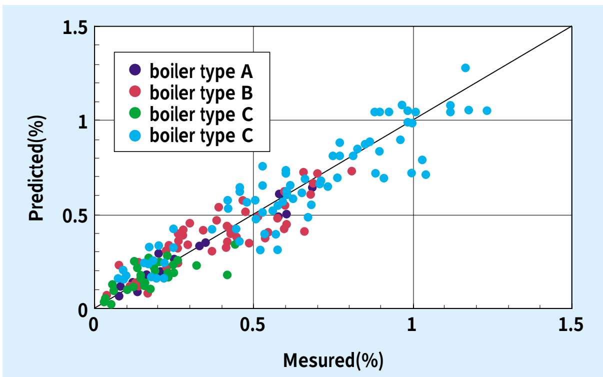


Fig. 4-3-5 Comparison of predicted value with measured value of uncombustion fraction

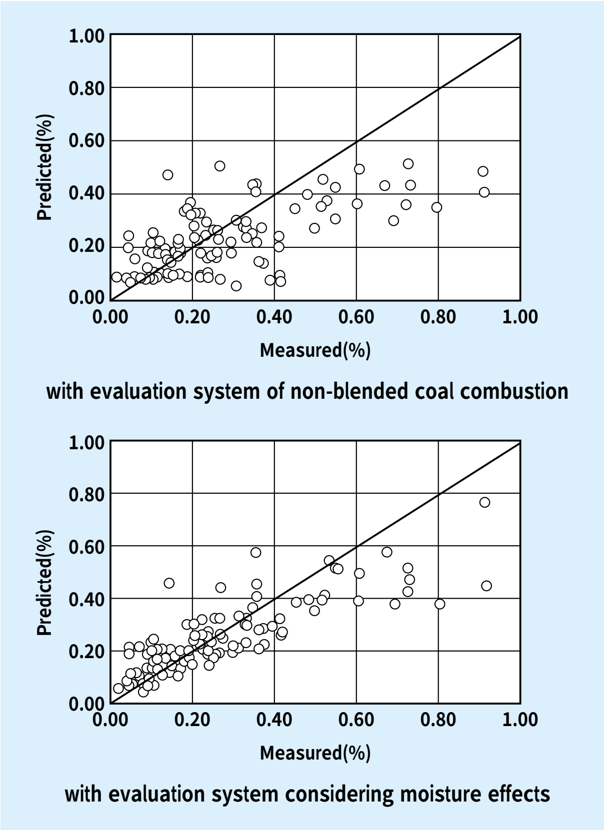


Fig. 4-3-6 Relation between prediction value and measured value for uncombustion fraction

and the combustion situation is strongly affected by moisture, whereas this evaluation expression did not include this effect. Hence, in order to consider the effect of moisture content on the increase of an unburned fraction during blended coal combustion, a new predictive expression was developed by adding a term of moisture content, as an inhibiting combustion factor to a term for evaluating the effect of coal properties on the increase of an unburned fraction during blended coal combustion. As a result, it became clear that unburned carbon concentrations during blended coal combustion could be evaluated more accurately as shown in Fig. 4-3-6 (2).

(2) Grindability

In pulverized coal fired power plants, coal is pulverized and is fired as fine particles. Grindability of coal varies greatly with coal properties, while the mill operating conditions and power consumption in mill, substantially subject to coal properties, and also greatly depend on the coal kinds. For this reason, if the power consumption of mill can be estimated from a grindability indicator of coal, it will become possible to preliminarily set a mill operating condition for the kinds of coal not being used in the past, and select coal that provides lower pulverizing power consumption on the mill. In addition, if the grindability can be estimated from coal properties. it will be possible to immediately estimate the pulverizing power from coal property without examining coal grindability.

Focusing on the Hardgrove Index (HGI) [1] that is generally used as a grindability indicator, a correlation between HGI of non-blended coal and the power consumption of mill is identified (**Fig. 4-3-7**), and then a system for predicting the power consumption of mill based on the relation is constructed. In addition, we clarified a relationship between coal properties (fuel ratio, FR) and HGI/power consumption, which enabled us to estimate the power directly from a fuel ratio without measuring HGI. Furthermore, it was clarified that the measurements of HGI at the use of blended coal showed close agreement with the estimations calculated from coal-blending ratio of various coal kinds and a HGI of each coal. It was also demonstrated that a power consumption at the use of blended coal could be predicted from a correlation between HGI and the power consumption obtained at the use of non-blended coal using HGI of blended coal estimated in this way.

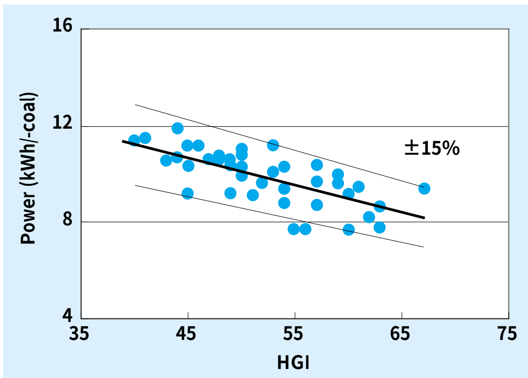


Fig. 4-3-7 Relation between coal pulverized power and HGI

1) Values indicating coal grindability and determined under a specified condition with the use of a hardgrove tester
2) JIS Standards has no provisions on the MB adsorption. However, MB adsorption has an almost linear relation with the amount of air entrainment agent (AE agent*), so it becomes an important measure for quality control in regulating air content in concrete. AE agent is admixture that is used to uniformly distribute a lot of micro-air foam in concrete.

(3) Coal ash properties

Electric power companies perform an important challenge for increasing a utilization ratio of coal ash as valuable ash. Current valuable ash is most used as cement admixtures. In this case, Methylene Blue (MB) adsorption amount [2], which highly correlates with the consumption of air entrainment agent (AE agent) is widely employed as the most important quality standard for coal ash that determines the availability. Therefore, CRIEPI selected a MB adsorption as an evaluation factor for formed ash properties and identified a relationship between coal properties/combustion conditions and the MB adsorption based on data obtained from an utility boiler in order to establish an evaluation system on which the availability of coal ash can be determined. As MB is estimated to adsorb to unburned carbon in fly ash, an evaluation expression was determined from a correlation between unburned carbon concentrations in fly ash and MB adsorptions, and the expression was demonstrated to accurately estimate MB adsorptions during non-blended and blended coal combustion. In addition, as unburned carbon concentrations in fly ash can be predicted from a fuel ratio of coal and combustion conditions such as two staged combustion as mentioned above, an evaluation expression was determined from a relation between these influential factors and MB adsorptions in the utility boiler in order to construct a system on which the adsorptions can be presumed from coal properties and combustion conditions.

(4) Spontaneous combustion

Spontaneous combustion of coal is a important subject when coal is stocked for a long term. The possible evaluation on spontaneous combustion enables effective prevention method such as optimization of a stock period, sprinkling systems and volume of water in coal stock yard management. CRIEPI identified relevance a relationship between spontaneous combustion of coal and coal properties for various coal currently used in utility boiler and reviewed a way of estimating the spontaneous combustion.

In this method, a correlation between analyzed values of coal properties (fuel ratio, O/C, volatile matter, oxygen concentration and moisture content) and apparent activation energy (E [kj/mol]) as an indicator for spontaneous combustion in coal oxidation was identified. Since an O/C has the highest correlation among these analysis items, an evaluation system using O/C as an evaluation factor for spontaneous combustion was established.

4-3-3 Evaluation System of Coal Adaptability for Power Generation

A "evaluation system of coal adaptability for power generation " (**Fig. 4-3-8**) that is available on Personal computers was developed by incorporating a "search system for coal operating instance" and a "coal adaptability evaluation system" into this system, so that it can be easily used and functionally in coal fired power plants.

(1) Emission characteristics of NOx and unburned carbon in fly ash

An evaluation form was shown in **Fig. 4-3-9**. The form supports several input sheets of coal properties (proximate and ultimate analysis) so that the emission characteristics on blended coal combustion can be evaluated, and values of coal properties at blended coal can be determined with a computer from each coal property and coal blending ratio. By input of combustion conditions (two stage combustion ratio, excess oxygen concentrations, a flue gas recirculation ratio, etc.) for each coal, NOx conversion ratios, NOx concentrations, unburned fraction, and unburned carbon concentrations in fly ash are calculated and displayed based on an

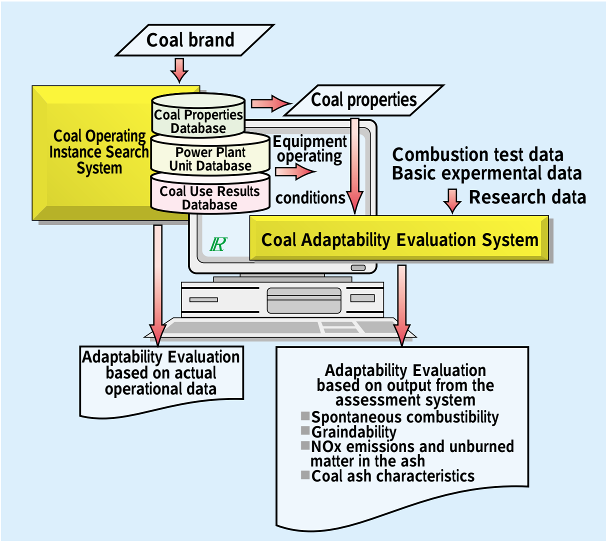


Fig. 4-3-8 Evaluation system of coal adaptability to power plant

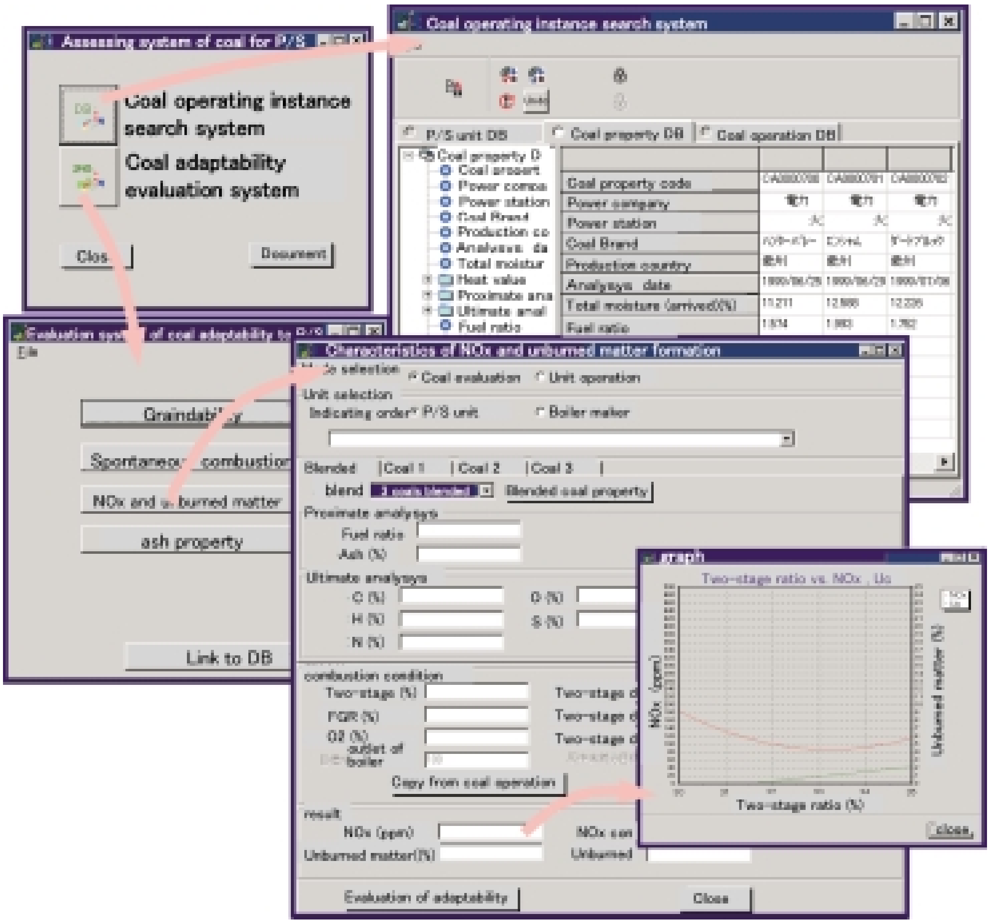


Fig. 4-3-9 Example of coal assessing system for power station —NOx and Unburned matter evaluation system—

evaluation expression. In addition, by input of coal properties and targeted NOx and unburned carbon concentrations in ash into them, the system presents a two stage combustion ratio that can accomplish each target concentration and also has a feature of graphically representing variation in NOx and unburned carbon concentrations in ash with the two stage combustion ratio.

(2) Grindability

A fuel ratio or HGI is entered as a coal property. Based on this system, HGI during blended coal combustion is calculated from HGI of each coal and a coal blending ratio in order to determine a power consumption of mill from HGI at blended coal.

(3) Coal ash properties

By input of an unburned carbon concentration in fly ash as a coal property, a MB adsorption is calculated and displayed. Even if an actual measured value for the unburned carbon concentration is unknown, the system has also a method on which the adsorption is estimated directly from coal properties and combustion conditions. The adsorption, similar with the method for emission characteristics of unburned carbon in fly ash, is evaluated, using a coal property input sheet for several coal into which proximate analysis values such as moisture content and volatile matter content can be entered and an input sheet for combustion conditions such as a two staged combustion ratio.

(4) Spontaneous Combustion

By input of oxygen and carbon content as a coal property spontaneous combustion characteristics are easily displayed.

In the future, we will improve this system that can be available for partial load and also intend to enhance the more accuracy of the system.

4－4 Future Plan

Due to the increase of energy sources and reduction of fuel costs, the expanded introduction of various kinds of coal has been increasingly required in these years. The development of a method to accurately and easily determine the applicability of these coal to thermal power plants and improvement of the accuracy of the method seem to be now strongly needed. The methods described in this chapter were developed focusing mainly on emission characteristics of NOx and unburned carbon in fly ash that may be the most important in current pulverized coal fired power plants. However, it can be believed that, the more accuracy of evaluating the plants and the expanded applicability of the evaluation methods to wide operation conditions will be desired for the improvement of reliability of pulverized coal fired power plants, while the development of an adaptability determination method for other evaluation items such as slugging and fouling features will be required.

We will now be able to apply the current system for adaptability evaluation on coal also to partial load operations and expand the system so that it can be applied to a wide variety of coal. Furthermore, in order to improve the more accuracy of the system, more data from utility boiler will be collected while the evaluation method will be improved based on the data. For the increase of evaluation items, we will investigate new estimation items that will be needed for evaluating coal properties in thermal power plants and develop a estimation method for the new items in order to improve the system as more useful one.

On the other hand, a method for evaluating coal characteristics used in a combustion test furnace, in which a combustion test is actually conducted to evaluate the properties, enables us to evaluate coal in extremely detail such as characteristics for many operation conditions and also to measure characteristics on coal kinds with extremely different properties, that have never been used in utility power plants. We will now evaluate the coal with more extreme properties in a pulverized coal combustion test furnace and expand/improve the evaluation method for the adaptability of coal for power generation while developing a method on which more evaluation items can be determined more accurately.

In order to evaluate coal characteristics in detail under a situation very closer to an utility boiler condition, a "demonstration test equipment for coal combustion characteristics" was installed that has three burners and enables the review on environmental protection technologies using a flue gas treatment equipment that has the same system as the utility boiler. We will perform on the development and improvement of a preliminary evaluation method for new coals in more diversified and effective investigation, combining this equipment with a coal combustion test furnace and other basic research facilities.

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Chapter

5

High Efficiency of Pulverized Coal Fired Power Plants

Chapter 5 High Efficiency of Pulverized Coal Fired Power Plants ● Contents

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Mikio Sato (Dr.)
Senior Research Scientist
Research Coordinator
Yokosuka Research Laboratory

Tetsuya Iwasaki
Manager
Engineering Gr.
Power Project Department Power Plant Division
Ishikawajima-Harima Heavy Industries Co.,Ltd

Akito Nitta (Dr.)
Associate Vice President
Komae Research Laboratory

5－1 Research Background

With the reconstruction of electric utilities in Japan after the World War II, steam conditions in thermal power plants have been continuously improved. In 1967, Anegasaki No. 1 unit 600 MW (538/566 °C) boiler, the Tokyo Electric Power Co., Inc., started to operate, and the thermal power plant entered a new era of a super critical pressure of 24.1 MPa and temperatures of 538/566 °C.

In pulverized coal fired power plants, as mentioned above, since EPDC's Matsushima No. 1 and 2 units (each for 500 MW) introduced the first coal fired power plant by using super critical condition in our country in 1981, high temperature and high pressure under steam conditions began in the Tomatoh-Atsuma No. 2 unit (600 MW) (1985, 538/566 °C), Hokaaido Electric Power Co., Inc. and the Tsuruga No. 1 unit (500 MW) (1991, 566/566 °C), Hokuriku Electric Power Co., Inc., and a reheating steam temperature reached 593 °C in the Hekinan No. 3 unit 700 MW (1993, 538/593 °C), Chubu Electric Power Co., Inc. Afterwards, the Chugoku Electric Power Co., Inc.'s Misumi No. 1 unit (1,000 MW) (1998, 600/600 °C) and Tohoku Electric Power Co., Inc.'s Haramachi No. 2 unit (1,000 MW) (1998, 600/600 °C) entered into an era of 600 °C of a main steam temperature and a reheating steam temperature. Following that, EPDC's Tachibanawan No. 1 and No. 2 units (1,050 MW) and EPDC's Isogo New No. 1 unit (600 MW) adopted a main steam temperature of 600 °C and a reheating steam temperature of 610 °C in 2000 and in 2002, respectively.

On the other hand, looking at the world, particularly in the United States, the Philo No. 6 unit 125 MW adopted a steam condition of 31 MPa and 621/566/538 °C in 1957, as a first ultra super critical pressure (USC) plant, and the steam condition entered a new period of USC. Afterwards, the Eddystone No. 1 unit with the world top steam condition was constructed, and thermal efficiency was improved with accomplished high temperature and pressure. During 1950s, many USC power plants were built in U.S., German and U.K., but the steam condition was not improved until these years. This is due to that austenitic materials often used for initial USC plants provoked cracking from heat stress occurring in thick-walled parts and negative cost efficiency, which did not provide the merit of USC.

However, with the oil crisis as a turning point, high efficiency of thermal plants was increasingly needed in terms of useful utilization of energy resources and energy-saving, and new materials that are applicable to the USC steam conditions and more economically have been developed by material manufactures, so higher steam conditions were sought toward improved thermal efficiency.

In Japan, EPDC has played a key role in developing a USC technology in cooperation with plant manufactures since 1980, and the development has been promoted as a national project led by the Ministry of Economy, Trade and Industry (former Ministry of International Trade and Industry) from 1982 to 2000. In Phase-1 (1980-1993), STEP-1 (31.4 MPa, 593/593/593 °C, ferrite materials) and STEP-2 (34.3 MPa, 649/593/593 °C, austenitic materials) were implemented according to steam conditions and main materials. In addition, in Phase-2 (1994-2000), ferrite materials, being more operational and economical, were adopted to implement R&D for early introduction of USC plants.

The National Institute for Materials Science (NIMS) has been developing ferrite heat resisting steel used for thick-walled pressure resistance parts of a USC boiler with 36 MPa and 650 °C since 1997 as part of a ultra steel materials research project.

High efficiency of pulverized coal fired power plants has been promoted mainly by accomplishing larger capacity of plants and steam conditions on higher temperature and pressure, but as an auxiliary power ratio in a pulverized coal fired power plant is higher than that in an oil fired power plant due to a lot of component equipment including a mill, the reducing of the auxiliary power ratio is also important for increasing plant thermal efficiency. For this reason, these years, through the introduction of a vertical type roller mill with less required power and an axial draft fan, a review on an increasingly reduced auxiliary power is being promoted.

5－2 History of Steam Temperature and Pressure Improvement

1) 1945-1960

It is no exaggeration to say that the history of increase of plant efficiency of thermal power plants is one for improvement of steam condition based on increasing temperature and pressure. **Fig. 5-2-1** shows the trend of steam condition of thermal power plants in Japan. (Steam condition refers to turbine inlet condition.) After the World War Ⅱ, 13 coal fired power plants were constructed until 1950, and all of them were designed and manufactured on the basis of technologies before and during the War. At this period, maximum steam condition was 4.4 MPa (45 kg/cm^{2}g) of main steam pressure and 450 ℃ of main steam temperature for 200 t/h boiler and combination of one steam turbine with several boilers was adopted. With the reorganization of the electric power network in 1951, and domestic boiler manufacturers introduced modern technologies from U.S. or European boiler manufactures under the license in order to establish design and manufacturing organization to accomplish higher steam temperature and pressure. As a result of this development, steam condition of thermal power plants continued to improve with the growth and development of the domestic industry, and steam pressure and temperature of 16.6 MPa (169 kg/cm^{2}g) and 566 ℃ were introduced until 1960. At that time, domestic coal fired power plants were constructed as a mainstream of thermal power generation while oil fired power plants emerged.

2) -1970

In the 1970s, a period of dominant domestic coal fired power plants was shifted to that of dominant oil fired power plants and construction of coal fired power plants was reduced. As represent coal fired boilers during this period, EPDC's Isogo No. 1 unit (265 MW) was constructed in 1967, as a natural circulation coal fired boiler with maximum capacity. Shimonoseki No. 1 unit (156 MW) of Chugoku Electric Power Co., Inc. adopted forced circulation boiler and Karatsu No. 1 unit (156 MW) of Kyushu Electric Power Co., Inc. adopted Sulzer type once through boiler.

3) -1990

After the oil shock in 1973 and subsequent soaring oil costs and the second oil shock or due to IEA's advice not to construct new oil fired power plants, multi-fuel application policy was adopted for power generation. According to this trend, new project for construction of coal fired power plants was revived. However, applied fuel coal was changed from domestic coal to imported coal from various countries by domestic coal development policy. In 1981, EPDC's Matsushima No. 1 and 2 units (500 MW) (main steam

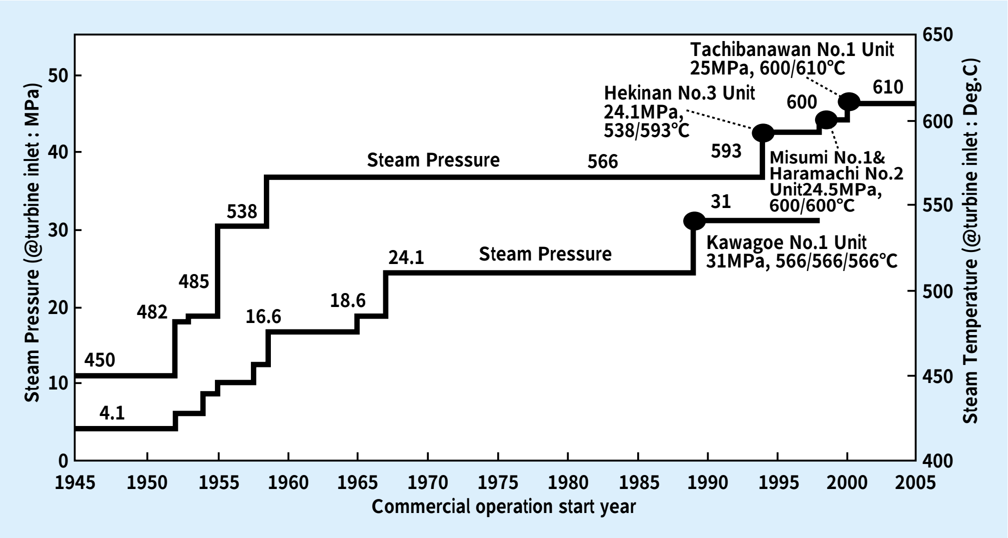


Fig. 5-2-1 Trend of steam condition in Japan

temperature: 538 °C, reheat steam temperature: 538 °C), which introduced as the first imported coal fired supercritical unit in our country, started commercial operation.

In 1985, Tomato-Atsuma No. 2 unit (600 MW) (main steam pressure: 24.1 MPa (246 kg/cm^{2}g), main steam temperature: 538 °C, reheat steam temperature: 566 °C) of Hokkaido Electric Power Co., Inc., was commenced commercial operation as various foreign coal-fired supercritical once-through variable pressure operation unit, which is currently being still a mainstream unit type. This steam condition was maintained for some time. This is due to that increase of plant efficiency and reduction of construction costs based on increase of plant capacity were more feasible than improvement of steam condition. In 1990, EPDC's Matsuura No. 1 unit (main steam pressure: 24.1 MPa (246 kg/cm^{2}g), main steam temperature: 538 °C, reheat steam temperature: 566 °C), a first 1,000 MW unit as a coal fired plant, started commercial operation.

In the meantime, increase thermal efficiency by improving steam condition for pulverized coal fired plants had been required for energy-saving. In response to this requirement, research and developments were carried out concerning application of ultra supercritical (USC) steam condition for dramatically improving thermal efficiency. This R & D had been promoted since the middle of 1980s. EPDC had been involved in developing this technology in STEP 1 and 2 since 1982, setting a goal shown in **Table 5-2-1** under support by the Agency of Natural Resources and Energy, the Ministry of International Trade and Industry (currently the Ministry of Economy, Trade and Industry). Some of accomplishments of STEP-1 were already adopted in actual power plants.

4) -Present

With adoption of improved heat resistance materials for higher steam temperature and pressure developed in above R&D, improved steam condition plants started commercial operation around 1990. **Fig. 5-2-2** shows the features of representative materials that were improved for higher steam conditions. Tsuruga No. 1 unit (500 MW) of the Hokuriku Electric Power Co., Inc., which started commercial operation in 1991, increased main steam temperature to 566 °C. In Hekinan No. 3 unit (700 MW) of Chubu Electric Power Co., Inc., which started commercial operation in 1993 with reheat temperature of 593 °C as the first steam temperature in Japan.

The accomplishment of steam condition of 593 °C became a driving force to construct higher steam condition thermal power plants in Japan. In 1998, Misumi No. 1 unit (1,000 MW) of Chugoku Electric Power Co., Inc. and the Haramachi No. 2 unit (1,000 MW) of Tohoku Electric Power Co., Inc., applied main steam pressure of 24.5 MPa, main steam temperature of 600 °C and reheat steam temperature of 600 °C. In 2000, EPDC's Tachibanawan No. 1 and 2 units (1,050 MW) adopted main steam pressure of 25 MPa, main steam temperature of 600 °C and reheat steam temperature of 610 °C. Relation between these steam condition and increase of plant thermal efficiency (relative values) is shown in **Fig. 5-2-3.**

EPDC's Isogo New No. 1 unit (600 MW), which started commercial operation in 2002, adopted full variable pressure operation and main steam pressure of 26.6 MPa at MCR (main steam temperature: 600 °C, reheat steam temperature: 610 °C) as the highest steam condition in Japan.

Table 5-2-1　Development Target USC plant（Based on 1,000MW unit)

		Comventional	Phase-1		Phase-2	Next Generation (For Refernce)
			STEP-1	STEP-2		
Principal applied material		Ferritic steel	Ferritic steel	Austenitic steel	Ferritic steel	Nickel Base
Steam Condition	Pressure（MPa)	24.1	31.4	34.3	30	約30
	Temperature (°C)	538/566	593/593/593	650/593/593	630/630	700（MST)
Gross Plant Efficiency（Design %)		42.1	44.2	44.9	44.1	46
Improvement of Plant Efficiency（%)		Base	5.0	6.5	4.8	9.3
Decrease Coal Consumptiion per year（ton)		Base	96,000	125,000	95,000	170,000
Decrease CO_2 Emission per year (10^6Nm^3)		Base	117	152	112	218

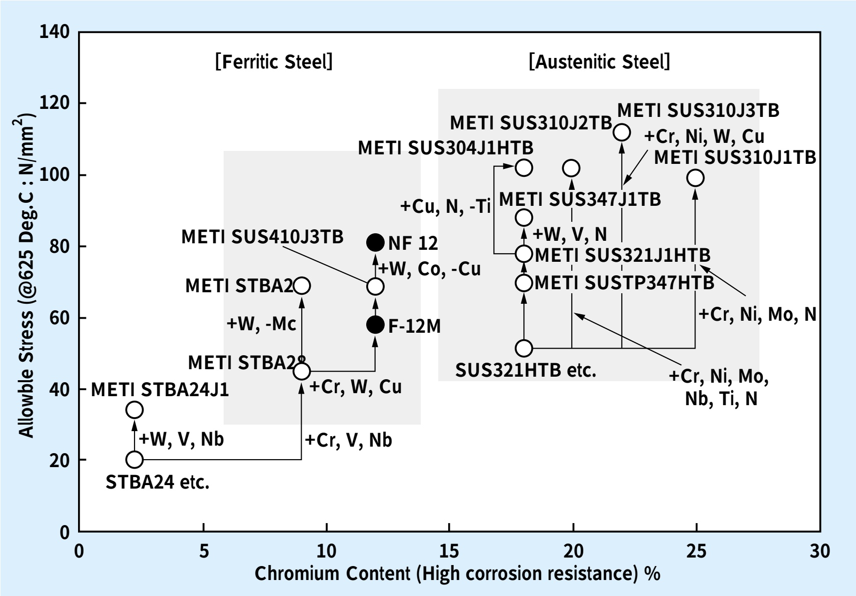


Fig. 5-2-2 Characteristics of High Temperature strength of Principal Materials

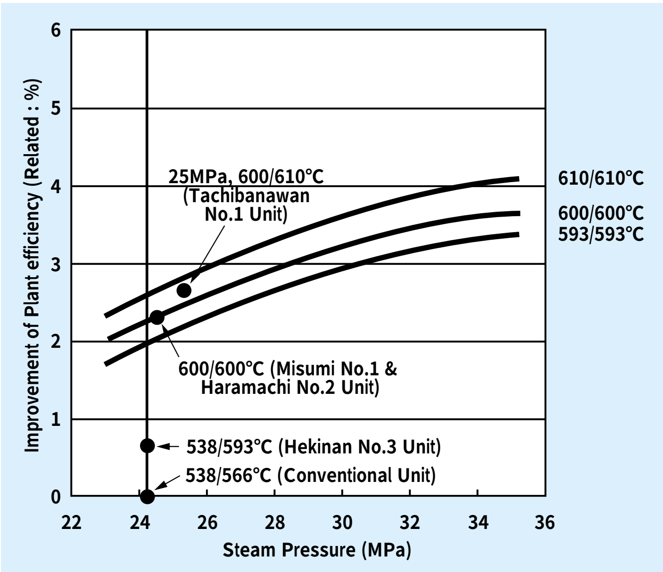


Fig. 5-2-3 Improvement of Plant Efficiency vs Steam condition

5－3 Advancement of High Temperature Materials

5-3-1 Technological Background

The boiler explosions frequently occurred in the U.S. during the early years of the 20th century built a ground swell of development of a uniform boiler design method. In order to define the method, the Boiler and Pressure Vessel Committee in the American Society of Mechanical Engineers (ASME) was established in 1914, leading to the establishment of "ASME Boiler & Pressure Vessel Code: Section I, Power Boilers." The code was incorporated into technical standards for thermal power plants in Japan, and constructed a concept of "design by formula." According to this design method, an allowable tensile stress at each temperature for a given material is determined, and a wall thickness meeting the stress value is calculated via a formula (an expression with which the minimum wall thickness required is calculated from a diameter of vessels and pipes, operating pressure and an allowable tensile stress). As the allowable tensile stress, a minimum value is selected among the results generated after multiplying yield strength, tensile strength and creep strength by a given safety factor. In particular, in a range of high temperature (almost 400～500 ℃ or more), within which creep (a phenomena in which material deformation gradually develops and leads to material fracture over time.) is concerned, allowable tensile stress of most materials is determined on the basis of 100,000-hour creep-rupture strength. Hence, the commercialization of high-temperature materials with increased creep-rupture strength enables a design wall thinning of high-temperature equipment, which accomplishes its high efficiency. So, the development of the high-temperature materials was being actively promoted. In particular, combined with the trend toward realization of an advanced power plant under Ultra Super Critical (USC) steam conditions, the development of high strength materials has been accelerated.

5-3-2 Progress of Development of Materials

Table5-3-1 Main material used in conventional boiler

Application	Main material
Economizer	Carbon steel（STB42, STB52）
Evaporator	Carbon steel（STB42） Low-alloy steel（STBA20, STBA23）
Superheater Reheater	Low-alloy steel（STAB24, STBA26） Stainless steel（SUS304HTB, SUS 321HTB, SUS316HTB, SUS347HTB）
Superheater/ Reheater,Header	Low-alloy steel（STPA24）
Main tube	Low-alloy steel（STPA24）
Feed water heater	Carbon steel（STPT49）
Steam drum Steam separator	Carbon steel（SB49） Low-alloy steel（SCMV3）

(note)
STB：Carbon steel tube for boiler and heat exchanger（JIS G3461）
STPT：Carbon steel tube for high temperature tube（JIS G3456）
SB：Carbon or Molybdenumsteel board for boiler or pressur vessel（JIS G3103）
STBA：Alloy steel tube for boiler and heat exchanger（JIS G3462）
STPA：Alloy steel for tube（JIS G3458）
SCMV：Chromium Molybdenum steel tube for boiler or pressure vessel（JIS G4109）
SUS-TB：Stainless steel tube for boiler and heat exchanger（JIS G3463）

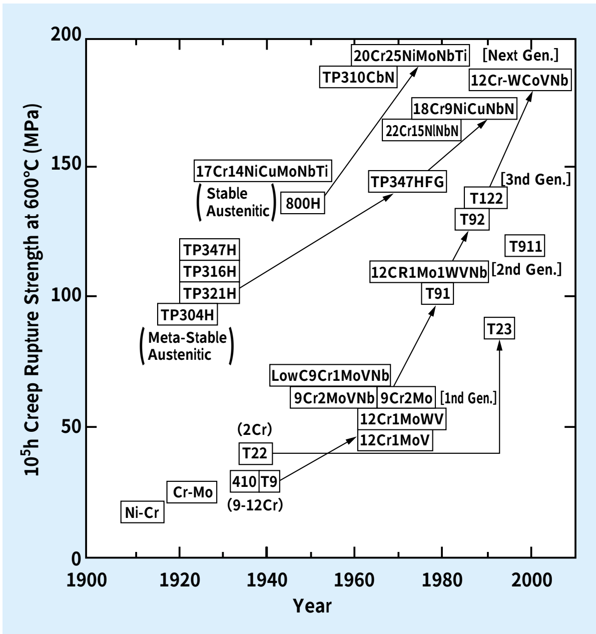


Fig. 5-3-1 The changes on strength of heat-resistant steel for boiler

Table 5-3-1 shows representative materials for conventional boilers whose allowable tensile stress under technical standards for thermal power plants and their corresponding JIS standards. In addition, **Fig. 5-3-1** [3][4] shows the changes of boiler materials developed after 1900 including these materials. (For materials designation in the figure, refer to the **Table 5-3-2**.) The vertical axis in the figure represents 100,000-hour creep-rupture strength at 600 ℃ on which allowable tensile stress will be based as described above, and shows that creep-rupture strength increases over time. Furthermore, a materials group at the bottom of the figure covers ferritic heat-resistant steel while other materials group at the top is austenitic heat-resistant steel. Ferrite is a metal structure whose crystal structure represents body-centered cubic lattice, and crystal structure of austenite represents face-centered cubic lattice. In general, ferritic steel has a small linear expansion coefficient and a large thermal conductivity, so it has a feature that its thermal stress generated becomes smaller than that of austenitic steel. On the other hand, due to that a ferritic self-diffusion coefficient is larger than austenitic one, ferritic steel becomes susceptible to creep that is dominated by high temperature diffusion. As found in Fig.5-3-1, however, recently, with its rapidly increasing heat resistance,

Table 5-3-2 Representative heat-resistant steels for boiler components and their corresponding code and nominal composition

Material		Designation (Nominal Composition)	Code		Chemical Composition (mass%)													
			JIS	ASME	C	Si	Mn	Ni	Cr	Mo	W	Co	V	Nb	Ti	B	N	others
Ferritic	2Cr	T22 (2.25Cr-1Mo)	STBA24	T22	0.12	0.3	0.45	-	2.25	1.0	-	-	-	-	-	-	-	-
		M2S (2.25Cr-1.6WVNb)	Ka-STBA24J1	T23	0.06	0.2	0.45	-	2.25	0.1	1.6	-	0.25	0.05	-	0.003	-	-
	9Cr	T9 (9Cr-1Mo)	STBA26	T9	0.12	0.6	0.45	-	9.0	1.0	-	-	-	-	-	-	-	-
		M9M (9Cr-2Mo)	Ka-STBA27	-	0.07	0.3	0.45	-	9.0	2.0	-	-	-	-	-	-	-	-
		T91 (9Cr-1MoVNb)	Ka-STBA28	T91	0.10	0.4	0.45	-	9.0	1.0	-	-	0.20	0.08	-	-	0.05	-
		616 (9Cr-0.5Mo-2WVNb)	Ka-STBA29	T92	0.07	0.06	0.45	-	9.0	0.5	1.8	-	0.20	0.05	-	0.004	0.06	
		F-9 (9Cr-1MoVNb)	-	-	0.06	0.5	0.60	-	9.0	1.0	-	-	0.25	0.40	-	0.005	-	
		EM12 (9Cr-2MoVNb)	(NFA49213)		0.10	0.4	0.10	-	9.0	2.0	-	-	0.30	0.40	-	-	-	
	12Cr	HT91 (12Cr-1MoV)	(DINX20CrMoV121)		0.20	0.4	0.60	0.5	12.0	1.0	-	-	0.25	-	-	-	-	
		HT9 (12Cr-MoWV)	(DINX20CrMoWV121)		0.20	0.4	0.60	0.5	12.0	1.0	0.5	-	0.25	-	-	-	-	-
		M12 (12Cr-1Mo-1WVNb)	Ka-SUS410J2TB	-	0.10	0.3	0.55	-	12.0	1.0	1.0	-	0.25	0.05	-	-	0.03	-
		12A (12Cr-0.4Mo-2WCuVNb)	Ka-SUS410J3TB	T122	0.11	0.1	0.60	-	12.0	0.4	2.0	-	0.20	0.05	-	0.003	0.06	1.0Cu
		F12 (11Cr-2.6W-2.5CoVNbB)	-	-	0.08	0.2	0.50	-	11.0	0.2	2.6	2.5	0.20	0.07	-	0.004	0.05	-
		E12 (11Cr-3W-3CoVNbTaNdN)	-	-	0.10	0.3	0.20	-	11.0	-	3.0	3.0	0.20	0.07	-	-	0.04	0.07Ta, 0.04Nd
Austenitic	18Cr-8Ni	SUS304HTB (18Cr8Ni)	SUS304HTB	TP304H	0.08	0.6	1.6	8.0	18.0	-	-	-	-	-	-	-	-	-
		Spr304 (18Cr9NiCuNbN)	Ka-SUS304J1HTB	TP304CuCbN	0.10	0.2	0.8	9.0	18.0	-	-	-	-	0.40	-	-	0.10	3.0Cu
		SUS321HTB (18Cr10NiTi)	SUS321HTB	TP321H	0.08	0.6	1.6	10.0	18.0	-	-	-	-	-	0.5	-	-	-
		A-1 (18Cr10NiNbTi)	Ka-SUS321J1HTB	-	0.12	0.6	1.6	10.0	18.0	-	-	-	-	0.10	0.08	-	-	-
		SUS316HTB (16Cr12NiMo)	SUS316HTB	TP316H	0.08	0.6	1.6	12.0	16.0	2.5	-	-	-	-	-	-	-	-
		SUS347HTB (18Cr10NiNb)	SUS347HTB	-	0.08	0.6	1.6	10.0	18.0	-	-	-	-	0.8	-	-	-	-
		TP347H (18Cr10NiNb)	Ka-SUSTP347HTB	TP347H	0.08	0.6	1.6	10.0	18.0	-	-	-	-	0.8	-	-	-	-
		TP347HFG (18Cr10NiNb)	-	TP347HFG	0.08	0.6	1.6	10.0	18.0	-	-	-	-	0.8	-	-	-	-
	15Cr-15Ni	17-14CuMo (17Cr14NiCuMoNbTi)	-	-	0.12	0.5	0.7	14.0	16.0	2.0	-	-	-	0.4	0.3	0.006	-	3.0Cu
		Esshete1250 (15Cr10Ni6MnVNbTi)	-	-	0.12	0.5	6.0	10.0	15.0	1.0	-	-	0.2	1.0	0.06	-	-	-
	20-25 Cr	SUS310TB (25Cr20Ni)	SUS310TB	TP310	0.08	0.6	1.6	20.0	25.0	-	-	-	-	-	-	-	-	-
		R3C (25Cr20NiNbN)	Ka-SUS310J1TB	TP310CbN	0.06	0.4	1.2	20.0	25.0	-	-	-	-	0.45	-	-	0.2	-
		Alloy 800H (21Cr32NiTiAi)	NCF800HTB	Alloy 800H	0.08	0.5	1.2	32.0	21.0	-	-	-	-	-	0.5	-	-	4.0Al
		A-3 (22Cr15NiNbN)	Ka-SUS309J4HTB	-	0.05	0.4	1.5	15.0	22.0	-	-	-	-	0.7	-	0.002	0.15	-
		709 (20Cr25NiMoNbTi)	Ka-SUS310J2TB	-	0.05	0.5	1.0	25.0	20.0	1.5	-	-	-	0.2	0.1	-	-	-
		E25 (22.5Cr18.5NiWCuNbN)	Ka-SUS310J3TB	-	0.10	0.1	1.0	18.0	23.0	-	1.5	-	-	0.45	-	-	0.2	3.0Cu
	High Cr-High Ni	R30A (30Cr50NiMoTiZr)	-	-	0.06	0.3	0.2	50.0	30.0	2.0	-	-	-	-	0.2	-	-	0.03Zr
		R6W (23Cr43NiWNbTi)	-	-	0.08	0.4	1.2	43.0	23.0	-	6.0	-	-	0.18	0.08	0.003	-	-

ferritic steel has possessed strength equivalent to austenitic heat-resistant steel. The following sections include movements and trends of development of ferritic and austenitic heat-resistant steel.

(1) Ferritic heat-resistant steel

As found in Fig. 5-3-1, in a ferritic system, low-alloy steel (STBA24, STPA24, etc.) and 9～12 Cr steel (STBA26 etc.) are representative materials that have been long used. However, the 100,000-hour creep-rupture strength (σr) of these materials reaches about

40 MPa at 600 ℃, and higher-strength materials were needed so that a superheater and a reheater could meet the requirements of higher temperature. Due to that the attainment of the σr value rose costs in 100 MPa-class 18 Cr-8Ni (SUS304HTB, SUS321HTB, SUS316HTB, SUS347HTB, etc.) austenitic stainless steels, efforts for increasing strength of 9～12 Cr steel were promoted. As a result, the first generation materials with σr of 60 MPa were developed from 1960 to 1970, and then the second generation materials with σr of 100 MPa were developed in 1980s. Also, the third generation materials with σr of 140 MPa were developed in 1990s. Subsequently, the next generation materials whose σr equals to 180 MPa were already developed for laboratory stage.

In particular, a modified 100 MPa-class 9Cr steel of which the (r is equivalent to 18Cr-8Ni stainless steel is widely used for superheater tubes, headers and steam pipes. For reference, the modified 9Cr-1Mo steel was adopted for a main steam pipe and a final superheater outlet header of the Kawagoe No. 1 unit (31.0 MPa, 566/566/566 ℃)[5], the first USC plant in Japan that started up in 1989.

Fig. 5-3-2[3] shows the development background of ferritic heat-resistant steel for boilers. In addition, typical materials and their corresponding specifications for these ferritic heat-resistant steel types and their nominal chemical compositions are listed in Table 5-3-2 (into which the tables in Refs.(3) and (4) were merged), along with austenitic heat-resistant steel described in the next section.

(2) Austenitic heat-resistant steel

The development background of austenitic heat-resistant steel is shown in **Fig. 5-3-3**[3][4]. For representative materials, their corresponding specifications and nominal chemical compositions, refer to Table 5-3-2.

18 Cr-8Ni stainless steel, a representative of austenitic heat-resistant steel, had been used for boiler materials in the world since the latter half of 1940s. In the Eddystone No. 1 unit (325 MW, 34 MPa, 649/565/565 ℃), an USC plant with the highest steam condition in the world that started up in 1960, TP316H was introduced into thick-wall pressurized parts of a header and a steam pipe. In addition, 17-14CuMo and TP321H were used in a superheater and a reheater.

For reference, the unit was constructed on the assumption of baseload operations, but in fact often started and stopped and caused creep damage to thick-wall pressure-proof parts. For this reason, the unit is currently being operated, decreasing its main steam pressure and temperature to 29.3 MPa and 588 ℃.

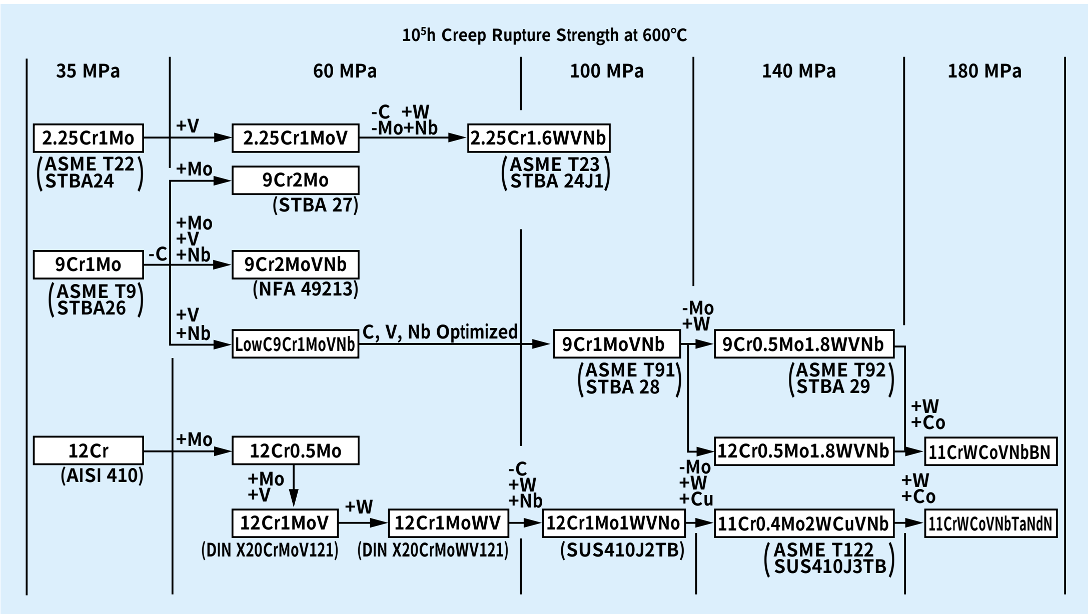


Fig. 5-3-2 The development of ferritic heat-resistant steel for boiler.

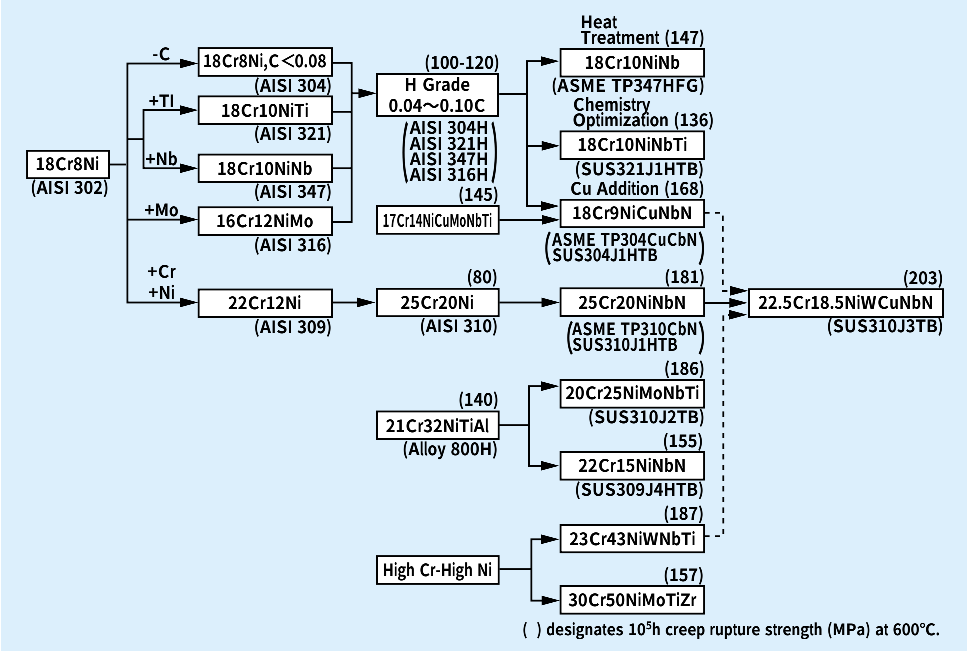


Fig. 5-3-3 The development of austenitic heat-resistant steel for boiler.

The subsequent development of high-strength materials progressed as shown in Fig. 5-3-1 and Fig. 5-3-3. New materials were developed that allow for environmental resistance to steam oxidation and hot corrosion and cost efficiency, in addition to strength applicable to boilers. For instance, resistance to steam oxidation became higher with finer grains of ASME TP347H, and ASME TP347HFG materials whose strength was increased were developed. These materials are used for final superheaters of the Kawagoe No. 1 and 2 units [(5)].

5-3-3 Advanced High-temperature Materials for USC Plants with Higher Thermal Efficiency

As described in the previous section, high-temperature materials greatly contributed to the attainment of higher temperature and pressure in steam conditions leading to high efficiency of thermal power plants. A high-grade austenitic steel was often used in initial ultra super critical pressure (USC) plants that were built in the U.S. and Europe at the latter half of 1950s. This was why that a focus on thermal stress on thick wall parts was not needed due to the assumption of baseload operations of these plants. However, a capability to regulate loads is required for recent thermal power generation, so the thermal stress cannot be ignored. For this reason, a ferritic steel, which provides smaller thermal stress than an austenitic one, is required to include high-temperature materials that possess high strength equivalent to that of austenitic materials. Under these circumstances, the National Institute for Materials Science has been promoting the development of ferritic heat-resistant steel used for thick-wall pressurized parts of USC boilers subject to 36 MPa and 650 °C since 1997 (6), as part of the Ultra-Steel Research Project.

In Japan, research and development on the realization of USC pulverized-coal fired plants started in 1980, and their higher temperature and pressure were gradually promoted [(7)(8)]. This process for their higher temperature and pressure had been accomplished with the development of high-strength and high-temperature materials, based on its basic design.

Firstly, in STEP-1 (31.4 MPa, 593/593/593 °C) of Phase-I (1980～1993), the latest ferritic steel at that time was adopted, for example, a modified 9Cr steel for boilers and a modified 12Cr steel (12Cr MoWVNb) for turbines. These are basically materials that are focused on as a continuation of traditional ultra critical pressure plant materials. Next, in STEP-2 (34.3MPa, 649/593/593 °C), a focus was placed on austenitic materials in order to accomplish the highest steam condition in the world. For instance, a Fe-base superalloy A286 became a candidate material for a turbine rotor. CRIEPI also shared research for evaluating these candidates and identified internal pressure creep rupture characteristics of a 17-14CuMo chromized tube and a 17-14CuMo/SUS310-clad tube for a boiler final superheater pipe and creep, thermal fatigue and other high-temperature and strength properties of modified 12Cr steel and A286 alloy for a turbine rotor [9][10][11].

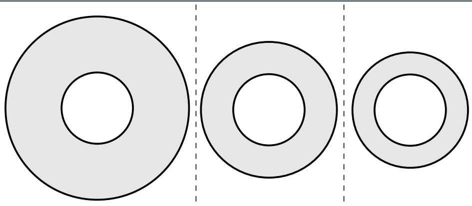
In Phase-II (1994～2000), in order to early realize an USC plant that is highly efficient efficiency, more economical and operational, ferritic new materials are increasingly used by setting a pressure of 30 MPa and a temperature of 630/630 °C as a steam condition. For instance, 9Cr-class steels such as 616 (9Cr-0.5Mo-2WVNb), 12Cr 12A (12Cr-0.4Mo-2Wcu VNb) and F12 (11Cr-2.6W-2.5CoVMbB) became candidate materials for a boiler ultimate superheater outlet header. **Table 5-3-3** [8] shows a comparison between dimensions of final superheater outlet header models made from current materials (STPA28) and these candidates, and the weight of the model based on the candidate materials becomes about 35～50 % of the that of the model based on the current materials. Therefore, the introduction of the candidates enables substantial wall thinning, which reduces thermal stress and provides cost efficiency. In addition, A286 alloy, which become a candidate material for a turbine rotor in STEP-2 of Phase-I, has high strength, but large thermal stress, less resistance to thermal fatigue, and it is difficult to produce its large ingot, so 12CrWMoCoVNbB steel is a candidate for a turbine rotor material in Phase-II that is being improved so that a 12Cr steel for 593 °C plants can be used at 630～650 °C. **Fig. 5-3-4** [12] shows the changes of past operating temperatures of rotor materials.

On the other hand, also in U.S. and Europe, research and development on USC plants were promoted [8][10]. In particular, in Europe, projects started recently that aim at higher steam conditions. One of them is a THERMIE program in Denmark that has been promoted since 1998 under a 17-year plan, aiming at the development of a 700 °C plant (target: 37.5 MPa, 700/720/720 °C) using Ni-base alloy. In addition, German has been independently developing a 700 °C USC plant (MARCKO DE2) since 1999 under on a 4-year plan. Furthermore, a COST522 project (1998～2003, target; 30 MPa, 620/650 °C) also started, focusing on the development of 650 °C ferritic steel materials.

5-3-4 Summary

As described above, research and development on USC plants in Japan outstripped that in U.S. and Europe, but has become recently behind that. Due to that the development, evaluation, demonstration and commercialization of new materials requires at least 10 years, efforts for past research and development in our country are now expected to continue while research and development on new materials to evolve and bring technological innovations.

Table. 5-3-3 Comparison between dimensions of ultimate superpeter outlet header models made from current material and farritic mew material

Material	STPA28 (current material)	616, 12A	F12
Shape 100mm			
Weight ratio	100	50	35

(1,000MW model)

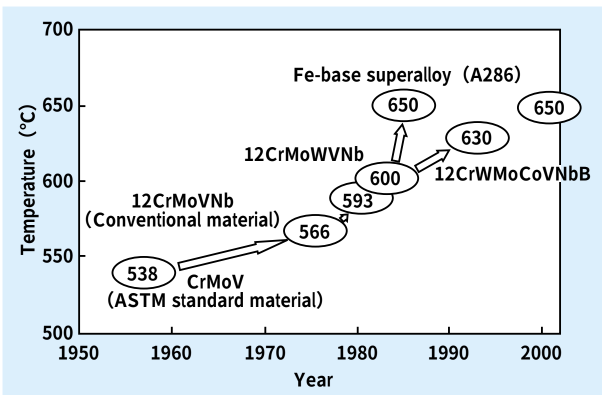


Fig. 5-3-4 The change of maximum operating temperature for steam turbine rotor material.

5－4 Improvement of Plant Efficiency by Reduction of House Load (Auxiliary Power)

Pulverized coal fired plants, which consists of lots of equipments, have higher auxiliary power ratio than other fuel fired plants. Its reduction is important for increase plant thermal efficiency. Recent power plants give considerations to the following items in order to reduce their auxiliary power.

1) Reduction of excess air ratio
2) Adoption of vertical type Pulverizer
3) Adoption of axial type Primary Air Fan
4) Without-application of Gas Mixing Fan
5) Adoption of super fineness Pulverizer
6) Application of low low temperature EP system
7) One line draft system

1) Reduction of excess air ratio

Excess air ratio for pulverized coal fired boiler had traditionally been applied 20 %, however, with advanced combustion technologies including development of high-performance burner, it has possible to reduce excess air ratio to 15 %. This 5 % reduction leads directly to reduce combustion air and flue gas flow rates of forced draft fan (FDF) and induced draft fan (IDF), so this auxiliary power for these fans can be reduced about 5 %.

2) Adoption of vertical type Pulverizer

Pulverizer (mill) type is broadly divided into horizontal type ball mill and vertical type roller mill. The horizontal type ball mill has a higher coal volume with inside and it makes advantage of rapid response during load change operation, however, in recent years, vertical type roller mill with low pulverizing power is generally adopted for coal fired plants.

In general, a vertical type roller mill can provide grinding power less 60～70 % than horizontal type.

3) Adoption of axial type Primary Air Fan

Required characteristics for Primary Air Fan is higher static head during low air flow rate condition at boiler low load operation, therefore, centrifugal fan was generally applied.

However, fan efficiency of centrifugal fan has of 60 to 70 % while axial fan has 80 % or more, so it is desirable that axial fan be adopted in order of reduce auxiliary power consumption. When axial fan is selected for PAF, it is necessary to consider deterioration of fan performance during operation so that stable fan operation can be accomplished even at boiler low load operation.

4) Without-application of Gas Mixing Fan

Gas Mixing Fan (GMF) was traditionally installed for pulverized coal fired boiler as countermeasure for NOx reduction same as fuel oil or gas boiler. With significantly advanced NOx reduction technologies for coal fired boiler including recent combustion technology and in-furnace NOx reduction technology has been reviewed, and it has been confirmed that the gas mixing provided less effects. For this reason, no need for installation of GMFs in recent coal fired boilers contributes to reduced auxiliary power.

5) Adoption of super fineness pulverizer

A super fineness pulverizer with increased pulverizing performance, an improvement of a vertical type mill, is practically used. In comparing to conventional type, the pulverizer expands pulverized area and applied rotating classifier for improvement of classified performances. By application of this pulverizer can reduce glinding power by a few percentages, and if excess air ratio can be reduced, the decrease of unburnt carbon in flyash and fan power can be expected.

6) Application of low low temperature EP system

A more efficient low low temperature EP system is often adopted for flue gas treatment system for recent domestic large coal fired units. The application of this system helps reduction of auxiliary power consumption.

In conventional low temperature EP system, IDF inlet gas temperature was designed as approximately 130～140℃. To compare with this condition, the temperature is set as about 90℃ in the recent low low temperature EP system. The reduction of IDF power consumption is achieved to the decrement of this flue gas temperature.

7) One line draft system

One line draft system can simplify the system and reduce draft loss. These years, one line draft system case has been increasing also in large utility boilers, and the case is applied in even 600 MW unit.

5－5 Future Plan

Coal fired power generation plants, that generates more CO_2 per unit heat value than natural gas or oil fired power plants, are desired to be more efficient in terms of protection of global environments. Also in Japan, a pressurized fluidized bed combustion (PFBC) power plant, or a high-efficiency coal fired power plant, has entered into a commercialization phase while a plan to construct a 250 MW demonstration unit for an integrated coal gasification combined cycle power generation (IGCC) is currently being pushed forward. Higher temperature and pressure for steam conditions are essential to attain high efficiency of pulverized coal fired plants. EPDC's Isogo New No. 1 unit (600 MW), which started up in 2002, adopted a main steam pressure of 26.6 MPa, a main steam temperature of 600℃ and a reheating steam temperature of 610℃.

This, as mentioned above, is the result of a national project of a developing company, EPDC and other plant makers, in cooperation with the Ministry of Economy, Trade and Industry (former Ministry of International Trade and Industry), through 1982 to 2000. Phase-2 for USC technological development finished in 2000, but pulverized coal fired power plants based on the conditions of Phase-2 is currently not planned due to slowdown in power demand. In addition, power retail services for large customers demanding 20,000 V and 2,000 kW or more started on March 2000, and an expanded range of electric power industry deregulation is now being reviewed. Under these circumstances, electric power companies are making more managerial efforts for cost reduction and are forced to have strong cost-consciousness in introducing new technologies.

On the other hand, international USC development projects were implemented in Japan, U.S. and Europe during 1980s. The EPRI-ICPP project, which was led by EPRI in U.S. and was participated in by Toshiba and GE, finished in 1991, and the continuing projects were only USC Phase-2 in Japan and COST501 in Europe (development of 600℃ USC materials).

However, a project for development of 650~700℃ USC plants started around 1998 in Europe where the dominant steam temperature of thermal power plants was 566℃.With the completion of COST501 led by U.K., COST522 (development of 650℃ USC materials), being supported by 16 countries in Europe, started in 1998. In addition, Denmark, which earnestly aims at the development of USC plants, often depends on district power generation plants to provide district heating and is keen on USC technologies, although having less interest in combined cycle plants. "THERMIE PROGRAM" started in 1998, on which a leading ELSAMPROJEKT (currently WISE-TECH) and other 40 companies in Europe aimed at developing a 700℃ USC plant under a 17-year project. Furthermore, Germany independently commenced the development of a 700℃ USC plant (MARCKO DE 2) within 4 years from 1999 and is currently scheduled to construct a coal fired USC plant (350 MW, 29 MPa, 600/625℃).

Future high efficiency of pulverized coal fired plants must be reviewed in consideration for power demand, plant cost-effectiveness and operability, and it should be important to develop technologies for small- and medium-sized equipment which is considered to have a possibility of improvement of efficiency. In addition, it is essential to increase the reduction of an auxiliary power ratio in pulverized coal fired plants with a lot of components.

Furthermore, from the standpoint of plant cost efficiency, reduction of manufacturing and processing costs of new materials for higher temperature and pressure, plant downsizing and a sophisticated method for designing casing structure and other construction will be important challenges.

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Chapter

6

Improvement of Environmental Technology of Pulverized Coal Combustion Power Plants

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Hisao Makino (Dr.)
Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

Hiromi Shirai (Dr.)
Senior Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

Naoki Noda
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

6－1 Research Background

With increasingly strict demand for environmental protection, various environmental protection technologies are being developed in pulverized coal combustion power plants. Particularly in Japan, after the latter half of 1960s when attention was focused on air pollution problems, environmental protection technologies were rapidly promoted, which substantially reduced emissions of environmental pollutants.

Environmental pollutants included particulate matters (dust), sulfur oxides (SOx) and nitrogen oxides (NOx) as air contaminants mainly.

Under "the Law Concerning Regulation of Smoke and Soot Emissions" in 1963 and "the Air Pollution Control Law" in 1968, an electrostatic precipitator with high collection efficiency was introduced in 1966 in order to control dust emission. Next, in order to control sulfur oxides (SOx) and control environmental influence, a low sulfur fuel was used and furthermore high stacks and centralized stacks were employed. In 1973, a high-efficiency flue gas desulfurization equipment using a limestone-gypsum process was developed, and the installment of the flue gas desulfurization equipment into power plants was started. In addition, in 1974, the introduction of regulation of total mass emission was incorporated into the Air Pollution Control Law.

The law concerning regulation of nitrogen oxide emissions was established in 1973, which promoted the development of a NOx reduction method based on control of combustion conditions, that is an improved low NOx combustion method and a low NOx burner. On the other hand, in 1977, a NOx removal (De-NOx) unit using a selective catalytic reduction process started to be introduced.

As coal has higher nitrogen, sulfur and ash content than that of oil and natural gas, the concentrations of NOx, SOx and dust generated from coal combustion become higher. For this reason, a technology for reducing emissions of these substances is very important.

Fig. 2-2-1 (page 12) shows an process flow of a usual pulverized coal combustion power plant in Japan. SOx was reduced with a wet type flue gas desulfurizer, while emissions of particulate matter were decreased with a combination of a high-performance electrostatic precipitator and a wet flue gas desulfurizer. At present, these emission concentrations are limited to the lowest level in the world. Now, more efforts to improve desulfurization and dust collection technologies toward higher environment protection and lower costs are being performed.

On the other hand, NOx is reduced with a combination of a De-NOx unit on a selective catalytic reduction method and a low NOx combustion technology (burner and total combustion technology). A De-NOx unit has an established technology, and the point which is required the improvement is only cost reduction and longer life of a catalyst. A low NOx combustion technology on which the amount of NOx generated is reduced with combustion control requires no substantial remodeling of equipment and allows reduction of necessary costs, so the development toward the higher performance combustion technology is energetically still being studied and developed, as one of the most important challenges for an advanced pulverized coal combustion technology.

6－2 Characteristics of Flue Gas Treatment System

A flue gas treatment system in a pulverized coal combustion power plant consists of a dust collector, a De-NOx equipment and a desulfurization equipment. Currently, a De-NOx equipment employs a selective catalytic reduction (SCR) method on which NOx is selectively reacted and decomposed into water (H_2O) and nitrogen (N_2) by a catalyst after blowing ammonia (NH_3) into a flue gas. A dust collector mainly uses a electrostatic precipitator which remove dust particle in the electric field by charging and a desulfurization equipment uses a limestone-gypsum method on which SOx is removed by the reaction with lime stone slurry. The configuration of the flue gas treatment system is determined according to the best operating temperatures of these systems.

In principle, a De-NOx equipment is set at a temperature of 350 ℃, while a desulfurization equipment is set at 40～50 ℃, so the De-NOx is installed upstream. An electrostatic precipitator (ESP) has a high temperature type operating at 350 ℃, a low temperature one at 150 ℃ and an advanced low temperature one at 90 ℃. The three types of flue gas treatment systems according to the operation temperature of ESP.

6-2-1 System Using a Low Temperature Electrostatic Precipitator

In currently operating pulverized coal combustion power plants, a system with a low temperature electrostatic precipitator operating at 130～150 ℃ in **Fig. 6-2-1** is mostly used.

The flue gas from a boiler enters into a De-NOx equipment at 300～400 ℃. After NOx is removed from the gas, the heat of the gas is heat exchanged for combustion air in an air heater and enters into a low temperature electrostatic precipitator which being operated at the temperature of 130～150 ℃. Then, the dust particle is removed the heat of the flue gas with low dust concentration is exchanged for treated flue gas in a gas-gas exchanger (GGH) and enters into a desulfurizer after being cooled to about a temperature of 90 ℃. Then, SOx is removed. This flue gas treated is heated to a temperature of 90～100 ℃ at GGH and released from a stack. In addition, there is another process on which desulfurized gas is heated with an

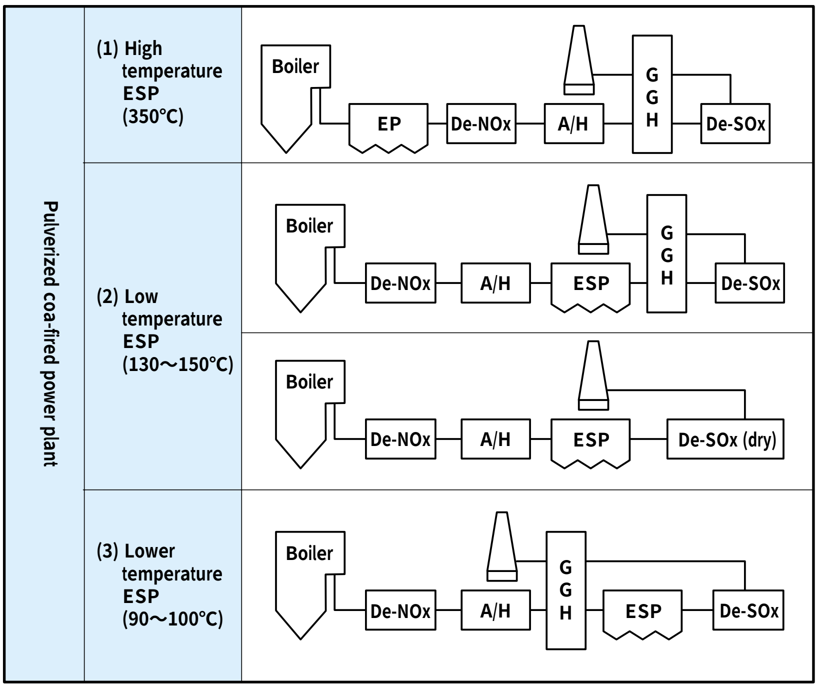


Fig. 6-2-1 Flue gas treatment system

afterburner without installment of GGH.

Until an advanced low temperature electrostatic precipitator was developed, this system was a mainstream. The following flue gas treatment system was adopted into most pulverized coal fired power plants by using an advanced low temperature electrostatic precipitator with higher collection efficiency.

6-2-2 System Using an Advanced Low Temperature Electrostatic Precipitator

The system is intended to reduce electric resistivity of coal ash and increase collection efficiency by the operation at a low temperature of about 90 °C. In this system, GGH is installed before an electrostatic precipitator, in contrast to the system using a low temperature electrostatic precipitator. Flue gas after the desulfurization and dust collection is heat exchanged for flue gas before the collection, GGH without gas leakage is used. In addition, there can be seen the system which increased collection efficiency by installing a wet electrostatic precipitator after a desulfurization unit. This system attained higher total efficiency with collection efficiency of particulate matter of 99.9% or more, De-NOx efficiency of 90% and desulfurization efficiency of 97 %.

6-2-3 System Using a High Temperature Electrostatic Precipitator

Electric resistivity of coal ash is decreased also at high temperatures. A system, which utilized this feature, is a high temperature electrostatic precipitator and in this system, ESP is installed before a De-NOx unit, and removes dust at a high temperature of about 350 °C. The heat of flue gas with low dust concentration is exchanged in GGH after De-NOx and desulfurization. This precipitator has not been constructed recently, as a unit size become larger because flue gas volume become larger.

6－3 Low NOx Combustion Technologies

6-3-1 Existing Low NOx Combustion Technologies

NOx generated from a fuel combustion is classified into fuel NOx from oxidation of nitrogen compound in fuel and thermal NOx from oxidation of nitrogen in air. Thermal NOx is generated at high temperatures, and some literatures reported that correspond to thermal NOx about 20 % of NOx emissions in coal combustion.

A concept of a conventional low NOx combustion is to control oxidation atmosphere and adjust a combustion condition to reduce the NOx formation as low as possible. The mainstreams of a low NOx combustion method were a low NOx burner that reduces NOx initially generated, a low air ratio combustion method and a two stage combustion method that weaken oxidation atmosphere and controls the formation of NOx, an exhaust gas recirculation method that decreases flame temperatures and controls the formation of NOx.

(1) Reduction of Initial NOx

A method to reduce NOx initially generated is a conventional low NOx burner, due to reduced NOx generated in a furnace. The structure of a SGR (Separate Gas Recirculation) burner is shown in **Fig. 6-3-1** as an example of this method. This burner control initial oxidation by introducing pulverized coal and the primary air from the center, combustion flue gas recirculation gas called SGR from the top and bottom stages of primary air stage, and combustion auxiliary air from the top or bottom stages of SGR. SGR, which introduces combustion flue gas in between primary and auxiliary air, is used to control early mixing of auxiliary air and oxidation atmosphere in a volatile combustion area where NOx is mainly formed, and reduce combustion temperatures.

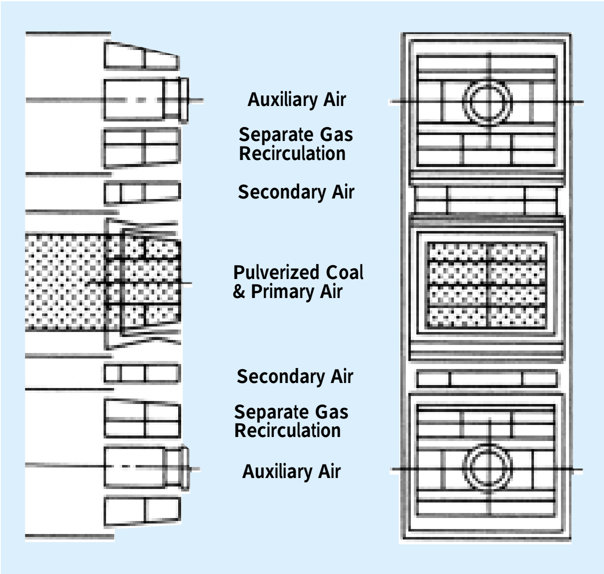


Fig. 6-3-1 Pulverized coal burner

(2) Decrease of Air ratio

As a method for decreasing air ratio of initial combustion area, the low air ratio combustion is utilized at first.

This method can reduce the volume of a flue gas and decrease heat loss from a flue gas, and ensures to decrease NOx concentrations with a reduced air ratio (excess O_2 concentration), as shown in **Fig. 6-3-2**. As shown in the figure, however, the method has a disadvantage of increase of unburned carbon concentration in fly ash (Uc: ratio of remaining combustibles in coal ash generated during combustion) and CO. In particular, as that CO tends to significantly increase under a condition of a lower air ratio, a low air ratio combustion has a limit to perform the reduction of NOx. At present, the operation of a combustion on a critical lowest air ratio in consideration for these factors has been already implemented.

Next, a two stage combustion method is implemented to decrease only an air ratio of primary combustion area near a burner that greatly affects the formation of NOx without extremely decreasing an overall air ratio. This method is a process on which a part of air supplied from a burner is divided and introduced into a wake flow of flame. Because of a reduction atmosphere of low air ratio around the burner, the formation of NOx is controlled and remaining unburned carbon can be re-burned by the two staged combustion air introduced from the air injection port. The effect of NOx reduction on the two stage combustion method is shown in **Fig.6-3-3**. A two stage combustion ratio (Rs) is a ratio of two stage combustion air (As) to total combustion air (AT) and is defined as Rs=As/AT.

In any coal type and furnace, NOx is reduced with an increasing two stage combustion air ratio, but a tendency cannot be avoided that unburned carbon concentration in fly ash increases with reduced NOx.

(3) Decrease of Combustion Temperature

A flue gas recirculation method, which is most common method for reducing gas temperature to

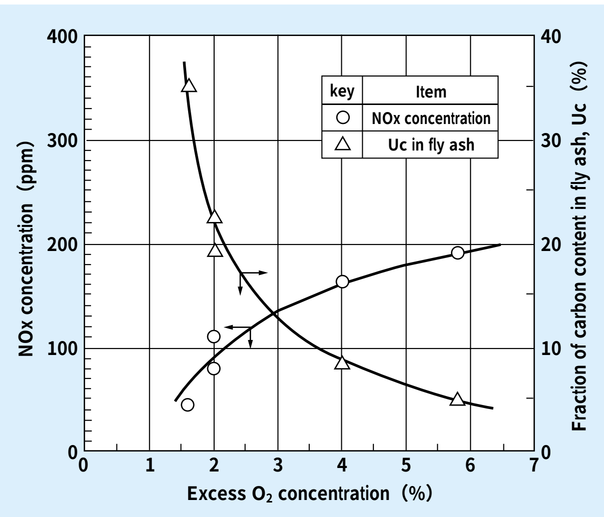


Fig. 6-3-2 Influence of excess O_2 concentration on NOx and Uc

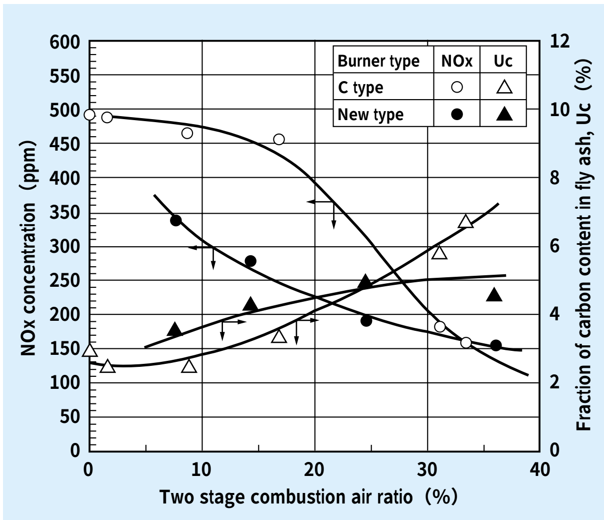


Fig. 6-3-3 Influence of two stage air ratio on NOx and Uc

control the formation of thermal NOx, is a process on which a flue gas is mixed into combustion air. This method is effective in control the thermal NOx formation, but is considered to have little effect on the reduction in pulverized coal combustion power plants generating mainly fuel NOx for the reason that fuel NOx is not reduced under slightly decreased combustion temperatures. As described above, a lot of low NOx combustion technologies based on the control of NOx formation have been developed and implemented so far, but only this method could not sufficiently reduce NOx and showed a tendency that unburned carbon concentrations in fly ash increased with reduced NOx . So, a combustion method on which reduction and decomposition of NOx generated are promoted to reduce NOx emission. This method is recently being developed and becoming the mainstream of a low NOx combustion method, as a method being particularly adequate for pulverized coal combustion mainly emitting fuel NOx.

6-3-2 Overview of Advanced Low NOx Combustion Technology

In order to develop a advanced low NOx combustion technology, an advanced low NOx burner that can form NOx reduction flame near a burner as fast as possible and reinforcement of NOx reduction flame through an overall furnace are investigated.

CRIEPI has developed an advanced low NOx combustion technology in order to reduce NOx generated from a pulverized coal combustion and control the increase of unburned carbon concentration in fly ash. A concept for this technology is shown in **Fig. 6-3-4**, in comparison with conventional low NOx technologies. In this combustion method, the nitrogen release from coal and reduction of remaining solid unburned carbon are accomplished by accelerating thermal decomposition of coal at a high-temperature field with a low air ratio condition during initial combustion near a burner, and NOx generated during initial combustion is decomposed and reduced in the

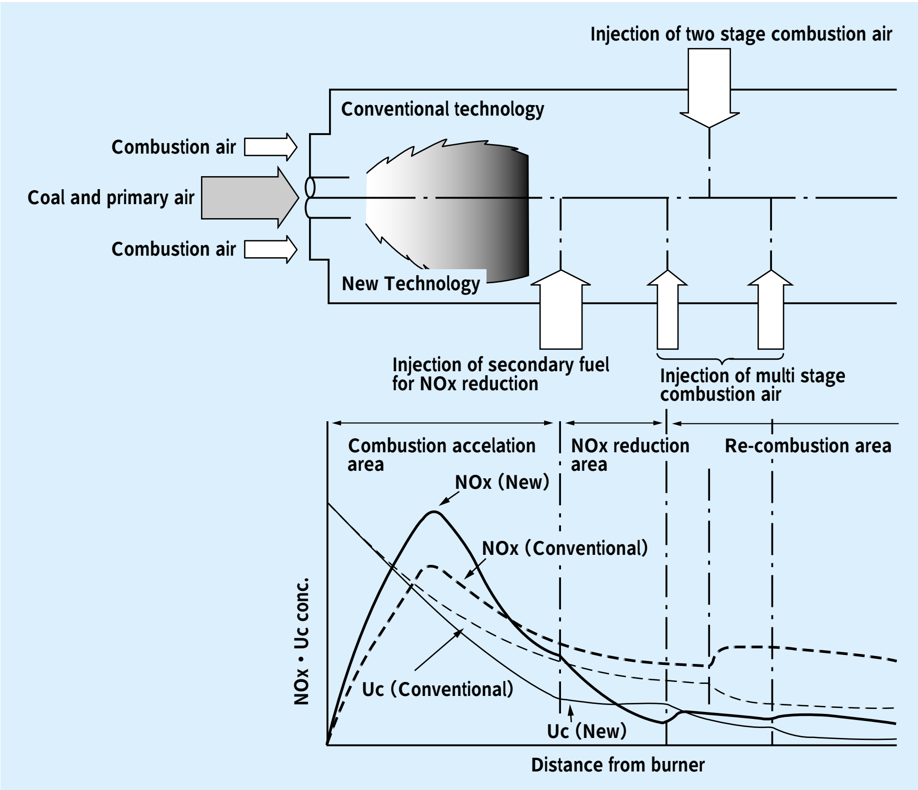


Fig. 6-3-4 Concept of low NOx and low unburned carbon combustion technology

flame of reduction atmosphere formed in a wake flow. Unburned carbon is re-burned and reduced by introducing two stage combustion air into the wake flow. In this case, the significant increase of a two stage combustion ratio is required for substantial decrease of NOx concentrations. However, as that re-burn of the unburned carbon at the air injection point for two stage combustion increases the amount of NOx re-generated, a multi-stage air injection method on which staged combustion air is introduced from several position is employed in order to control the regeneration of NOx at the staged air injection point. This enables effective reduction of NOx and unburned carbon concentration in fly ash.

6-3-3 Development of Advanced Low NOx Combustion Technology

(1) Development of advanced low NOx burner

In order to provide an adequate burner for a low NOx combustion concept as described above, the burner should have the functions to be able to form a high-temperature reaction field where thermal decomposition of coal is more accelerated and oxygen is consumed faster and ensure sufficient residence time of pulverized coal particulates in this high-temperature reaction field. CRIEPI started to develop a low NOx burner that accelerates ignition of pulverized coal and extends residence time of the coal particles in the reaction field using recirculation flow as shown in **Fig. 6-3-5** and commercialized the burner based on the following procedures, in a cooperative research with the Ishikawajima-Harima Heavy Industries Co., Ltd. (hereafter referred to "IHI").

a) Investigation on a burner structure using on cold-flow model

In order to elucidate the effect of a burner structure on the formation of a recirculation flow, the characteristics of flow in a non-combustion field were investigated. After introducing NO, as a tracer gas into a primary air nozzle where pulverized coal is carried in an actual burner, whether a flow blown out from the burner would extend in a way of forming a recirculation flow or go straight, was determined from a mixing state of secondary and tertiary air shown on a shape of NO isoconcentration. in order to evaluate structures of a burner nozzle, three types of nozzles of convergent, straight and extended structures for primary, secondary and tertiary air pipes were prepared.

Fig. 6-3-6 shows a flow state in the case of nozzle structures for secondary and tertiary air are same but different from the structure for a primary air nozzle. In the case that a primary air nozzle has a straight structure, a tracer extends radially immediately after air injection into a furnace, which demonstrates the formation of a recirculation flow in which air with low tracer concentrations is introduced into an axis part of a burner. In contrast, in the case that a primary air nozzle has a convergent shape, a tracer tends to extend in a flow direction under a dominant straight flow, which clarifies a flow pattern greatly varies with the shapes of a primary air nozzle. Based on these considerations, it was demonstrated

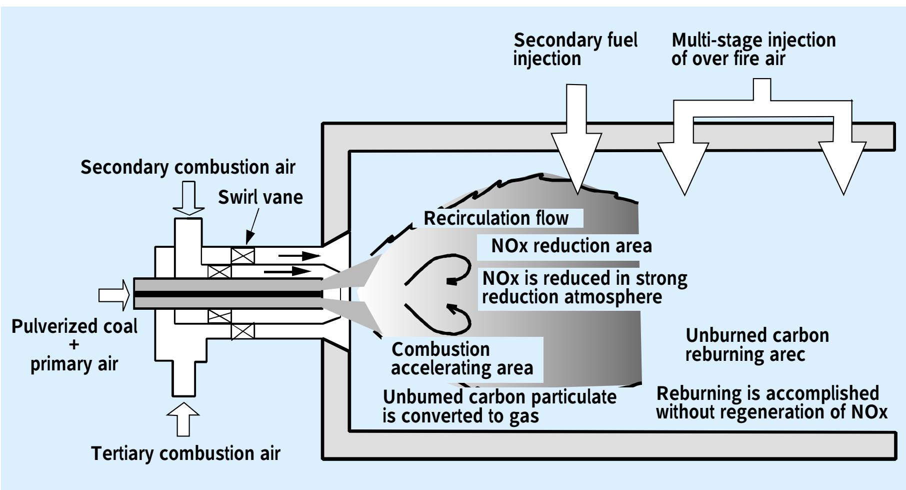


Fig. 6-3-5 Concept advanced low NOx burner

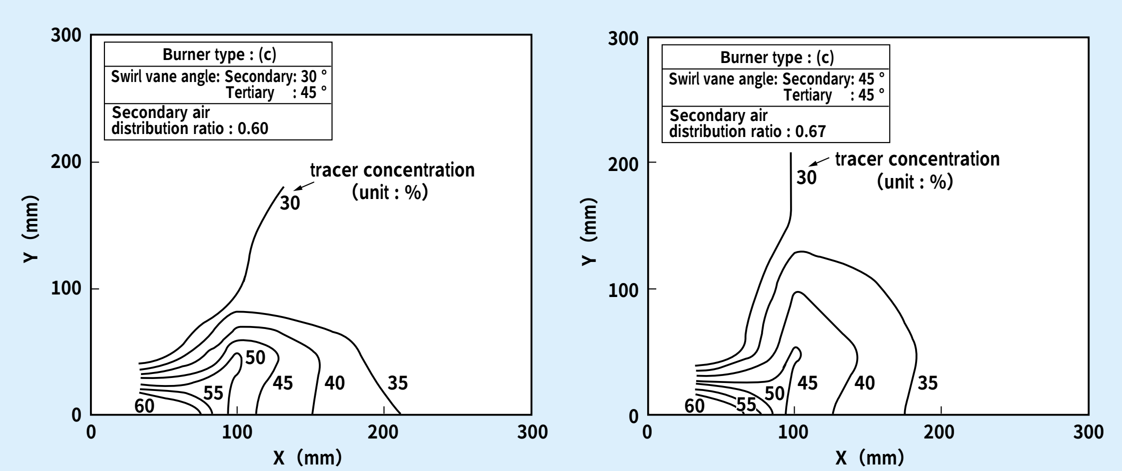


Fig. 6-3-6 Influence of swirl vane angle and secondary air distribution ratio on the formation of recirculating flow

that in an extended shape flame that forms a recirculation flow could be generated only in a straight-shape primary air nozzle and that the best recirculation flow was formed in convergent-shape secondary and extended-shape tertiary air nozzles.

b) Investigation on burner operating conditions using pulverized coal combustion test facility

The combustion characteristics of the burner which is estimated suitable shape by a cold-flow test was investigated in CRIEPI's pulverized coal combustion test facility with a coal feed rate of 100 kg/h.

Fig. 6-3-7 shows four types of burners used for a combustion test. Of them, Type II is a shape of the burner that was evaluated to be the best in the cold-flow test, while Type I is a shape of an IHI's conventional low NOx burner (DF burner). A difference between Type I and Type II lies in nozzle shapes for primary and tertiary air. So, in order to separately evaluate the effects of the two different points, using the two types of burners whose primary air nozzles were replaced, combustion characteristics is evaluated. A burner that is most effective in NOx reduction in an actual combustion field was selected after studying the effects of a combustion air rate and swirl conditions on the emission characteristics of NOx and unburned carbon in fly ash and conducting a experimental comparison of the performance of four types of burners.

Fig. 6-3-8 showed the effect of a secondary air distribution ratio (ratio of secondary air rate to a sum of secondary and tertiary air rates) on NOx concentrations. Any of Type I to IV burners provides a minimum value of a NOx concentration for a secondary air distribution ratio of about 20 %. In this ratio, an air ratio in a primary combustion area near a burner, total air ratio of primary air and secondary air injected from the outside of primary air, reaches about 0.4. Under a condition exceeding this air ratio, a NOx concentration becomes higher due to insufficient reduction of NOx. On the other hand, under a condition below this air ratio, the amount of NOx generated in a primary combustion area decreases, but the amount of other nitrogen compounds generated such as NHi and HCN increases and these compounds easily react with tertiary air introduced from the surrounding area or two stage combustion air and are converted to NOx, which is considered to result in an increased NOx concentration. Under a condition of a higher secondary air distribution ratio in an area without plotting as shown in the figure, the flame is blown off. A Type II burner shows that the flame of type II burner can exist stably under the widest condition and also the type II burner provided the lowest NOx concentration under all test conditions in four burners. A Type III burner provided the second lowest NOx concentration while there was not much difference between NOx concentrations in Type I and IV burners. This demonstrates that the shape of a primary air nozzle blowing out pulverized coal has a

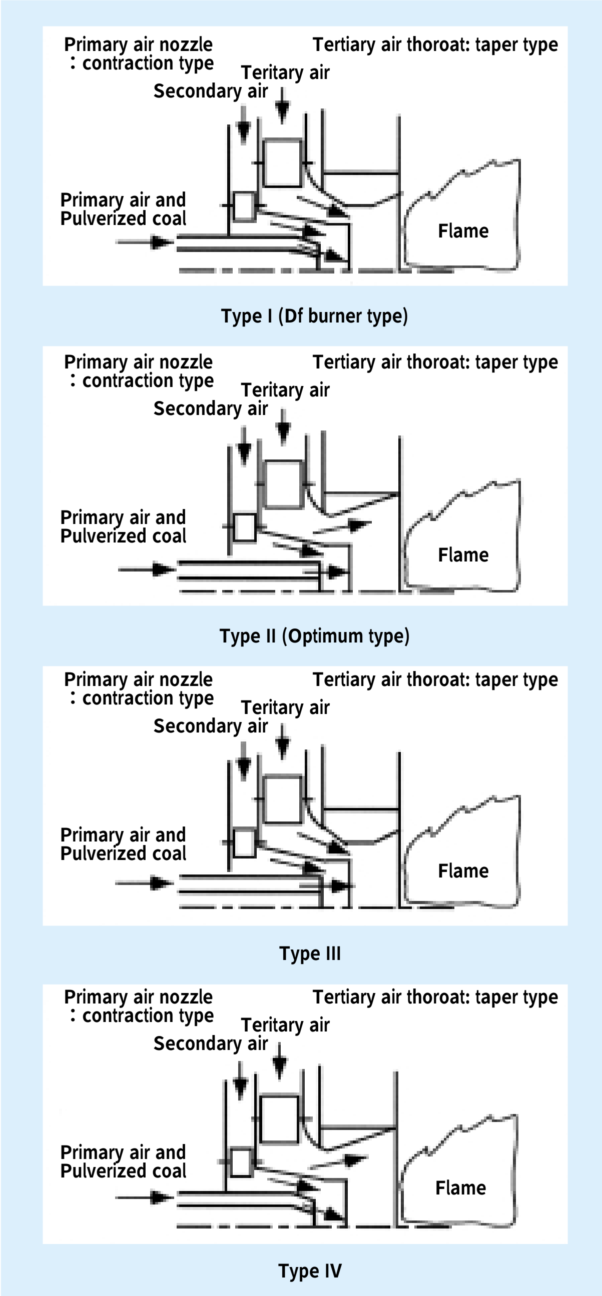


Fig. 6-3-7 Illastration of four burners

greater effect on NOx concentrations than that of a tertiary air nozzle.

These characteristics were evaluated also when swirl strength of primary, secondary and tertiary air. As a result, it was clarified that a Type II burner had the best shape, and the optimal air injection condition (injection air ratio and swirl vane angle) was found. Based on these results, it was decided that this type burner was employed as a advanced low NOx burner (CI-**α** burner: CRIEPI-IHI Advanced Low

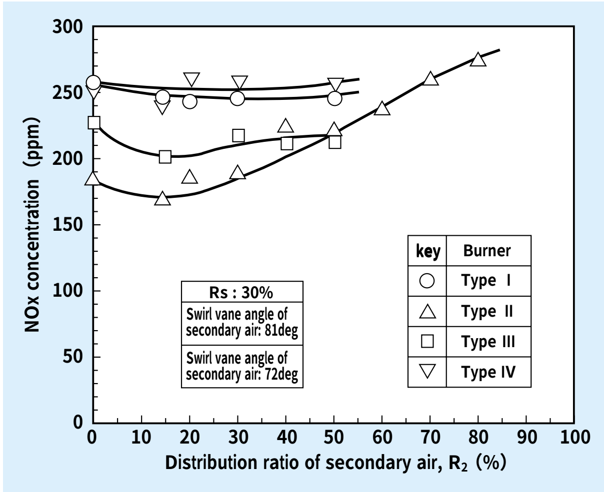


Fig. 6-3-8 Relation between NOx concentration and distribution ratio of secondary air (Rs: Two stage combustion air ratio)

Pollution High Ability Burner).

c) Investigation on scale-up of CI-α burner

As descried in the previous section, CI-**α** burner that can promote fast thermal decomposition and formation of reduction flame was developed in the pulverized coal combustion test facility using a single burner, with a coal feed rate of 100 kg/h. In an actual utility boiler, several large-capacity burners with a coal combustion rate of a few tons/h are used. In this case, a recirculation flow near the burners becomes larger and the flame interacts each other, so it is necessary to clarify these effects by using a large-capacity burner or a multi-burner for the utilization of this burner. In order to determine the applicability of CI-**α** burner to an actual utility boiler, CRIEPI evaluated combustion characteristics when CI-**α** burner is scaled up to a medium-capacity multi-burner (a coal combustion rate of 375 kg/h × 4 burners) and a large-capacity single burner (1.5t/h × 1burner) in IHI's large test furnace.

A relationship between NOx and unburned carbon concentration in fly ash when CI-**α** burner is scaled up to a medium-capacity multi-burner is shown in **Fig. 6-3-9**. CI-**α** burner was demonstrated to significantly reduce both of NOx and unburned carbon concentrations in fly ash, in comparison with conventional type burners. In particular, it became clear that CI-**α** burner provided a greater reduction effect under a combustion condition of lower NOx concentration and had higher performance during

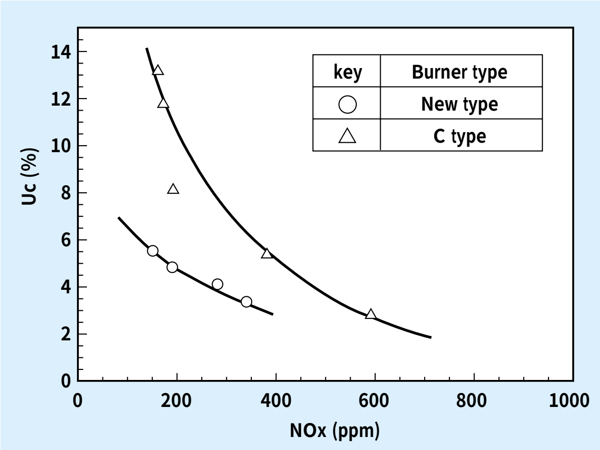


Fig. 6-3-9 Relation of NOx and fraction of carbon content in fly ash

lower NOx combustion. In addition, a large-capacity single CI-**α** burner showed the same tendency. It becomes clear that a scaled-up CI-**α** burner provides sufficient reduction effect of NOx and unburned carbon in fly ash.

Based on these results, this burner was employed for the industrial power plants corresponding to 149 MW on April 1999, and its high performance was confirmed.

(2) Development of multi-stage air injection method

a) Optimization of two stage combustion method

In a two stage combustion method that has been often used as a low NOx combustion technology, NOx reduction greatly depends on air injection positions. **Fig. 6-3-10** shows a relation between injection positions of two stage combustion air and NOx, unburned carbon concentration in fly ash in CRIEPI's test furnace. As an air injection position is moved away from a burner, a region of reduction atmosphere is extended, NOx concentration decrease, showing a tendency of their significant reduction particularly at a position 2～3 m from a burner. In contrast, unburned carbon concentration in fly ash increases as a position is moved away from burner, sharply increasing particularly at a position 3 m or more from a burner. This position is slightly further position than an air injection point where NOx concentration significantly reduce. Considering effective reduction of both of NOx and unburned carbon in fly ash based on this tendency, there is an optimal injection point for a two stage combustion. And that is about 3 m away from a burner in this test furnace.

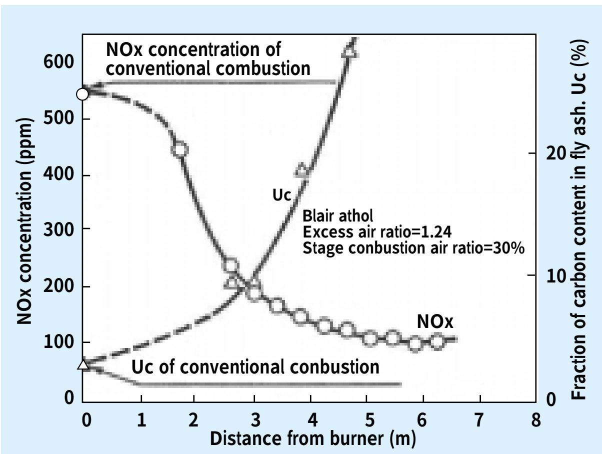


Fig. 6-3-10 Relation between injection point of over fire air and NOx emission, fraction of carbon in fly ash

Even if a two stage combustion air injection position is set at the best point, NOx concentration tend to decrease with increasing a two stage combustion air ratio under a condition of a lower combustion ratio, forever NOx concentration slightly reduce at a two stage combustion ratio of around 30 % while rising NOx at a two stage combustion air ratio of 30 % or more. In the case that a two stage combustion air ratio is extremely increase, NOx is sufficiently reduced in the primary combustion area before a two stage combustion air injection position, but unburned carbon remains in large quantity and this unburned is re-burned at the air injection position, which regenerates NOx and increases the concentration at a furnace outlet.

b) Investigation on multi-stage air injection method

In order to control the re-generation of NOx at a two stage combustion air injection position, an multi-stage air injection method was considered as a method on which a staged combustion air is separately introduced. A NOx concentration distribution on the center axis of a burner is shown in **Fig. 6-3-11** when a staged combustion air is separately injected at the positions of 2.99 m and 4.99 m from the burner with a two stage combustion air ratio of 40 %. NOx generated near the burner is sufficiently reduced in the primary combustion area before a two stage combustion air injection position, and the concentration decreases to about 100ppm. However, when 40 % of total staged

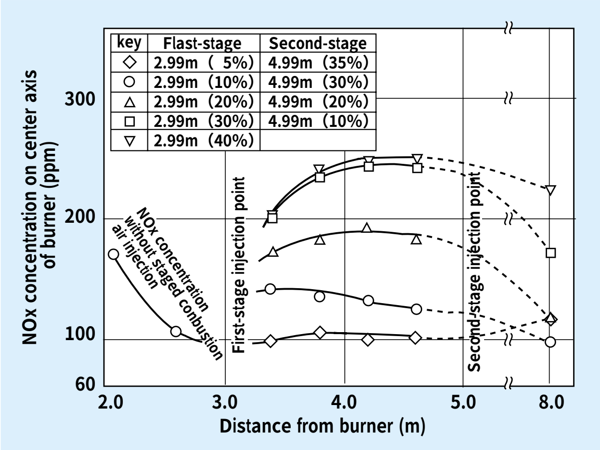


Fig. 6-3-11 Distribution of NOx concentration on center axis of burner

combustion air is introduced at a first stage injection position, NOx is re-generated, and the concentration increases to 250ppm. Allocating a part of injected air to a second stage injection position reduces the amount of NOx re-generated, but when the amount of a two stage combustion air injected at the first stage position is extremely reduced, the amount of air injection at the second stage increases, which increases the amount of NOx re-generated there.

From this tendency, it is considered that appropriate allocation of a two stage combustion air on multi stage air injection system can control the re-generation of NOx and effectively reduce NOx concentrations.

Fig. 6-3-12 shows the comparison of NOx concentration on the condition of 3% unburned carbon in fly ash, based on a conventional combustion method (a combination of an conventional low NOx burner and two stage combustion), a combination of CI-α burner and a two stage combustion and a combination of CI-α burner and an air multi-stage injection method. It is demonstrated that an multi-stage air injection method can reduce a NOx concentration by about 30 % and that a combination of a CI-α burner and an multi-stage air injection method enables 50 % reduction of NOx compared to the conventional low NOx technology.

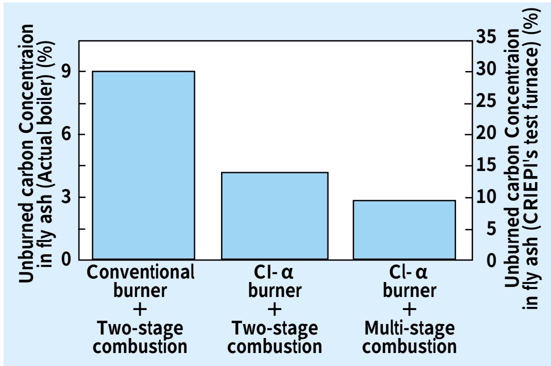


Fig. 6-3-12 Comparison of unburned carbon concentration in fly ash at 100ppm of NOx concentration

6－4 De-NOx Technology

6-4-1 Overview of Selective Catalytic Reduction Type Denitrification Unit

In pulverized coal combustion power plants, a selective catalytic reduction (SCR) method is used. In this method ammonia (NH_3) is blown into flue gas and NOx selectively react with NH_3 by catalysis and decompose NOx into moisture (H_2O) and nitrogen (N_2) as shown in equations of 6-4-1 and 6-4-2. In a De-NOx equipment, as dust is contained in flue gas, a grid or plate type catalyst shown in **Fig. 6-4-1** is mainly used. The catalyst is charged into a reactor as shown in **Fig. 6-4-2**.

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \qquad \text{6-4-1}$$

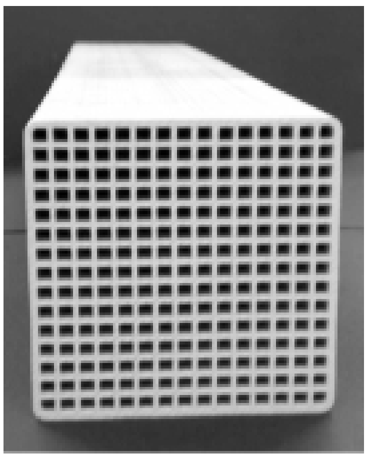


Fig. 6-4-1 De-NOx catayst

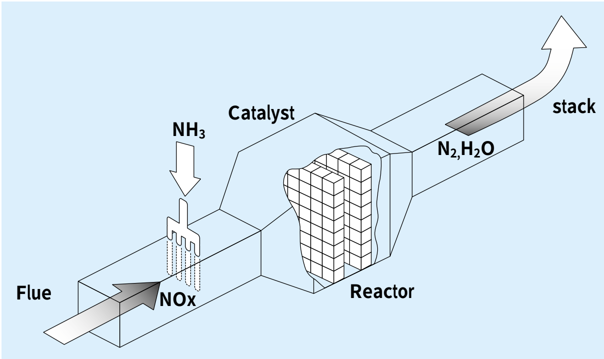


Fig. 6-4-2 Outline of De-NOx unit[9]

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \qquad 6\text{-}4\text{-}2$$

At operating temperature ranges over 300 to 400 °C, a catalyst has the highest activity. In addition, The concentration of leaked NH_3 from a De-NOx equipment is at lower than 5ppm. In the case of high leaked NH_3 concentration, NH_3 reacts with SO_3 in flue gas and generates NH_4HSO_4 that is deposited at an air preheater, and plugs it.

A De-NOx efficiency equals to about 80 to 90 % in pulverized coal combustion power plants. On the other hand, in order to support a large boiler, it is important that NH_3 must be uniformly distributed into flue gas and mixed with the gas. Various measures for this task include that a plate of gas flow control, called guide vane, is installed at a gas inlet and that the gas inlet is divided in a grid form and a NH_3 injection nozzle at each part of the grid is placed.

6-4-2 De-NOx Performance

De-NOx performance depends on a mole ratio of NH_3 to NOx (NH_3/NOx), a space velocity [1/h] (SV) representing a ratio of gas flow rate to a charging volume of catalyst and catalyst activity. **Fig. 6-4-3** shows a relation between a De-NOx efficiency and NH_3/NOx.

A higher mole ratio of NH_3/NOx increases a De-NOx efficiency, but unreacted NH_3 (Leaked NH_3) contained in a wake flow, increases. Increasing a charging volume of catalyst and decreasing SV can improve a De-NOx efficiency and reduce leak NH_3. In addition, a De-NOx efficiency is represented with an approximate equations of 6-4-3 or 6-4-4, and leak NH_3

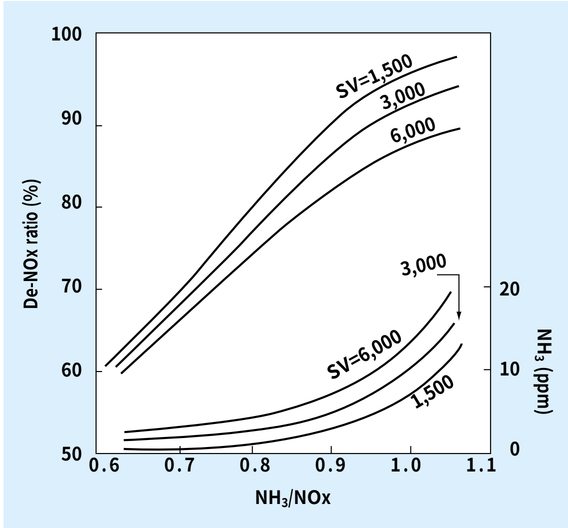


Fig. 6-4-3 Influence of NH_3/NOx on De-NOx ratio[10]

concentrations can be determined from the equation of 6-4-5.

$$\eta = 100 \times [1 - \exp(-k/SV)] \qquad 6\text{-}4\text{-}3$$

$$\eta = 100 \times R_{NH3/NOx} \times [1 - \exp(-k/SV)] \qquad 6\text{-}4\text{-}4$$

$$C_{out,\,NH3} = C_{in,\,NOx} \times (R_{NH3/NOx} - \eta/100) \qquad 6\text{-}4\text{-}5$$

η: De-NOx efficiency
$R_{NH3/NO}$: Mole ratio of NH_3 to NOx
k: Kinetics constant
SV: Space velocity
$C_{out,\,NH3}$: Leaked NH_3 concentration
$C_{in,\,NOx}$: Inlet NOx concentration

6-4-3 Operating Temperature and De-NOx Performance

Under lower temperature than 300 °C, SO_3 in a flue gas reacts with NH_3 to NH_4HSO_4 that covers a catalyst surface and reduces De-NOx efficiency. At higher temperature than 350 °C, as this NH_4HSO_4 is decomposed, higher De-NOx performance can be obtained, without the influence of SO_3 concentration. However, as leaked NH_3 is oxidized at higher temperature than 400 °C and reduces, and a De-NOx efficiency is dropped.

6-4-4 Degradation of De-NOx Catalyst

As catalyst's degradation during a long-term use cannot be avoided during actual operation, its performance must be watched. When leaked NH_3, increases by the degradation of catalyst, it will be necessary to add a new De-NOx catalyst, replace or regenerate the used catalyst. The causes of catalyst degradation include a thermal degradation of sintering, chemical degradation resulting from inactivation of catalyst elements and physical degradation resulting from dust-covered catalyst surface.

Main degradation factors in pulverized coal combustion power plants include adhesion of $CaSO_4$ formed by reaction between CaO and SO_3 and adhesion of fine dust composed in mainly coal ash. In order to regenerate the degradated catalyst, a catalyst surface is polished to expose its new surface and renew the catalyst.

6－5 Dust Removal Technology

A dust collector is used to catch fly ash (coal ash) generated from combustion of pulverize coal. In Japan, an electrostatic precipitator is mainly employed that has a low pressure loss and an easy maintenance.

(1) Principle of electrostatic precipitator

In the electrostatic precipitator (ESP), dust particles in the flue gas are charged by corona current and removed by the electric field. There are two types of ESP, one stage and two stage. In the one stage ESP, dust charging and separation are performed simultaneously. In the two-stage type, particle charging is performed in the first stage, and collection of the charged particles is performed later. The one stage ESP, shown in **Fig.6-5-1**, is most common. This type of ESP with flat plate collection electrodes is easy to scale up. The wire discharge electrodes are centered between two parallel flat collection electrodes. The pressure drop in the ESP is very low compared to the fabric filter or granular bed type. The ESP is suitable for dust collection in large scale facilities.

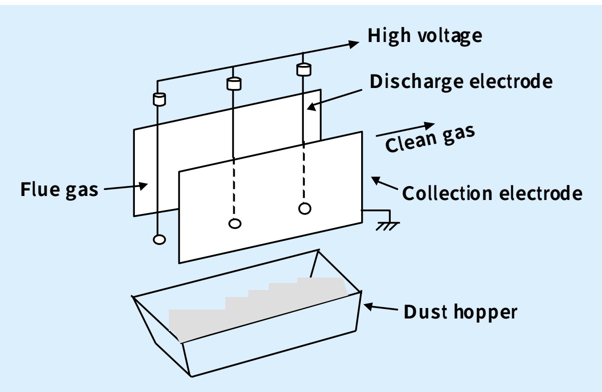


Fig. 6-5-1 Electrostatic Precipitator

A negative high voltage is applied to the discharge electrodes and the collection electrodes are grounded. The negative ions generated by the corona at the discharge electrodes collide with the dust particles in flue gas to charge the particles. The particles then move toward the collection electrodes by the electric mobility due to the electric field formed between the discharge and collection electrodes.

The collected dust particles are released to the hopper under the ESP. The particles adhering to the discharge and collection electrodes are dislodged by the tapping the electrodes and fall into the hopper.

The ESP is utilized as a dust collector in large scale plants, such as thermal power plants, because it has a high collection efficiency and is capable of handling large flue gas volume flow rates.

(2) Collection Efficiency of electrostatic precipitator

In the ESP, the dust particles are charged by the ions in the field generated by corona discharge. The collection efficiency is depend on the amount of charge and electric field strength etc.

The relationship between applied voltage and collection efficiency for the ash from residual oil combustion is shown in **Fig.6-5-2**. The collection efficiency of the ESP increases with increasing applied voltage, and saturates at high voltage.

On the other hand, the amount of charge is determined by particle size, electric field strength, corona current density, and residence time.

The mechanisms responsible for particle charging are field charging and diffusion charging. In diffusion charging, the particle charge is not affected

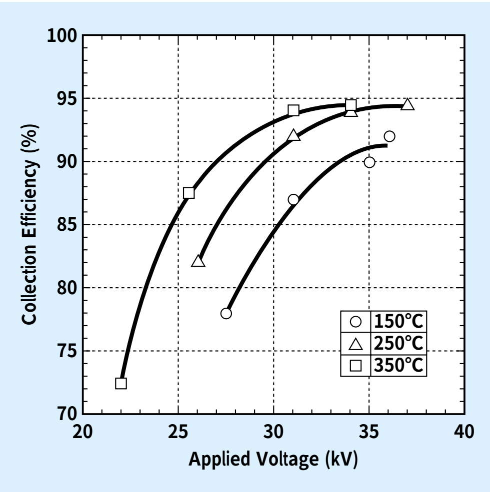


Fig. 6-5-2 Applied Voltage and Collection Efficiency

by the electric field strength and tends to increase linearly with particle size. In the field charging, the particle charge increases with increased electric field strength and tends to increase linearly with the square of the particle size. In general, diffusion charging is most effective for fine particles under 1 μ m in diameter while the field charging is most effective for particles larger than 1 μ m.

On the other hand, a moving speed in a electric field becomes higher as particles become fine. Hence, a large particle is easily charged ,but is difficult to move ,and a small particle easily move but is difficultly charged. From this phenomena, it becomes difficult for an electro-static precipitator to collect an about 0.5(m particle, which is in a middle range between the small and large particles.

The overall collection efficiency of an ESP is approximately 99%, and the fractional collection efficiency , which is the collection efficiency for the respective particle size, has a minimum value in the range of particle size of 0.1～1.0 μ m as shown in **Figure 6-5-3**.

As the dust particles accumulate at the collection electrodes, they discharge electrons. The performance parameters of the ESP, such collection efficiency, applied voltage and corona current depend the dust resistivity, as shown in **Fig.6-5-4**. In the regions of $<10^2$ Ω・m and $>5\times10^8$ Ω・m, the corona current is high but the collection efficiency is low. On the other hand, in the region of 10^2 Ω・m< $<5\times10^8$ Ω・

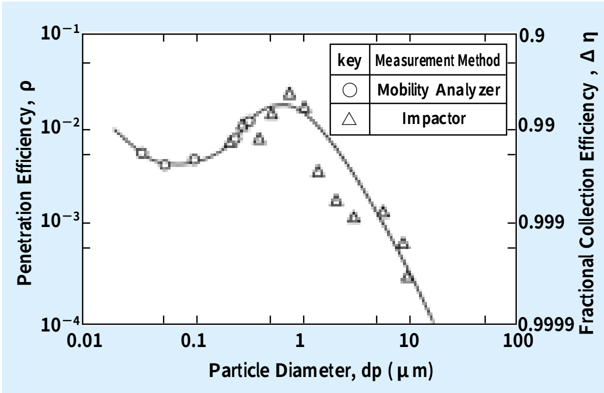


Fig. 6-5-3 Fractional Collection Efficiency of ESP

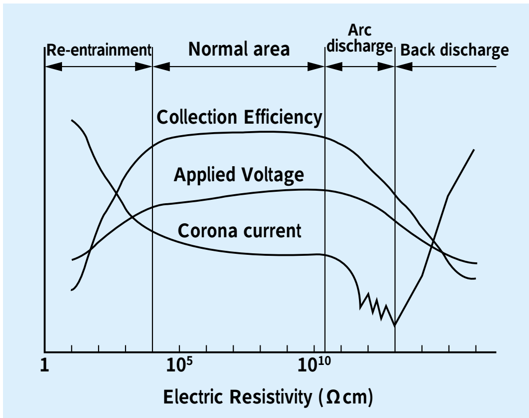


Fig. 6-5-4 Collection Characteristics and electric Resistivity

m, although the corona current is low, the collection efficiency is high. This tend is explained as follows.

In the case of $<10^2$ Ω・m, when the dust particles accumulate at the collection electrodes, they discharge the electrons immediately and are charged to the same electrostatic potential by the electrostatic conductor. Then the dust particles are re-entrained in the direction of the discharge electrode and the collection efficiency is decreased. In the case of $>5\times10^{10}$ Ω・cm, it is difficult for dust particles to discharge on the collection electrodes and the electrons are stored in the dust layer so the applied voltage is decreased by the dust layer. In addition, as the effective electric field strength becomes lower, the collection efficiency decreases. If becomes higher than 10^{13} Ω・cm, back discharge ensues and the collection efficiency is significantly decreased.

On the other hand, in the case of 10^4 Ω・cm< $<5\times10^{10}$ Ω・cm, the discharge rate of dust particles is moderate and the collection efficiency remains high. The resistivity is affected by ash properties of coal and represents >10^{11} (·cm for almost coal ash. In order to consistently remove the high resistivity's dust, a variety of technology has been developed.

(3) Dust Collection of High Resistivity Particles

Improvements in technology to deal with the decrease in the collection efficiency for high electric resistivity ash are very important to flue gas clean-up.

The resistivity is affected by dust properties, temperature, humidity, etc. The relationship between of coal ash and the temperature for various humidity conditions is shown on **Fig. 6-5-5**. The resistivity has a maximum value in the temperature range 100～200℃, except under condition of 0% humidity. At the same temperature condition, the resistivity becomes higher with decreasing humidity. This tendency is explained as follows.

In the low temperature region, the coal ash particles adsorb moisture from the atmosphere and form a water layer on particle surfaces. Ions can move easily through this water layer so resistivity is reduced. This layer becomes thicker with decreasing temperature and increasing humidity, therefore the resistivity becomes lower. On the other hand, in the high

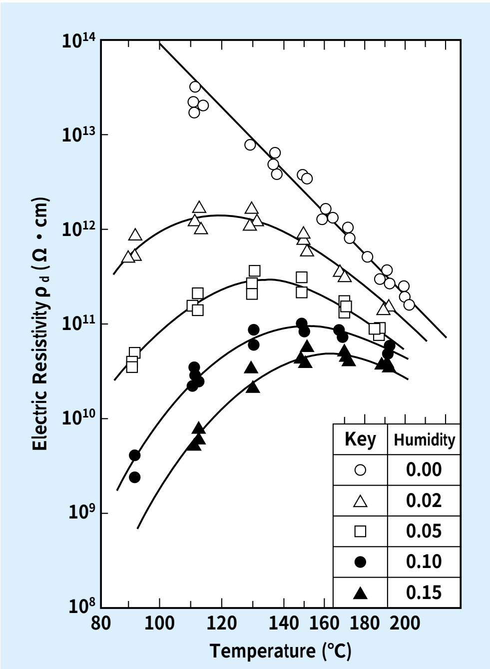


Fig. 6-5-5 Electric Resistivity of Fly Ash

temperature region, electrical conduction must take place through the particles because there is no surface water layer under high temperature conditions. In this case, the electric resistivity decreases with increasing of temperature. Overall, the resisivity is determined by a combination of these mechanisms so the resistivity show maximum values in the temperature range between 120 C and 160 C depending on the humidity.

One approach is the high temperature ESP operating at 350℃. This ESP utilizes the fact that the resistivity of coal ash is less at high temperature. Although the gas volume increases with increasing gas temperature and the corona power increases with increasing corona current, the high temperature ESP can use the higher corona power for high electric resistivity ash because arc discharge is suppressed. But recently, the type of ESP operated below 100℃ is introduced because unit capacity is bigger and applied voltage is not got enough.

Another method to reduce dust resistivity is to inject SO_3. When the SO_3 concentration in flue gas is high, a liquid layer is formed on the surface of the ash particles by the condensation of SO_3 and the collection efficiency is improved due to the decreased resistivity of the ash. The effect of SO_3 concentration on the collection efficiency and the dust concentration at the ESP outlet is shown in **Fig. 6-5-6**. With decreasing temperature, the collection efficiency becomes higher and the dust concentration at the ESP outlet decreases. The method which utilizes this trend

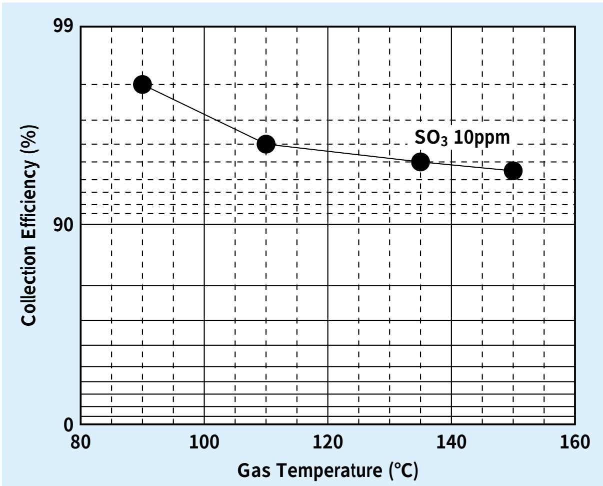


Fig. 6-5-6 Influence of Collection Efficiency of ESP by Low Temperature Operation

is a new development in low temperature ESP's. This type of ESP is operated below 100 °C. The relationship between gas temperature and the collection efficiency is shown in Fig. 15. The collection efficiency is remarkably improved below 120 °C. In the future, this type of ESP will be the ESP of choice for high resistivity ash.

On the other hand, because the reduction in collection efficiency for ESP's operating with high resistvity ash is due to the adhered dust layer on the collection electrodes, methods to minimize this problem are being developed. One technique is a moving collection electrode in which the dust is removed by a brush. Another is the semi-wet type ESP in which the dust layer is removed by washing with water. These two methods offer potential for performance improvement.

Furthermore, a charging method was improved. A pulse charging method is in practical use. This type adds the high voltage pulse to the DC charging. By this method, a high and uniform ion density can be achieved with no restriction on the shape of the discharge electrode or dust adhesion to the electrode.

6－6 Desulfurization Technology

A wet limestone-gypsum method is used as current typical desulfurization equipment. This method includes a high performance and reliable technology and is used in almost all pulverized coal fired power plants. At the same time, a dry desulfurization method and a simultaneous desulfurization /De-NOx method have been developed, aiming at reduction of wastewater treatment.

6-6-1 Limestone-Gypsum method

The water slurry of limestone, which is cheap and easy-to-handle and produced in Japan, is reacted with SO_2 into gypsum ($CaSO_4 \cdot 2H_2O$) in a flue gas. A summarized reaction is as follows:

$$CaCO_3 + SO_2 + 0.5O_2 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

This includes a separated system for oxidizing on which an oxidizing tank is separately installed as shown in **Fig. 6-6-1** and an integrated oxidizing system on which an oxidizing is done at same absorber. In a separated system, SO_2 in a flue gas is reacted with absorbent slurry sprayed from the top of an absorber, and is converted to hydro sulfurous ion (HSO_3^-) and absorbed. The SO_2 absorbent slurry is collected in the bottom of the absorber and converted to calcium bisulfite ($CaSO_3 \cdot 0.5H_2O$) by limestone slurry supplied. This calcium bisulfate slurry is fed to a oxidizing tank. Calcium bisulfite is dissolved into the solution with sulfuric acid and then is oxidized with air to obtain gypsum ($CaSO_4 \cdot 2H_2O$).

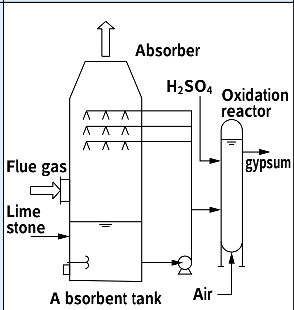
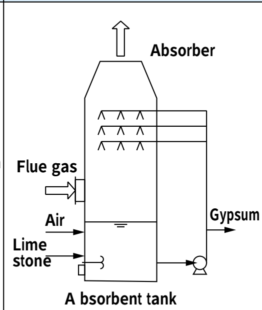
Type	Separated oxidation type	In-situ oxidation type
Basic flow		
Feature	• Oxidation reactor: need • H_2SO_4: need • $CaCO_3$ surplus ratio: high • Influence of oxidation: week	• Oxidation reactor: Non • H_2SO_4: Non • $CaCO_3$ surplus ratio: Low • Influence of oxidation: strong

Fig. 6-6-1 Lime stone-gypsum desulfurization method

In an integrated oxidizing system on which even gypsum is formed without an oxidizing tank, SO_2 is reacted with the absorbent slarry in the absorber and dissolved as hydro sulfurous ion (HSO_3^-). HSO_3^- is oxidized with air in an absorbent tank and converted to sulfate ion (SO_4^{2-}), and is reacted with limestone slurry and converted to gypsum ($CaSO_4 \cdot 2H_2O$).

Gypsum formed at the absorber is dewatered and gypsum is sold as building materials. Wastewater after dewatering is recycled to a desulfurization equipment and reused to produce limestone slurry. However, at recycling the wastewater, various elements such as chlorine and fluoro are accumulated in an absorbent slarry and reduce gypsum quality and desulfurization performance, so some of the wastewater is fed to wastewater treatment equipment, and cleaned water is recycled to absorber.

In addition, a limestone-gypsum method includes the system on which a soot collector (cooling tower) for dust removal and cooling is installed upstream and a soot mixing system without a dust collector (cooling tower). The dust separating system is employed when gypsum with high purity and without dust is required. Currently, however, a high performance dust collector such as an advanced low electrostatic precipitator that removed dust at 90 ℃ has been developed and dust concentration is lower. From this reason, a soot mixing system with a lower cost of equipment has been increasingly employed.

6-6-2 Dry Desulfurization and Simultaneous desulfurization/De-NOx Methods

A limestone-Gypsum desulfurization method requires a great amount of industrial water and advanced wastewater treatment equipment. For this reason, the development of a dry system not requiring water and waste treatment was developed. And also the attention has been paid to a dry simultaneous desulfurization /De-NOx method. However, advantage of this method is not clarified to a wet desulfurization method in terms of costs and is only used in several power plants.

(1) Dry Desulfurization method using coal ash

In this method, sorbents are newly produced from coal ash, calcium hydroxide ($Ca(OH)_2$) and spent sorbents, and these sorbents are used to remove SO_2 in a flue gas. **Fig. 6-6-2** shows an overview of this process flow. This process includes a manufacturing process of sorbents. In this process, SO_2 is removed by $Ca(OH)_2$. A desulfurization efficiency of 90 % or more can be accomplished at flue gas temperatures of 100 to 200 °C.

(2) Activated carbon absorption method

An activated carbon absorption method can remove both SO_2 and NOx. In this method, SO_2 in a flue gas is reacted with NH_3 sprayed in a flue gas in a desulfurization tower at 140～160 ℃ and converted to ammonium hydro sulfate (NH_4HSO_4), and ammonium sulfate ($(NH_4)_2SO_4$) for its absorption and removed. Then, in a De-NOx tower, NH_3 also is spayed to decompose NOx into nitrogen and moisture. A desulfurization efficiency of 97 % or more and a De-NOx efficiency of 80 % or more are accomplished. **Fig. 6-6-3** shows an overview of this process. The spent activated carbon is heated at a desorption tower, and NH_4HSO_4 and other elements absorbed in the actirated carbon are decomposed into NH_3 and SO_2, By this operation the activated carbon can be regenerated and reused. SO_2 released is recover as sulfuric acid or elemental sulfur.

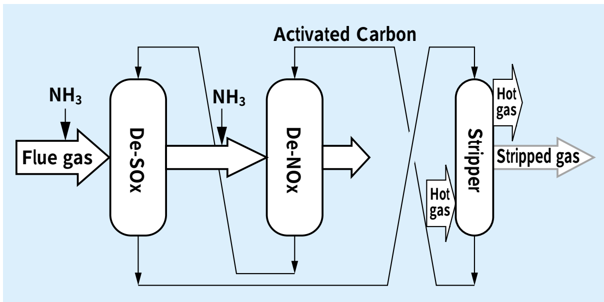


Fig. 6-6-3 De-SOx and De-NOx Simultaneou removal method with activated carbon

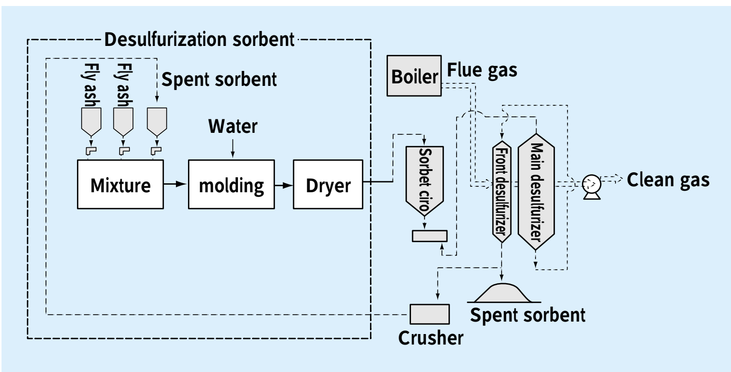


Fig. 6-6-2 Dry type desulfurization method using Calcium-fly ash sorbent

6－7 Future Plan

Environmental regulation has been increasingly tight, such as total mass control standards of NOx and SOx, more stringent regulation of wastewater concerning fluoro, selenium and boron and establishment of PRTR law, and it is considered that it will now become important to improve flue gas treatment technologies.

A high performance and reliable technology of flue gas treatment for SOx, NOx and dust has already been developed, so it will now become important to further developed the technology for additional emission control and reduction of treatment costs. It is absolutely essential to advance a conventional low NOx combustion technology available for a wide variety of coal kinds.

On the other hand, attention is paid to trace elements, but as they have very low concentrations and their behaviors depend greatly on gas temperature conditions, their behavior in thermal plants is not still currently clarified. It can be considered necessary in the future to clarify their accurate behavior in the plants and develop their removal technologies according to the tendency of regulation.

Furthermore, how to dispose of coal ash collected by an electrostatic precipitator will be now an important subject. Currently, 60 % or more of coal ash is reused as clay alternative materials for cement. It is necessary to investigate the expansion of reuse of coal ash and cost reduction of use for particularly commercial ash. So, in addition to the development for new utilization method of coal ash, the development of a combustion technology that produces coal ash whose characteristics is available for commercially valuable ash can be considered as one of important issues in the future.

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Column 1: Development of Continuous Speciation Monitor of Mercury

Why is continuous analysis on each chemical form of mercury required?

Mercury is considered one of the hazardous air pollutants of greatest concern to public health. Mercury emission from coal-fired power plants will be regulated in the USA. Mercury emissions from anthropogenic sources occur in three main forms: solid particle - associated mercury, gaseous divalent mercury (Hg^{2+}), and gaseous elemental mercury (Hg^0). Elemental mercury is insoluble and low adhesive. Divalent mercury is water soluble and highly adhesive. Therefore chemical forms of mercury affect the behavior in combustion process. Because of the investigation of the behavior in a plant, to speciate mercury is important.

Important point for development

The official method for analysis on mercury speciation is only defined in U.S. This method is necessity for a long time to analyze. Therefore, change of the chemical form of mercury in a short time is unknown. In order to identify mercury behavior in detail, CRIEPI developed a method for on-line analysis on each chemical form of mercury. Our monitor consists of a separation section for each chemical form separating mercury into Hg^0 and Hg^{2+} and a measuring section continuously analyzing separated mercury (**Fig. 1**).

Accuracy of CRIEPI's analysis method

A capability is required that allows analysis on a concentration of 1 μ g/m^3_N that was reported as a mercury concentration in combustion flue gas. So, reference gas of mercury that has each chemical form was generated in order to identify a measuring range and accuracy of this method. The method has a measurement error of about 5 % even at low concentrations and a measuring range of 0.3 μ g/m^3_N to 100 μ g/m^3_N for each chemical form. Furthermore, mercury in actual combustion gas was continuously analyzed by our method and various methods including JIS. Consequently, this method was applicable to analysis on mercury speciation in combustion gas with great accuracy (**Fig. 2**).

Fig. 1 Continuous speciation monitor of mercury

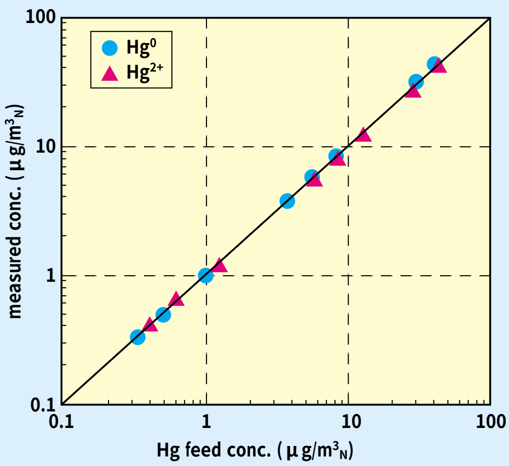

Fig. 2 Accuracy of measurement

Chapter

7

Improvement of Operability for Pulverized Coal Fired Power Plants

Chapter 7 Improvement of Operability for Pulverized Coal Fired Power Plants ● Contents

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Column 2: Technology for an On-line Apparatus Measuring Pulverized Coal Particle Size Distribution and Concentration 87

Hisao Makino (Dr.)
Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

Yusou Oki (Dr.)
Research Scientist
Energy & Mechanical Engineering Department
Yokosuka Research Laboratory

Masayoshi Kimoto
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

Tetsuo Ono (Dr.)
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

7－1 Research Background

In 1980s, pulverized coal fired power plants were increased again by new plant construction or fuel conversion of oil fired power plant to coal. The ratio of coal fired power plant in power resource currently exceeds 10 %. On the other hand, the ratio of oil fired power plants dominating thermal power plants before 1980s has been significantly decreasing. Such a changing ratio in power resource has greatly influenced the required roles of pulverized coal fired power plants. That is to say, pulverized coal fired power plants, which were traditionally defined as a base load power source, a operability is desired to improve the ability of load control because of the latest requirement to be operated as both middle and peak power plant.

In order to reduce the load in pulverized coal fired power plants, conventionally, pulverized coal feed amount to each burner was reduced, and besides, some burners were extinguished for substantial reduction of its load. However, the reduction range of load is narrow and the load changing rate is slow because the operation of the extinction of burners requires a lot of time. In contrast, a method for load control without the extinction of burners can carry out the high rate load control, but this method will reduce pulverized coal feed amount to each burner according to power demand. The supply method of pulverized coal particles into a boiler are air transportation in pulverized coal fired power plants because pulverized coal is solid. Reduction of a feed amount of pulverized coal during low load operation will decrease pulverized coal concentration in carrier air which in called primary air. The decrease of pulverized coal concentration will cause a lean fuel situation and make stable combustion difficult, when load is significantly reduced. Of course, this problem can be resolved if a carrier air amount is decreased according to the reduction of pulverized coal feed amount. However, if a flow velocity of the air is reduced in this case, a sedimentation of pulverized coal will be easily caused in primary air flow line, and it becomes difficult to continuously feed the pulverized coal to burners. Based on this situation, in order to stabilize combustion of pulverized coal of low concentration during low load operation, it becomes important to develop a technology that can concentrate pulverized coal partially and raise pulverized coal concentration to an appropriated level.

In order to improve a load control ability on power demand, it is important not only to carry out a stable combustion of pulverized coal during low load condition but also to fasten a load change rate during the increase or the decrease of load. During load change, pulverized coal concentration becomes unstable, which makes stable combustion difficult, so pulverized coal fired power plants are forced to control the load changing rate lower than oil fired power plants. That is to say, adding a capability that can adjust pulverized coal concentrations to an appropriate level even during load change allows the improvement of the load changing rate.

In order to improve these demerits, the unstable combustion due to low pulverized coal concentration during low load operation and the difficulty to increase of a load changing rate due to unstable of pulverized coal concentrations during load change, CRIEPI developed a wide-range [(1)~(5)] burner that has a capability of concentrating pulverized coal and an advanced low NOx wide-range burner that enabled lower NOx combustion than the wide-range burner. This chapter will present these technologies.

7−2 Improvement of Low Load Combustion Stability

7-2-1 Concept of Burner for Low Load

Concentration of pulverized coal blown from a pulverized coal burner is usually controlled based on an indicator called Air/Coal (weight ratio of primary air flow rate which carries pulverized coal to pulverized coal feed rate, hereafter referred to A/C). **Fig. 7-2-1** shows a relation between a mill load and A/C.

Under low load conditions, a pulverized coal feed rate will be reduced, but there is a limit to reduction of primary air flow rate due to the preventing of the sedimentation of pulverized coal. Hence, if a load reduces to a certain level, A/C will significantly increase. A/C on which a pulverized coal burner can maintain the stable combustion was considered about 2.5～3.0, and a minimum load that enables stable combustion corresponding to this A/C was 35～40% load.

In order to extend a load range of stable combustion and improve the load control ability of a pulverized coal boiler, it is effective to locally concentrate pulverized coal during low load condition and locally raise concentration of pulverized coal near the outlet of a burner. A wide load range burner that has a pulverized coal concentration function as shown in **Fig. 7-2-2** was already developed and used in actual boilers. But few these load burners were not introduced for existing thermal power plants at alteration construction due to the complication of their structure and the requirement of external anxiety equipment, although they were employed in new thermal power plants.

Therefore, CRIEPI and IHI started a cooperative research for the development of a compact and low-cost burner that has a pulverized coal concentration function in the inside of a burner with the almost same size as a conventional burner, in order to enable stable combustion at 20 % load which is equivalent to minimum load of oil fired power plants and also allow the replacement to existing thermal power plants.

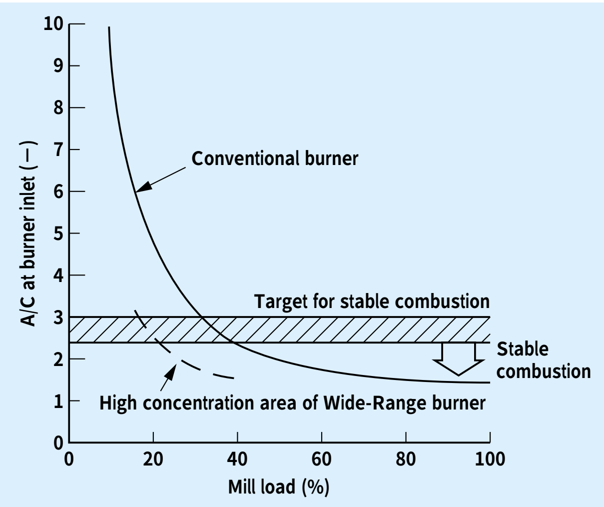


Fig. 7-2-1 Relation between mill load and A/C

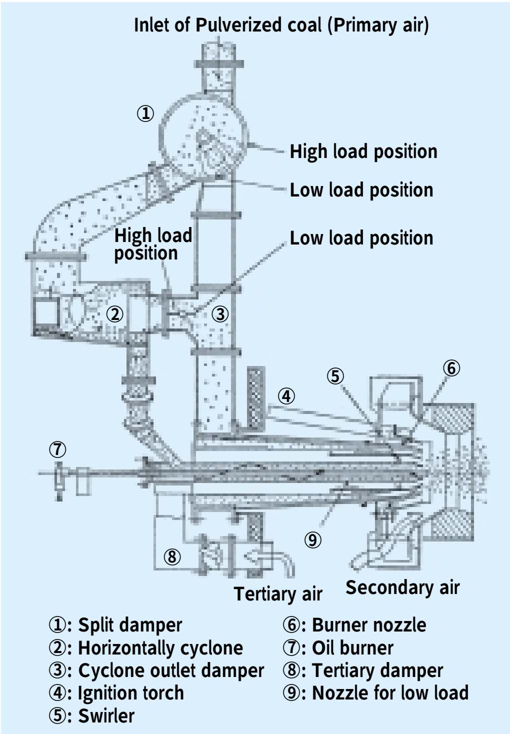


Fig. 7-2-2 Conventional turn-down burner

7-2-2 Basic Structure of Pulverized Coal Concentrating Function

Considering that the use of centrifugal force is effective in concentrating low concentration pulverized coal in a limited space of the inside of a pulverized coal burner, a compact type of wide range burner (hereafter referred to wide range burner) shown in **Fig. 7-2-3** was devised.

A wide range burner has a baffle ring called the concentration control ring. The exit of burner is constructed by triple concentric nozzles.

A swirling air flow with pulverized coal coming from a tangential direction is concentrated outer part of the nozzle when over-passing the control ring. Moving the control ring to the outlet of nozzle, pulverized coal concentrated in the outer side of the nozzle is blown from the outer path between outer and intermediate nozzle. When moving the control ring away from the outlet of burner, concentrated pulverized coal disperses again, and is also blown from both outer path and inner path. In this way, moving the control ring on load demand will increase concentration of pulverized coal at the outlet of a burner locally and improve ignitability during low load condition.

When blowing concentrated pulverized coal from one port of the triple nozzle, the optimum blowing position has never been investigated as a comparison of outer port, intermediate port or inner port for the stable combustion. So, a triple nozzle burner with a combustion rate of 150 kg/h was fabricated. Experimental research was carried out by changing the combination of the blown position for pulverized coal flow which was simulated to high concentration pulverized coal flow, with the blown position for air flow which was simulated to low concentration pulverized coal flow. Comparing combustion states under each condition, the results shown in **Fig. 7-2-4** were obtained.

From these results, the difference among blowout positions of pulverized coal greatly affects a shape of flame. When pulverized coal was blown from the outer port, short flame with a wide flame angle and higher brightness was easily formed, which provided favorable combustion. On the other hand, when pulverized coal was blown from the intermediate part, a flame shape did not become stable. When pulverized

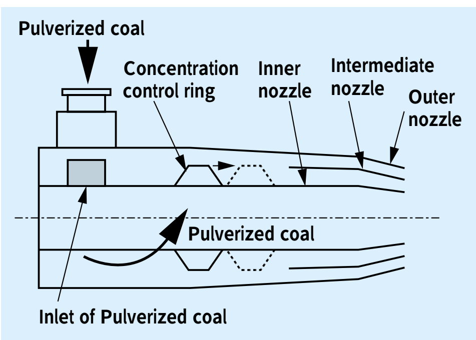
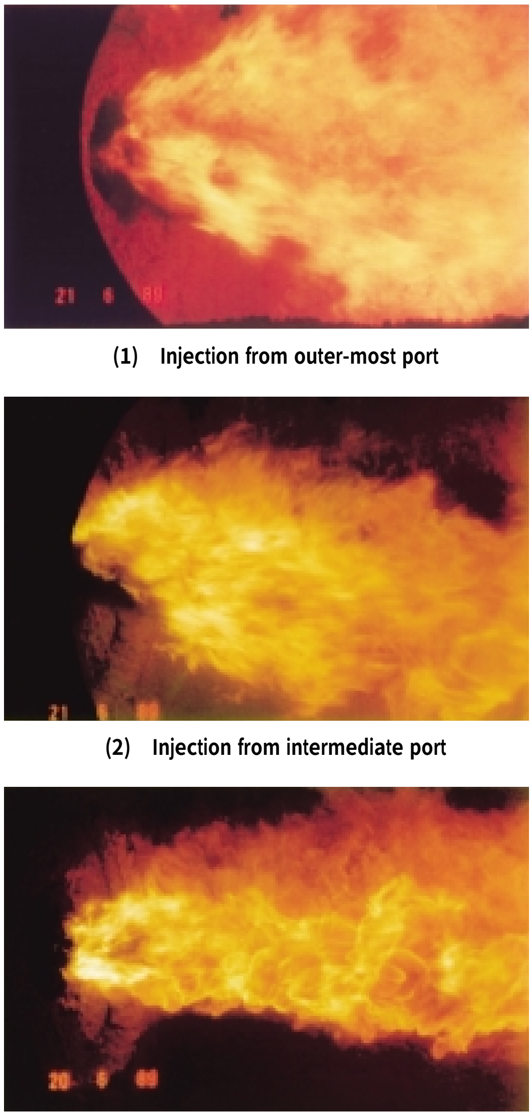


Fig. 7-2-3 Newly developed Wide-Range burner



(1) Injection from outer-most port

(2) Injection from intermediate port

(3) Injection from inner-most port

Fig. 7-2-4 Combustion state of triple-pipe burner

coal was blown from the inner port, a flame shape became slender and an ignition point was unstable. These results demonstrated that blowing pulverized coal concentrated from the outer part formed the most stable flame. When pulverized coal is concentrated with centrifugal force, it is structurally easy to blow concentrated pulverized coal from the outer part, so it was decided that this method would be introduced.

7-2-3 Optimization of Parts of Burner

An important point for a pulverized coal concentrating function is a concentration control ring installed in a burner nozzle. The effects of the shape and the ring position on the pulverized coal concentrating characteristics must investigated, because the characteristics depend greatly on the shapes.

So, an acrylic model of a burner was fabricated in order to conduct visualization tests for the inside of a burner and measurement tests for pulverized coal concentration at the outlet of the burner. As a result, a trapezoidal ring was selected as an optimal ring shape while a recommended value for a ring installment position on load demand was identified.

In this way, a burner with the most suitable structure judged by cold-flow tests was made for CRIEPI's pulverized coal combustion test furnace (combustion rate of the burner of 120 kg/h) to conduct combustion tests.

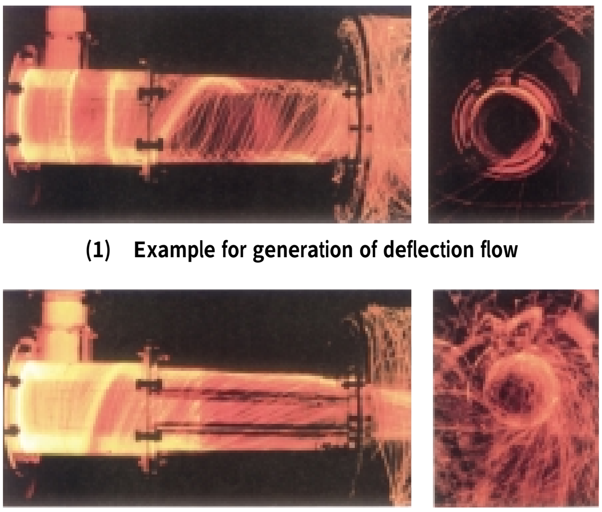
As a result, it was confirmed that stable combustion up to a load of 25 % could be ensured, based on combustion tests with the use of imported coal with fuel ratio of 1.6. Furthermore, in order to enable stable combustion up to a target value, a load of 20 %, a situation in which combustion becomes unstable at low load was observed in detail. This revealed that a collapsed flame shape resulting from deviation of pulverized coal flow was a cause of unstable combustion. This deviation is a phenomenon under which concentrated pulverized coal flow becomes one or two stripes and blown from only a part of a burner outlet. Distribution of pulverized coal concentration in the radius direction becomes significantly uneven. Hence, visualization tests for a flow pattern in the inside of the burner shown in **Fig. 7-2-5** was conducted in order to optimize the length, number and shape of a deflector angle (partition bar that was installed in the inside of the outer nozzle of the burner to disperse pulverized coal and to form uniform distribution of pulverized coal concentration in the radius direction).

After some modifications on visualization tests and the verification on combustion tests, we were successful in maintaining stable combustion up to 20 % of a standard load in a bench scale combustion burner.

7-2-4 Scale-up of Burner Capacity

A good result was obtained in a bench scale combustion test, but it is important to scale up a burner for the application to actual utility boilers. So, a pilot scale burner with a capacity of 2.35 t/h was fabricated to conduct a combustion test. In this research so, a conventional type burner with the same capacity was also fabricated in order to compare their performance. **Fig. 7-2-6** shows the result of comparison tests.

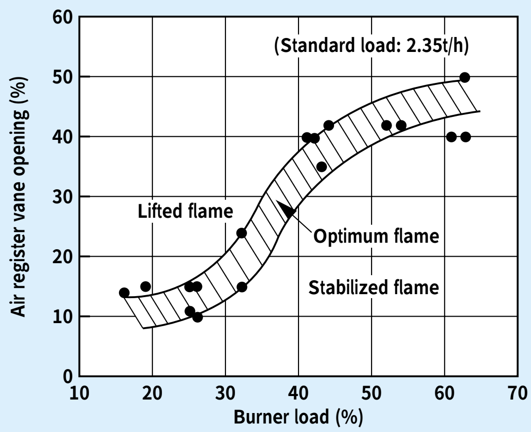
In this figure, load is taken as a horizontal axis and the air register vane opening level which is controlling swirl strength of secondary air is taken as a vertical axis. A range in which the best combustion state can be maintained at each load is hatched.



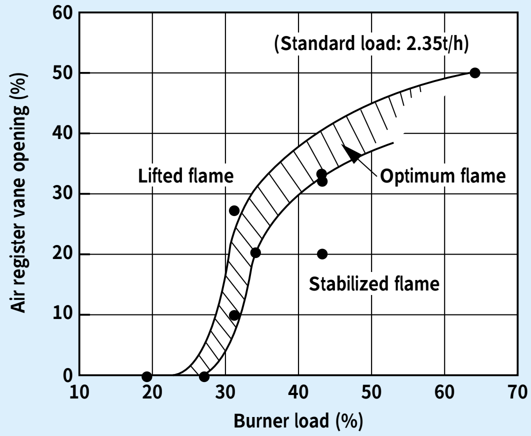
(1) Example for generation of deflection flow

(2) Example for uniform flow after improvement of burner structure

Fig. 7-2-5 Visualization test for optimum burner structure



(1) Combustion stability of Wide-Range burner



(2) Combustion stability of conventional burner

Fig. 7-2-6 Comparison of combustion stability

Usually, when pulverized coal concentration becomes low with decreased load, an ignition point moves away and blow-off of flame occurs. In this case, generally, an air register vane opening level is decreased and swirl strength of secondary air is increased in order to maintain an good ignition point. As found in this figure, a conventional type burner makes it impossible to control the swirl strength due to closing the register at a load of 30 %. However, the wide range burner can maintain stable combustion by moving a concentration control ring even under an extremely low load condition which is 20 % load or less. We confirmed this burner enabled stable combustion to about a load of 16 %.

7-2-5 Utilization of Wide Range Burner

Based on the result of scale-up tests, an actual utility burner with a capacity of 7.3 t/h was fabricated to conduct a demonstration test in No. 2 boiler (250 MW) of the Saijo Power Plant, Shikoku Electric Power Co., Inc. The test was intended to confirm performance of minimum load of a burner and verify its durability (identifying abrasion characteristics of sections that are exposed directly to pulverized coal flow and causes abrasion concerns such as a concentration control ring and selecting the section which abrasion resistance steel is used) in an actual utility boilers.

This boiler has three-stage and four-row opposed firing burners. 8 burners marked * of 16 burners for B and D mill line systems shown in **Fig. 7-2-7** are used during minimum load operation. Of these 8 burners used during this operation, 4 burners for the B mill system were replaced to a wide range burner. For reference, in consideration for pulverized coal-based abrasion, abrasion resistance materials were used for a part of a burner.

A combustion situation of burner during the tests was continuously evaluated with several optical combustion diagnostic systems by temporally placing a special two-color thermometer, along with a flame detector and a combustion diagnostic system.

As a result, in minimum load tests, it was confirmed that stable combustion could be maintained without temporary change of combustion state for the worse up to 50 MW, at a minimum load operation and also during load changing. Because of the accomplishment for single-fuel firing of coal up to a minimum load of 50 MW on which heavy oil was burned in a conventional type burner, as shown in **Fig. 7-2-8** and, usage of heavy oil at low load was substantially reduced. Time required for load changing was decreased by 100 minutes during load drop and by 55 minutes during load rise. These results verified the immediate load control was enabled.

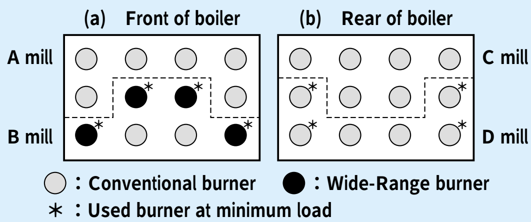


Fig. 7-2-7 Burner arrangement of tested boiler

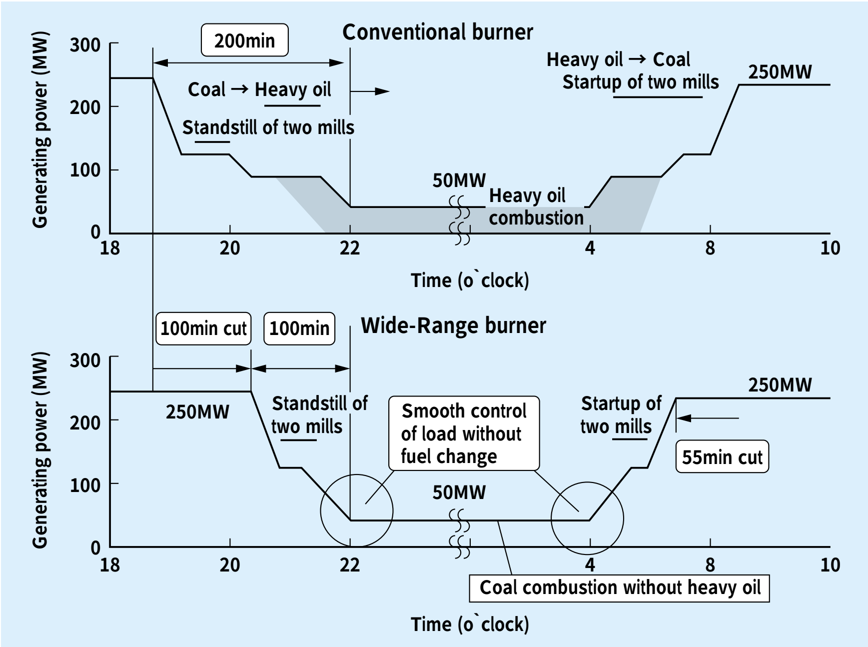


Fig. 7-2-8 Effect by installation of Wide-Range burner

In addition, owing to the introduction of a wide range burner, the quick fuel change from heavy oil to coal at the start up of a boiler was enabled. It was confirmed that heavy oil for startup could be reduced about 5 ton per one startup.

After operating with two kinds of burners made by erosion resistance steel or made by stainless steel for about a year, the difference of erosion states between two burners were compared to examine burner durability. As a result, by providing hardfacing and thermal spraying to significantly erosion concerned parts of a burner, it was found that almost of parts including a concentration control ring made from stainless steel could be accepted, and it was confirmed that this enabled cost reduction.

Based on the result of demonstration tests for an actual utility boiler, a wide range burner is being successfully introduced. Demand for replacement to this burner is increasing, and total of 190 wide range burners were installed in 10 boilers at domestic and overseas power plants including No. 2 boiler of the Saijo Power Plant and are being successfully operated.

7－3 Combination with Low NOx Combustion

7-3-1 Concept for Concentrating method of Pulverized Coal for Advanced Low NOx Burner

The installation of above-mentioned function of a wide range burner to an advanced low NOx burner (CI-α burner) described in the section 6-3 not only can support the operatability on wide load conditions and but also can substantially reduce NOx and unburned carbon in fly ash. CRIEPI developed an advanced low NOx wide range burner with a combination of these two burners in cooperation with IHI.

An advanced low NOx burner can lengthen residence time of pulverized coal near the burner and promote combustion. So, this burner not only reduces NOx and unburned carbon in fly ash lower than conventional low NOx burner but also enables stable combustion at a low load of 30 % that is lower than that of 40 %, which is a limit for stable combustion of conventional low NOx burners [6]. Considering a pulverized coal concentration at this load as a lowest limit for stable combustion, it can be believed that pulverized coal should be concentrated 1.5 times or more than a mean concentration in a primary air nozzle at a load of 20 %, CRIEPI's target value for low load combustion. However, this burner cannot effectively form the NOx reduction flame that is important to reduce NOx if a swirl exists in pulverized coal flow when the coal is blown into a furnace. For this reason, it can be considered that a pulverized coal concentrating method of the wide range burner using a swirl flow cannot be applied directly to a advanced low NOx burner. In developing an advanced low NOx wide range burner, the following two pulverized coal concentrating methods were devised for the solution of this problem.

① Method on which to restrain swirl with a straightener installed at the outlet of the primary air nozzle after concentrating pulverized coal with a swirl flow as done in a wide range burner (tangential flow-in type concentrating method)
② Method on which to concentrate pulverized coal in a flow field without swirl by installing a streamlined ring in a primary air nozzle of an advanced low NOx burner (streamlined ring type concentrating method)

Based on these concepts, it was demonstrated that these methods provided sufficient concentrating characteristics from cold-flow tests using a small-scale burner and then the influence of the increasing burner capacity on concentrating characteristics was identified. Subsequently, the influence of pulverized coal concentrating on combustion characteristics was clarified using a small-scale burner and a large-scale burner corresponding to an actual utility boiler.

7-3-2 Structure of Pulverized Coal Concentrating Equipment

(1) Tangential flow-in type concentrating method

Fig. 7-3-1 shows structure of a primary air nozzle of a burner using a tangential flow-in type concentrating method. A concentrating method of pulverized coal in this burner is the same as that of a wide range burner, and provides a mechanism on which primary air including pulverized coal flows into the nozzle from a tangential direction to generate a swirl. Pulverized coal concentration is controlled with a movable trapezoidal ring that was installed at the path of pulverized coal. An intermediate nozzle is incorporated into an outlet of an air puzzle to maintain pulverized coal concentration to the outlet of the primary air nozzle after concentrating pulverized coal. A shape of the outlet of a primary air nozzle shall be the same straight shape as that of an advanced low NOx burner, and a shape of the line from pulverized coal flow inlet to straight parts becomes a convergent shape with a taper. A swirl of concentrated pulverized coal flow is controlled with a straightener that was installed along an axial direction of a primary air nozzle.

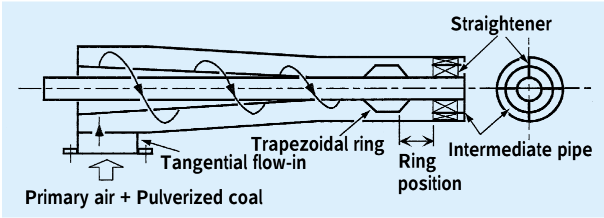


Fig. 7-3-1 Primary air nozzle of tangential flow-in type burner

(2) Streamlined ring type concentrating method

Fig. 7-3-2 shows structure of a primary air nozzle using a streamlined ring type concentrating method. In this type of a burner, pulverized coal is concentrated only with a streamlined ring that was installed at a primary air nozzle of an advanced low NOx burner. This streamlined ring type burner is in common with tangential flow-in type burner in that the ring is movable and that an intermediate nozzle is installed at an burner outlet to maintain concentration of pulverized coal after concentrating pulverized coal.

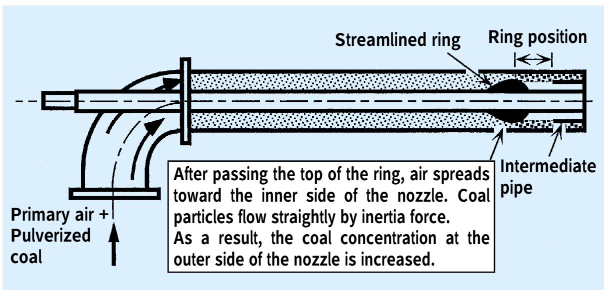


Fig. 7-3-2 Primary air nozzle of streamlined ring type burner

Concentrating characteristics of pulverized coal particles were evaluated on a simulation of a flow field in order to select a shape of the ring that provides the most effective concentration [7]. A streamlined ring shown in Fig. 7-3-2 can reduce the formation of vortexes at the wake flow and smoothly expand air flow to the inner side after passing through the ring. On the other hand, pulverized coal flows on the outer side of a primary air nozzle by the inertia force for a while after passing through the ring. As a result, pulverized coal concentration of the outer side can be kept high. In addition, extreme collision and rebound of coarse particles with high inertia force can be reduced, because the inclination angle on the upper flow part of the ring is a gentle slope. For instance, a behavior of particles on which particles collide a surface of the ring and then the outer part of a primary air nozzle, rebound again and return to the inner side, inhibiting the concentrating effect can be prevented.

7-3-3 Concentrating Characteristics of Pulverized Coal

Taking, for instance, a small-scale tangential flow-in type burner (capacity of 0.12 t/h), its concentrating characteristics of pulverized coal are indicated [8][9]. **Fig. 7-3-3** shows a relation between a pulverized coal concentration ratio in the inner and outer parts of a primary air nozzle at the outlet (a ratio to mean concentration of pulverized coal in primary air) and a ring position.

It was demonstrated that concentrating effectiveness of pulverized coal become larger as a ring position was closer to the outlet of the primary air nozzle and enabled the concentrating to 1.5 times which is a target value. When there is no need for concentrating of pulverized coal, the concentration can be controlled near to a mean concentration in a primary air nozzle by moving a ring position away from the outlet of the nozzle. It is clear that control of the ring position allows the setting of an optimal concentration according to burner loads.

A burner with a capacity of a few t/h to 10 t/h of coal feed rate used in an actual utility boiler provides a larger path of pulverized coal than a small-scale burner, and behaviors of air flow and pulverized coal particles in the large scale burner is different from that in the small scale one. Hence, performance of this tangential flow-in type concentrating method was evaluated in a large-scale burner with a capacity of 1.5 t/h, and it was clarified that a concentrating effect equivalent to 1.5 times or more could be accomplished and that ring position adjustments allowed control of pulverized coal concentrations [10][11].

In the tangential flow-in type concentrating method, swirl strength of air flow must be controlled after concentrating pulverized coal. Increasing the length and number of a straightener installed at the outlet of a primary air nozzle expands an area that swirling air flow collides, so swirling strength of air flow is reduced. In order to identify the most favorable

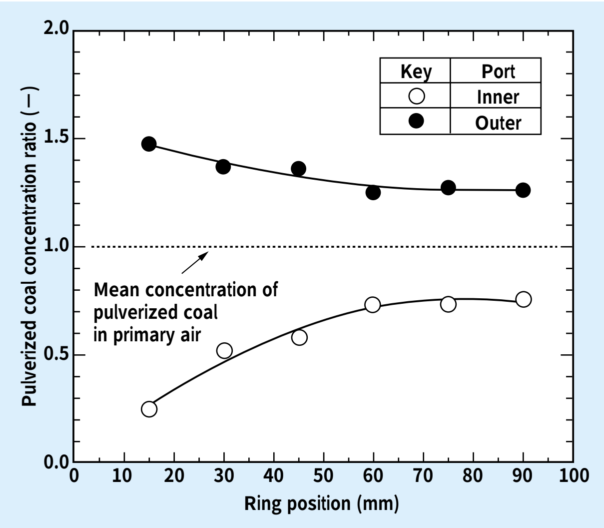


Fig. 7-3-3 Relatin between pulverized coal concentration ratio and ring position

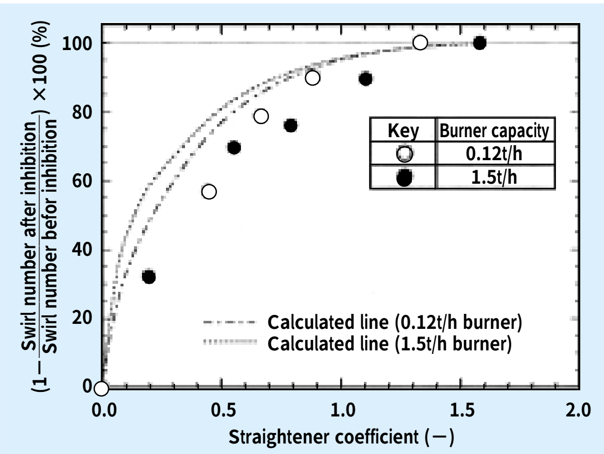


Fig. 7-3-4 Inhibition effect of swirl by straightener

conditions for installing a straightener to control swirl strength of air flow, a quantified index from straightener conditions was compared with the effects of controlling swirl strength. As a quantified index of the conditions, a straightener coefficient, which is expressed in a form of a ratio of the gross area of the straightener to the cross section area of the primary air nozzle, was defined. The effects of various straightener conditions and initial swirling strength for small-scale burners were evaluated. As a result, it was demonstrated that a straightener coefficient of 1.2 or more could almost control swirl strength for any of the conditions [8][9]. In addition, this tendency was observed also in a large-scale burner with 1.5 t/h of coal feed rate, and it became clear that the provision of a straightener coefficient to 1.2 or more could control swirl strength regardless of a burner scale [10][11].

For reference, a streamlined ring type concentrating method also attained the same concentrating characteristics of pulverized coal as the tangential flow-in type method, regardless of a burner capacity [6], [12]~[16], and it is considered that the two types of concentrating methods are same in performance.

7-3-4 Evaluation of Combustion Characteristics in Combustion Field

(1) Effect of pulverized coal concentration control on combustion characteristics

Fig.7-3-5 shows a relation between burner load and combustion efficiency (burned ratio of combustibles in coal) when an advanced low NOx burner with a tangential flow-in type concentrating method is used in a pulverized coal combustion test furnace, along with a relation using the burner without a concentrating function. Concentrating of pulverized coal improved combustion stability during low load operation and could accomplished stable combustion at a minimum load of 20 %, a target value corresponding to that in oil fired power plants. Furthermore, it improved combustion in a muddle load range, and a burner with a concentrating function had higher combustion efficiency in a load level of 50 % or less.

Fig. 7-3-6 shows combustion efficiency and NOx concentrations for each load when concentrating of pulverized coal at the outlet of the nozzle is adjusted by changing a ring position. Under low load conditions (50 % and 25 % loads), raising a pulverized coal concentration at the outer part by moving the ring position to the outlet of the nozzle increases combustion efficiency, and their effectiveness is remarkable at lower loads. In this case, NOx concentrations slightly increase with improved ignition.

On the other hand, under a high load condition of 83 %, concentrating of pulverized coal provide excessive concentration of pulverized coal at the outer part by moving the position to the outlet of the nozzle, so combustion efficiency was slightly decreased. Hence, it is desirable to control a ring position according to loads in order to maintain high combustion efficiency in a wide range of loads [8][9]. For reference, these tendencies in the tangential flow type method was observed as the same in a streamlined

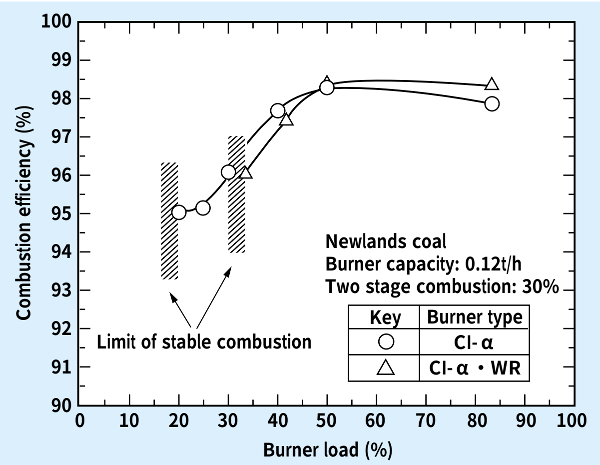


Fig. 7-3-5 Comparison of combustion efficency

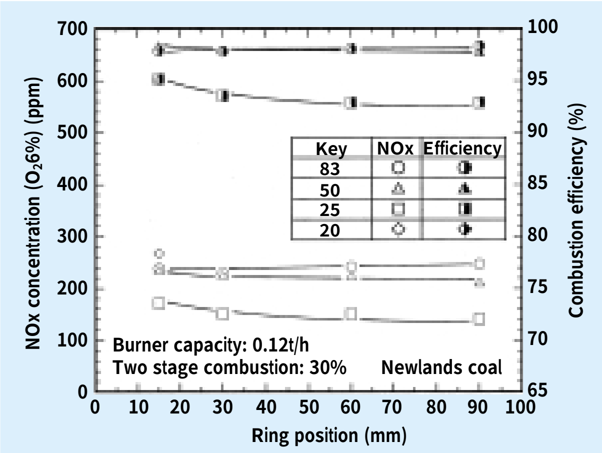


Fig. 7-3-6 Influence of ring position on NOx and combustion efficiency

ring type concentrating method [14]~[18].

(2) Effect of scale-up on combustion characteristics

Scaling up a tangential flow-in type burner to a large-scale burner with 1.5 t/h could significantly improve combustion stability during low load condition as in small-scale burners [10][11]. **Fig. 7-3-7** shows the emission characteristics of NOx and unburned carbon in fly ash of small- and large-scale burners during load changing. It is found that both of the burners can accomplish a minimum load of 20 %. Under a load condition of 40 % or more which are the same excess air ratio in the two burners, scaling up a burner capacity makes large flame and also expands reduction flame, so NOx concentrations in a large-scale burner decrease less than those in a small-scale burner for any load condition. In addition, owing to a decrease of heat loss from a furnace wall with increased furnace capacity, unburned carbon concentrations in fly ash was also decreased. Furthermore, change of NOx and unburned carbon in fly ash on load changing indicated common tendency in small- and large-scale burners.

Fig. 7-3-8 shows a comparison of the emission characteristics of NOx and unburned carbon in fly ash at load changing among three large-scale burners, an advanced low NOx burner equipped with a tangential flow-in type or a streamlined ring type concentrating system and the burner without a

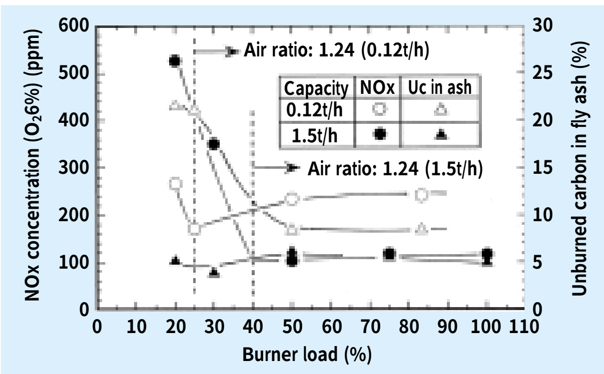


Fig. 7-3-7 Influence of burner capacity on NOx and unburned carbon in fly ash

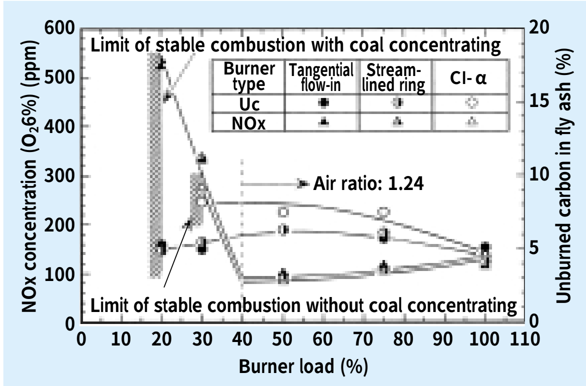


Fig. 7-3-8 Comparison of burner performance

concentrating function [13][16].

An advanced low NOx burner with a concentrating function allows stable combustion at a 20 % load of a target value, even with any of the two types while maintaining the same concentrations of NOx and unburned carbon in fly ash as an advanced low NOx burner without a concentrating function at 100 % load. In a middle load range, NOx concentrations became equal regardless of a concentrating function, but unburned carbon concentration in fly ash could be substantially reduced by a concentrating function. The difference of unburned carbon in fly ash between a burner with and without a concentrating function was expanded according to a decrease of load. This demonstrated that an advanced low NOx burner with a concentrating function had both excellent functions of a wide range burner and an advanced low NOx burner. Especially, it was cleared that this burner was significantly effective in reducing unburned carbon in fly ash in a middle load range. These characteristics are same regardless of concentrating methods. So, when applying the burner with a concentrating function to an actual utility boiler, it may be desirable to select a concentrating method that is easily provided, in consideration for various factors such as an installment space of a burner, connection feeding line for pulverized coal to burners and an easiness of construction, and so on.

7－4 Future Plan

A function of controlling loads for pulverized coal fired power plants will be increasingly required in the future. It can be considered that DSS operation, which means daily startup and stop, will be needed in some of the plants.

In this case, the most important function is considered to include a technology for improving combustion stability during low load condition described in this chapter, a technology for reducing emissions of NOx and unburned carbon in fly ash and a combustion technology with higher rate load controlling. It is most important to control a pulverized coal concentration to a reasonable value during low load operation or load changing condition in order to realize these technologies. Both of a wide range burner and an advanced low NOx wide range burner can be said to have an adequate function for a minimum load, owing to the accomplishment of the stable combustion at load of 20 %. In particular, an advanced low NOx wide range burner has significantly high performance which can maintain concentrations of NOx and unburned carbon in fly ash at a load of up to 40 % with a same level at a standard load. In the future, it would be important to upgrade these functions, reducing more NOx and unburned carbon in fly ash and searching how to immediately detect the change of concentrations during load control and make a burner condition be controlled with a load. In addition, because coal kinds used for pulverized coal fired power plants have been diversified recently, it is required to attain high-grade technologies that enable adequate low load operation and high rate load controlling operation for low quality coal, whose combustibility is poor.

At low load, a mill is required to be operated at low load operations. Technologies for anxiety equipment will be considered to make some problems such as erosion of a pulverizing part. These issues will become more important with increasing period of low load operation, but may not be extreme problems, because it is expected that these problems will not occur from initial term of plant operation at least. These are considered to be issues that should be judged from some viewpoints including total cost, for instance, what prevention method is best for solving these problems or whether they can be solved by increasing a frequency of replacement for erosion parts.

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Column 2: Technology for an On-line Apparatus Measuring Pulverized Coal Particle Size Distribution and Concentration

In operating pulverized coal fired power plants at middle load operation, it is essential to enable stable combustion also at low loads. In order to provide a technique for this stable combustion, CRIEPI has developed a wide range burner that concentrates pulverized coal flow whose concentration decreases at low loads and enables stable combustion. This burner is intended to control concentration of pulverized coal to the best level for combustion. For this reason, it will be required to identify the concentrating conditions of pulverized coal concentrations that become lower with reduced loads. In order to identify the concentrating conditions it is necessary to measure the concentrations and also particle size distribution of pulverized coal carried to burners, so CRIEPI developed these on-line measuring systems as well as the wide range burner.

A concentration and particle size distribution on-line measuring system was configured to sample pulverized coal from a fuel line by isokinetic sampling, detect the concentration and then carry it to a particle size distribution detector.

In a particle concentration detector, it was decided that a differential pressure type fluid flowmeter would be employed which is responsive to control of pulverized coal concentrations and can continuously and easily detect signals. For the application, the detector was modified so that it could measure a low concentration range for pulverized coal of pulverized coal fired power plant. On the other hand, a particle size distribution measurement system was developed that collects small to large particles in two stages of louver and cyclone classifiers per particle size and determines particle size distributions from their classification sizes and collection efficiency.

These modified and developed measuring systems were upgraded to evaluate basic characteristics of the two detectors, and as a result, it was verified that the systems allowed more accurate measurement. In addition, it was demonstrated that the systems were used for measuring pulverized coal in primary air line of pulverized coal fired power plants and could be sufficiently applied also to measuring concentrations and particle size distribution of pulverized coal in an actual utility boiler.

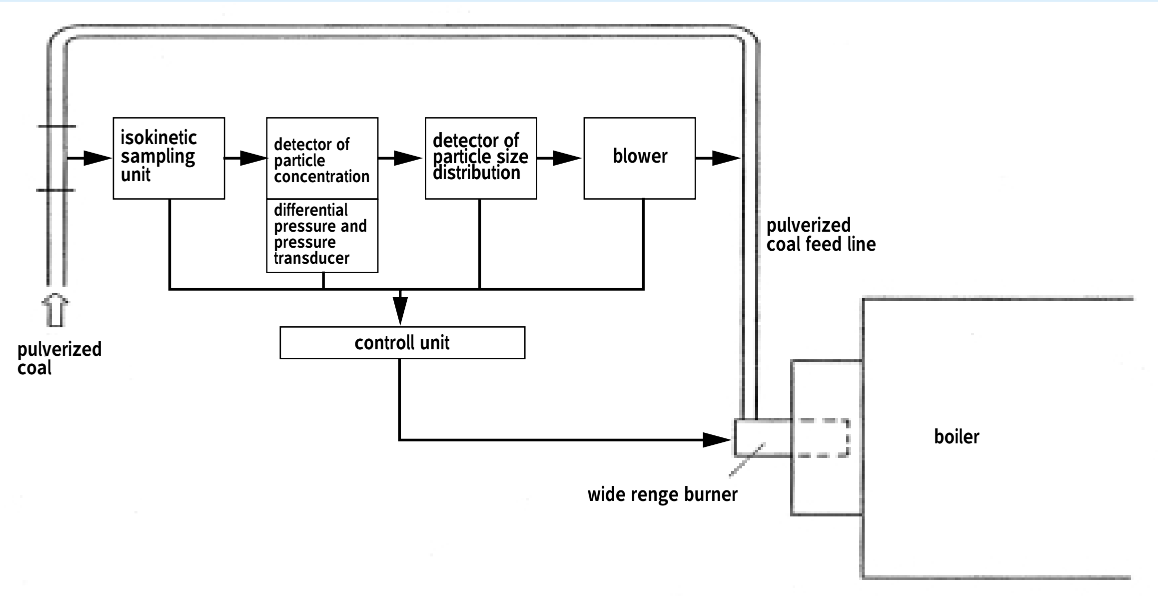

Fig. System flow of an on-line apparatus measuring pulverized coal particle concentration and size distribution.

Chapter

8

Diversification of Coal Rank for Thermal Power Station

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Hisao Makino (Dr.)
Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

Michitaka Ikeda
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

Yoshiko Hiei
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

Hideki Kanda (Dr.)
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

8－1 Background

Coal is an important energy resource to meet the future demand of electricity because its reserve is more abundant than those of other fossil fuels. At present, the main utilization of coal in power stations is for pulverized coal combustion, and bituminous coal is generally utilized for those in Japan [(1)]. However, from the viewpoints of fuel security and fuel cost, it will be necessary for power stations to use low rank coal, which is rich in moisture or ash content and has a calorific value lower than bituminous coal [(2)].

Low rank coal with moisture content higher than 20% is called sub-bituminous coal or lignite, and is mined in large amounts throughout the world [(3)]. Due to the 20-40% moisture content, sub-bituminous coal is difficult to ignite and NOx emission in sub-bituminous coal combustion becomes higher.

Although the coal usually fired in Japanese power stations contains ash under 20wt%, coal contained ash higher than 30wt% is mined throughout the world. Therefore, it is important to identify the effects of the ash content in coal on the pulverized coal combustion characteristics.

On the other hand, it is desired to utilize not only low rank coals with high moisture and high ash contents, but also coals with high fuel ratio. Although high fuel ratio coals have higher calorific values, they are not used very often in Japanese power stations because of their low ignitability. It is, therefore, important to clarify the combustion characteristics of the high fuel ratio coals and to develop a new combustion technology for them.

In this chapter, the combustion characteristics of low rank coals and high fuel ratio coals are presented. As the low rank coals, high moisture content coals and high ash content coals are considered. The experiments were done using a pulverized coal combustion test furnace with coal combustion rate of 100 kg/h at the rated load.

8－2 Utilization of Low Rank Coals

8-2-1 High moisture content coals

In this study, sub-bituminous coal, which contains moisture between 20 and 40 %, was used because it is most abundant among other low rank coals. The effects of amount of moisture content in coal on the combustion characteristics and the optimal combustion air injection conditions for the sub-bituminous coal were investigated from the viewpoint of the lower NOx emission and unburned carbon in fly ash. In addition, the combustion characteristics of the blended coal of bituminous and sub-bituminous coals were examined.

(1) Combustion characteristics of sub-bituminous coal

(a) Combustion characteristics under the air injection conditions optimized for bituminous coal

When sub-bituminous coal is pulverized, part of moisture remains in the coal and part is vaporized. In this section, the influence of these moisture conditions on combustibility was investigated [(4)(5)]. The moisture content remaining in the coal was controlled by changing the temperature of the hot air in the pulverizer. The concentration of vaporized moisture in the primary air was controlled by supplying moisture vapor from the evaporator.

As sub-bituminous coal, Wara mined in Indonesia was used. The moisture content of Wara is comparatively high at about 40%. To clarify the influence of moisture remaining in coal on combustion characteristics, various samples of pulverized coal, in which levels of remaining moisture in coal were different, were prepared. Cr is defined as the weight ratio of remaining moisture to the weight of dry coal. In this experiment, the Cr conditions used for Wara were 0.20, 0.30 and 0.67 [kg-H_2O/kg-dry coal]. Cv is defined as the weight ratio of vaporized moisture to the weight of dry coal. Total moisture content is defined as the sum of Cr and Cv. In the combustion test, total moisture content of Wara was set to constant values of 0.67.

Coal combustion characteristics of the three different levels of coal moisture content were evaluated with the combustion air injection conditions optimized for bituminous coal. **Fig. 8-2-1** shows the distribution of the oxygen concentration in the furnace for Wara and Newlands (Bituminous) coal combustion. When the Newlands coal was fired, the combustion flame was stable. The consumption of oxygen progressed gradually from the burner outlet. The reduction area between the burner outlet and the injection port for two-stage combustion air was widely formed in the furnace. Distribution of the oxygen concentration for Wara coal combustion was then compared under the three levels of remaining moisture content. On Wara coal combustion, the ignition become worse than that on Newlands combustion and the flame diffuse widely. When Cr increased, the ignition worsened more and the combustion flame became diffused wider, so that the reduction area was decreased. It was considered that the reason for the delay of oxygen consumption was that the latent heat of evaporation increased.

Fig. 8-2-2 shows the distribution of the NOx concentration at the center axis in the furnace. When bituminous coal was fired, NOx was formed rapidly at the burner exit. However, NOx was immediately reduced at the reduction area between the burner outlet and the air injection port for two-stage combustion. In the case of sub-bituminous coal combustion, NOx formation and decomposition were delayed. When Cr increased, NOx formation was

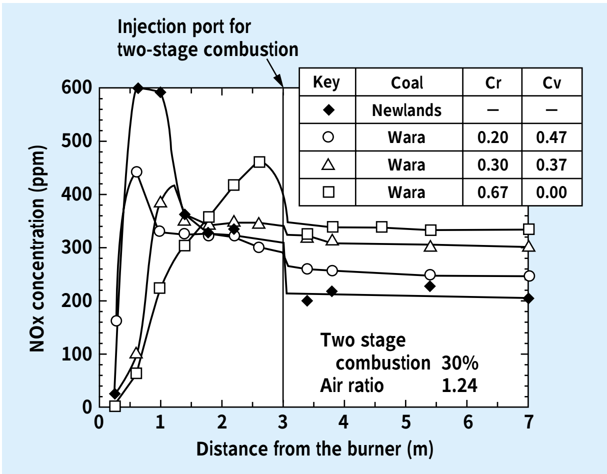

Fig. 8-2-2 Distribution of the NOx concentration at the center axis in the furnace

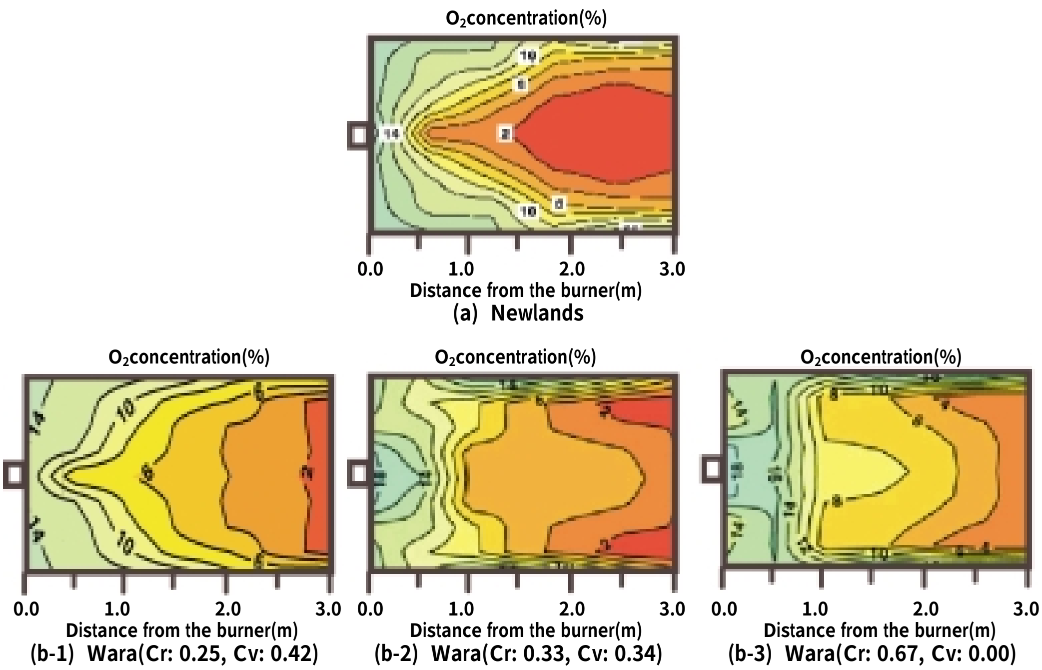

Fig.8-2-1 Distribution of the oxygen concentration in the furnace for Wara and Newlands coal combusion

delayed and decomposition of NOx at the reduction area decreased because of the worsening of combustibility. Therefore, NOx concentration at the exit of the furnace increased as the remaining moisture content in coal became higher.

(b) Adjustment of combustion air injection conditions for sub-bituminous coal

Since NOx concentration at the exit of the furnace was high in the case of combustion air injection condition optimized for bituminous coal, the volume and the swirl strength of combustion air were controlled in order to improve combustion stability. The influence of the flow rate of secondary combustion air to the sum of secondary and tertiary combustion air on NOx concentration at the exit of the furnace indicated tendencies similar with bituminous coal combustion. The influence of the swirl vane angle of tertiary combustion air was also shown to have a similar tendency with bituminous coal combustion. On the other hand, the swirl vane angle of secondary air (Ss) had an effect on NOx emission different from bituminous coal combustion. The influence of Ss on NOx concentration is shown in **Fig. 8-2-3**. When bituminous coal was fired, the optimum Ss was about 80 deg. The intensive swirl strength was suitable for bituminous coal combustion. However, sub-bituminous coal had unstable combustion at the same Ss. When the Ss was between 50 and 60 deg, the NOx concentration at the exit of the furnace was the minimum for sub-bituminous coal combustion.

The emission characteristics of NOx and unburned carbon concentration were compared with Cr of 0.20, 0.30 and 0.67, with the same Ct of 0.67. **Fig. 8-2-4** shows the influence of Cr on NOx concentration at the exit of the furnace and the unburned carbon concentration in fly ash. When the Ss was optimized for sub-bituminous coal combustion, both NOx concentration and the unburned carbon concentration decreased. When Cr became lower, NOx concentration decreased. When Cr was high, the effect of NOx reduction by adjusting the combustion air injection conditions became higher because ignition was improved considerably. When the Air/Coal was 1.9, the emission of both NOx and unburned carbon decreased further. It was clarified that the ratio of NOx reduction was achieved about 40% with a Cr of 0.67. By optimizing the burner conditions or by reducing moisture content of coal, not only NOx emission but also unburned carbon concentration could be reduced.

(c) Influence of two-stage combustion

We have already shown that emissions of NOx and unburned carbon can be reduced by adjusting the air injection conditions from the burner to better situation for sub-bituminous coal combustion. However, the reduction is insufficient compared with bituminous coal combustion. The purpose of this study is to investigate the influence of two-stage air injection conditions on NOx and unburned carbon concentration in fly ash and to clarify the optimum air injection conditions in order to reduce those emissions [6].

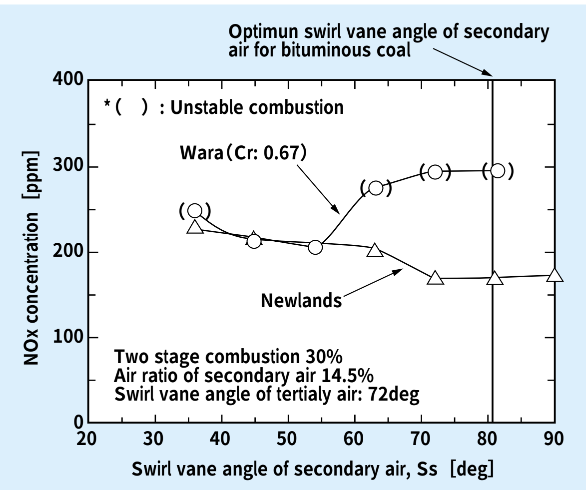

Fig. 8-2-3 Influence of vane angle of secondary air on NOx concentration

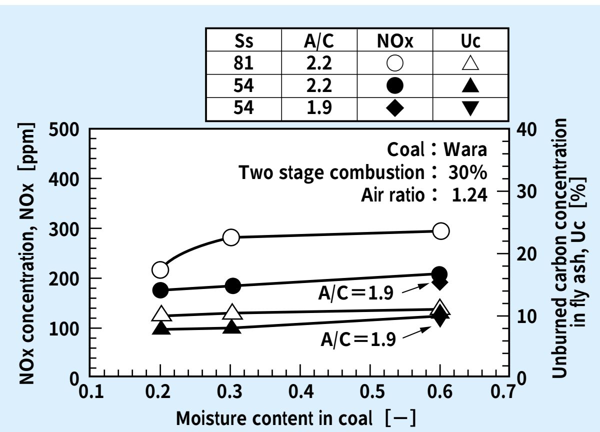

Fig. 8-2-4 Influence of Cr on NOx concentration at the exit of the furnace and the unburned carbon concentration in fly ash

Fig. 8-2-5 shows the influence of the distance of air injection point for two-stage combustion from the burner, L/D, on emissions of NOx and unburned carbon in fly ash. L/D is defined as the distance from the burner divided by the diameter of furnace. The swirl vane angle was fixed at the optimum value for sub-bituminous coal. When the air injection point was shifted downstream in the furnace, NOx concentration at the exit of the furnace decreased. The effect of NOx reduction worsened at the injection point after an L/D distance of 4.5. On the other hand, the unburned carbon concentration in fly ash increased when the air injection point was shifted downstream in the furnace. The tendency of increase in the unburned carbon concentration became much higher after the same 4.5 L/D distance. Though the optimum air injection point was L/D 3.5 for bituminous coal combustion [7], that point was shifted to 4.5 for sub-bituminous coal combustion. The reason of this difference was the delay of oxygen consumption due to the latent heat of the evaporation of moisture in the sub-bituminous coal and the decrease of partial oxygen pressure around coal particles caused by the existence of vaporized moisture. Therefore, the optimum air injection point for two-stage combustion was shifted to the exit of the furnace.

Influence of air injection ratio for two-stage combustion on emissions of NOx and unburned carbon in fly ash was investigated with the air injection point for two-stage combustion fixed at the injection point of 4.5. **Fig. 8-2-6** shows the relation

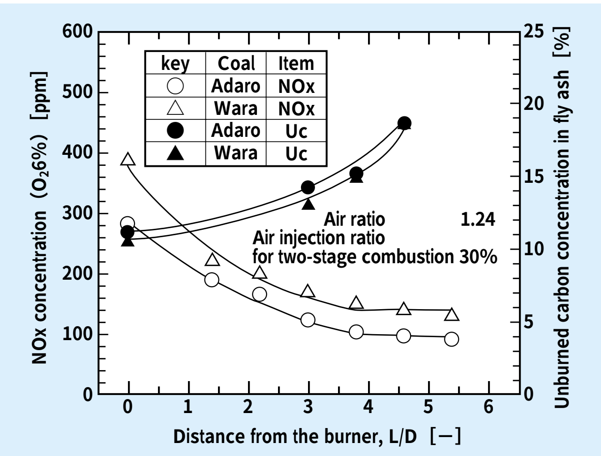

Fig. 8-2-5 Influence of the distance of air injection point for two-stage combustion from the burner, L/D

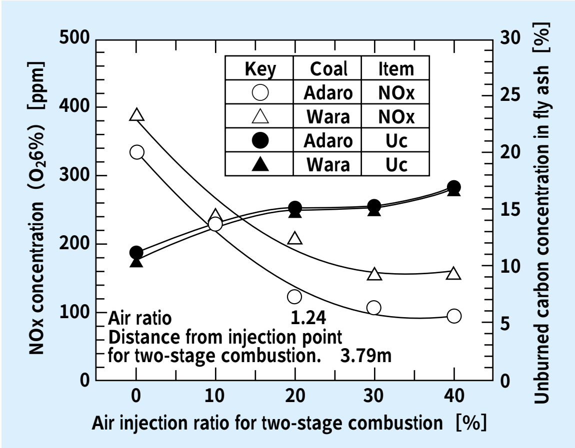

Fig. 8-2-6 Relation between air injection ratio for two-stage combustion and emissions of NOx and unburned carbon in fly ash

between air injection ratio for two-stage combustion and emissions of NOx and unburned carbon in fly ash. When the air injection ratio for two-stage combustion increased, NOx concentration at the exit of the furnace decreased. The effect of NOx reduction tended to be saturated with an air injection ratio for two-stage combustion over 30%. On the other hand, the unburned carbon concentration in fly ash became high when the air injection ratio increased. The unburned carbon concentration was highest with an air injection ratio of 40 %. The unburned carbon concentration with an air injection ratio of 30% was almost same as that of 20%. The reason for this was considered as follows. Under the condition of an air injection ratio of 20%, as the amount of secondary and tertiary air of the burner was larger than that with an air injection ratio of 30%, the swirl strength was intensive and coal particles moved to outer side in the furnace since sub-bituminous coal is fine and a low density. Therefore, sub-bituminous coal was not fired efficiently at the combustion accelerating area under an air injection ratio of 20%.

Fig. 8-2-7 shows the effect of the air injection conditions for two-stage combustion on emissions of NOx and unburned carbon in fly ash. It was clarified that NOx emission was much lower when the air injection condition for two-stage combustion was suitable for sub-bituminous coal combustion. Unburned carbon concentration had almost the same value. By adjusting the burner and staged air injection conditions, NOx and unburned carbon were reduced to almost the same value as those of bituminous coal

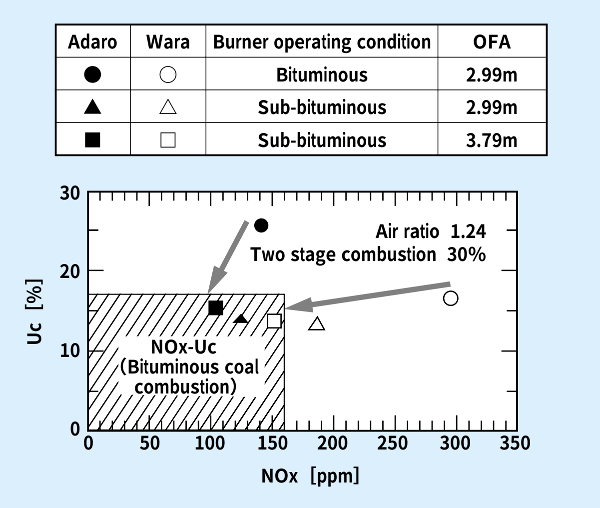

Fig. 8-2-7 Effect of the air injection conditions for two-stage combustion on emissions of NOx and unburned carbon in fly ash

combustion.

(2) Blends combustion characteristics of bituminous / sub-bituminous coals

(a) Emission characteristics of NOx and unburned carbon in fly ash

In the case of the utilization of sub-bituminous coal in Japan, it is considered that, in the near future, sub-bituminous coal will be applied to conventional boilers designed for bituminous coal combustion. However, oxygen consumption during the combustion of sub-bituminous coal with high moisture content is delayed. Therefore, sub-bituminous coal is utilized for blended combustion with bituminous coal.

The purpose of this study is to investigate the influence of the blend ratio of sub-bituminous coal on combustion characteristics, such as NOx emission and combustion efficiency [8][9]. As sub-bituminous coal, Wara and Adaro mined in Indonesia were used. Moisture content of Adaro is about 20%. In this experiment, the Cr conditions for Adaro were 0.11 and 0.25. In the combustion test, total moisture contents of Wara and Adaro were set to constant values of 0.25 and 0.67, respectively.

Sub-bituminous coal was fired with bituminous coal in the advanced low NOx burner in which air injection conditions were optimized for low NOx combustion of bituminous coal. shows the relationship between NOx concentration at the exit of the furnace

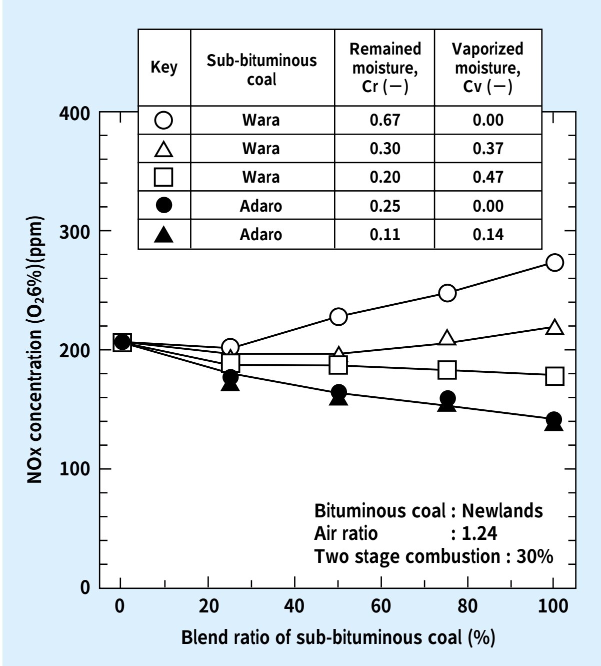

Fig. 8-2-8 Relation between NOx concentration at the exit of the furnace and the blend ratio of sub-bituminous coal

and the blend ratio of sub-bituminous coal. NOx concentration at the exit of the furnace is different depending on the amount of remaining moisture in coal, Cr. As Cr increased, NOx concentration became higher. The reason for this has already been clarified for sub-bituminous coal combustion. When Cr increased, oxygen consumption was delayed. The NOx reduction region before the air injection point for two-stage combustion became narrow, and NOx concentration at the exit of the furnace became high. NOx concentration became higher with increasing Cr. In spite of Cr, NOx concentration in blended combustion of sub-bituminous coal indicated in the mean value estimated from those in non-blended combustion of bituminous coal and sub-bituminous coal respectively. When the blend ratio of sub-bituminous coal increased, NOx concentration in blended combustion approached that in sub-bituminous coal combustion.

NOx formation in pulverized coal combustion depends on fuel nitrogen [10], and nitrogen content differs among coal. The conversion ratio of fuel nitrogen to NOx was compared in blended combustion. The conversion to NOx is defined as follows:

$$CR_{NOx} = C_{NOx} / C_{CalNOx} \times 100 \qquad (8\text{-}1)$$

where CR_{NOx} [%] is the conversion ratio of fuel nitrogen to NOx, C_{NOx} [ppm] is measured NOx concentration at the exit of the furnace. C_{calNOx} [ppm] is defined such that all of the fuel nitrogen is converted to NOx. **Fig. 8-2-9** shows the relationship between conversion to NOx and blend ratio of sub-bituminous coal. Although the fuel ratio of sub-bituminous coal is lower than that of bituminous coal, CR_{NOx} in sub-bituminous coal combustion is higher than that in bituminous coal combustion. When Cr increased, CR_{NOx} became high in the combustion of both only sub-bituminous coal and blend of sub-bituminous coal with bituminous coal. CR_{NOx} in blended combustion approached that in sub-bituminous coal combustion with increasing amount of sub-bituminous coal.

Fig. 8-2-10 shows the relationship between unburned carbon concentration in fly ash and the blend ratio of sub-bituminous coal under the same conditions as in the case of Fig. 8-2-8. The unburned carbon concentration in fly ash in blended combustion is higher than that in non-blended combustion of each coal. However, unburned carbon concentration in fly ash is dependent on ash content. Even if combustion efficiency is high, unburned carbon concentration in fly ash is high in the case of low ash content coal. Therefore, it is very difficult to compare combustibility using unburned carbon concentration in fly ash. Then, the unburned fraction defined in equation (8-2) is used for the investigation of combustion characteristics:

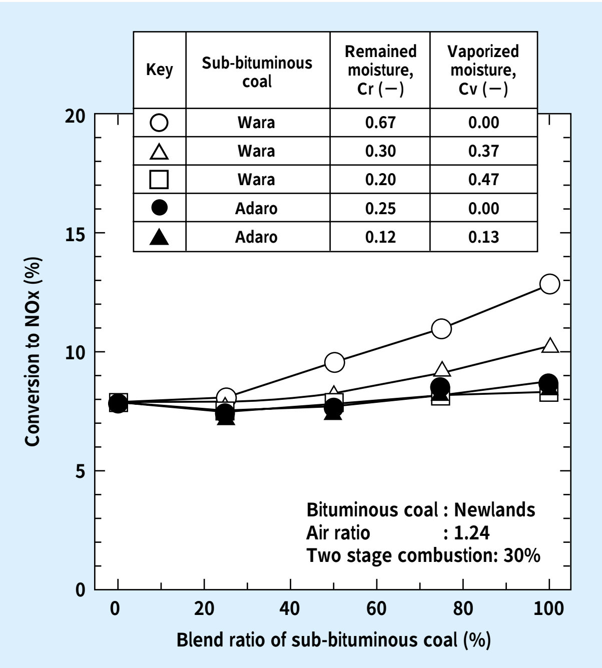

Fig. 8-2-9 Relation between conversion to NOx and blend ratio of sub-bituminous coal

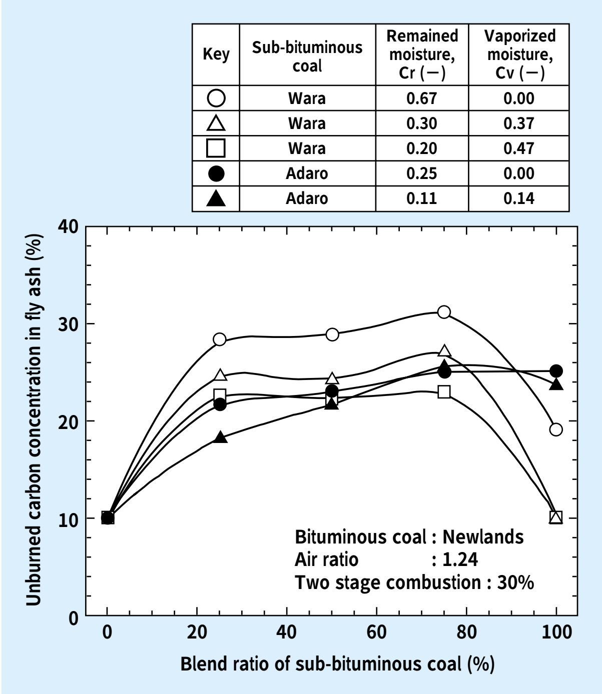

Fig. 8-2-10 Relation between unburned carbon concentration in fly ash and the blend ratio of sub-bituminous coal

$$Uc^{*} = 100 - \eta = \frac{Uc}{100 - Uc} \times \frac{C_{Ash}}{100 - C_{Ash}} \times 100 \qquad (8\text{-}2)$$

where Uc^{*} [%] is the unburned fraction, η [%] is the combustion efficiency, Uc [%] is the unburned carbon concentration in fly ash and C_{Ash} [%] is the ash content in coal.

Fig. 8-2-11 shows the relationship between the unburned fraction and the blend ratio of sub-bituminous coal. The unburned fraction had a maximum value when the blend ratio of sub-bituminous coal was about 25%. This was presumably caused by the moisture in sub-bituminous coal hindering the combustion process of the bituminous coal, because in blended combustion, moisture in sub-bituminous coal exists around not only sub-bituminous coal particles but also bituminous coal particles. Then, as the partial oxygen pressure of circumstance of bituminous coal and the gas temperature decreased, combustion efficiency of bituminous coal became low.

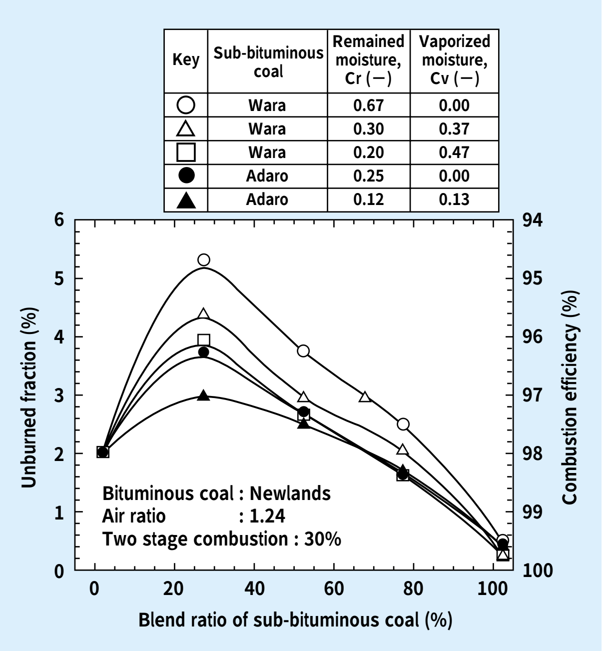

Fig. 8-2-11 Relation between the unburned fraction and the blend ratio of sub-bituminous coal

(b) Reduction technology of unburned carbon during low blend ratio combustion of sub-bituminous coals

When sub-bituminous coal is fired in power stations, main utilization method is low blended combustion of sub-bituminous coal. The purpose of this study is to investigate the blend condition in order to reduce unburned carbon concentration in fly ash when sub-bituminous coal is blended under 30% (11)(12).

Fig. 8-2-12 shows relationship between unburned carbon concentration in fly ash and blend ratio of sub-bituminous coal. When blend ratio of sub-bituminous coal increased, unburned carbon concentration in fly ash became higher. This reason is considered as follows. As blend ratio is high, injected moisture amount into the furnace increases and combustibility of bituminous coal becomes worsen. Unburned carbon concentration in fly ash on blended combustion with higher moisture content coal (Wara) became higher than that on blended combustion with low moisture content coal (Adaro) becomes of more injected moisture. To investigate this result, unburned fraction was evaluated using injected moisture amount into the furnace shown in **Fig. 8-2-13**. It was cleared that the worse of combustibility of bituminous coal was affected by on injected moisture amount into the furnace.

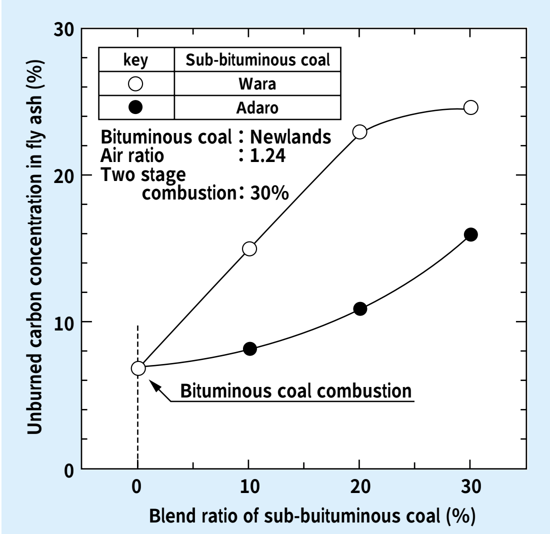

Fig. 8-2-12 Relation between unburned carbon concentration in fly ash and blend ratio of sub-bituminous coal

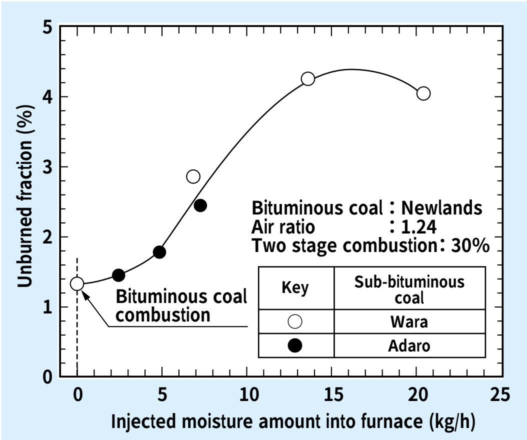

Fig. 8-2-13 Relation between unburned fraction and injected moisture amount into furnace

Fig. 8-2-14 shows the relationship between unburned carbon concentration in fly ash and blend ratio of sub-bituminous coal with bituminous coal. In this experiment, three kinds of bituminous coal are used and fuel ratio of bituminous coal is different. Increase of unburned carbon concentration in fly ash on blended combustion is high when fuel ratio of bituminous coal is high. On the other hand, when fuel ratio of bituminous coal decreased, increase of unburned carbon concentration in fly ash became low. Especially, when bituminous coal, which was same fuel ratio as sub-bituminous coal, was fired with sub-bituminous coal, increase of unburned carbon concentration in fly ash is extremely low. As a result,

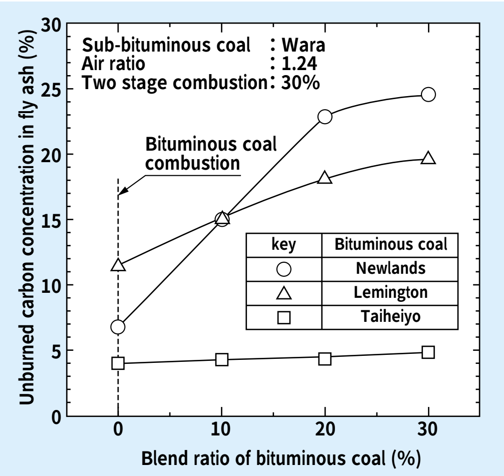

Fig. 8-2-14 Relation between unburned carbon concentration in fly ash and blend ratio of sub-bituminous coal with bituminous coal

it was cleared that the worse of combustibility of bituminous coal during blended combustion of sub-bituminous coal was remarkable for low combustibility coal.

Fig. 8-2-15 shows the relationship between increase of unburned carbon concentration in fly ash and fuel ratio of bituminous coal during low blended combustion of sub-bituminous coal. When moisture content in sub-bituminous coal was high, or, fuel ratio of bituminous coal was high, the increase of unburned carbon concentration in fly ash became higher. It was cleared that the increase of unburned carbon concentration in fly ash could be reduced when blended coals were selected suitably.

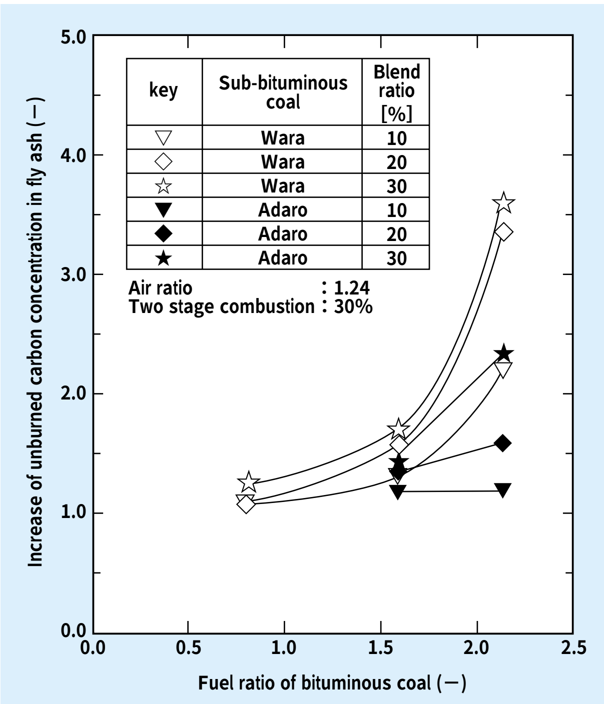

Fig. 8-2-15 Relation between increase of unburned carbon concentration in fly ash and fuel ratio of bituminous coal during low blended combustion of sub-bituminous coal

8-2-2 High ash content coals

For the utilization of high ash contend coal, the influences of ash content on pulverized coal combustion characteristics was experimentally investigated using Ikeshima coal with different ash contents of 36, 44 and 53%, in a pulverized coal combustion test furnace. The ratio of the two-stage combustion air to the total air (two-stage combustion ratio) is 0 or 30%. Hereafter, the conditions where the two-stage combustion ratios of 0 and 30% are referred to as "non-staged combustion condition" and "staged combustion condition", respectively.

Fig. 8-2-16 shows the axial distributions of gas temperature, O_2 and NOx concentrations in the furnace in the non-staged combustion. As the ash content increases, the gas temperature decreases, while the O_2 consumption and the NOx formation and reduction are delayed near the burner. Although the gas temperature and the O_2 concentration at the exit of the furnace tend to approach certain values independent of the ash content, NOx concentration becomes higher with ash content. This is due to the shortage of the NOx reduction time because of the delay of the oxygen comsumption.

Fig. 8-2-17 shows the relationship between the conversion of fuel bound nitrogen to NOx, CR_{NOx}, and the index of the fuel ratio divided by the fuel bound nitrogen, FR/FN, for Ikeshima coal, together with that for some typical bituminous coal with low ash content of 7.0-18% (non-staged combustion). In pulverized coal combustion, most of NOx is thought to be formed from fuel bound nitrogen, and so CR_{NOx} defined by equation (8-1) is used as a indication of NOx formation characteristics. Usually, CR_{NOx} for bituminous coals tends to increase linearly with FR/FN. On the other hand, although CR_{NOx} for Ikeshima coal with the ash content of 36% is almost on the averaged line

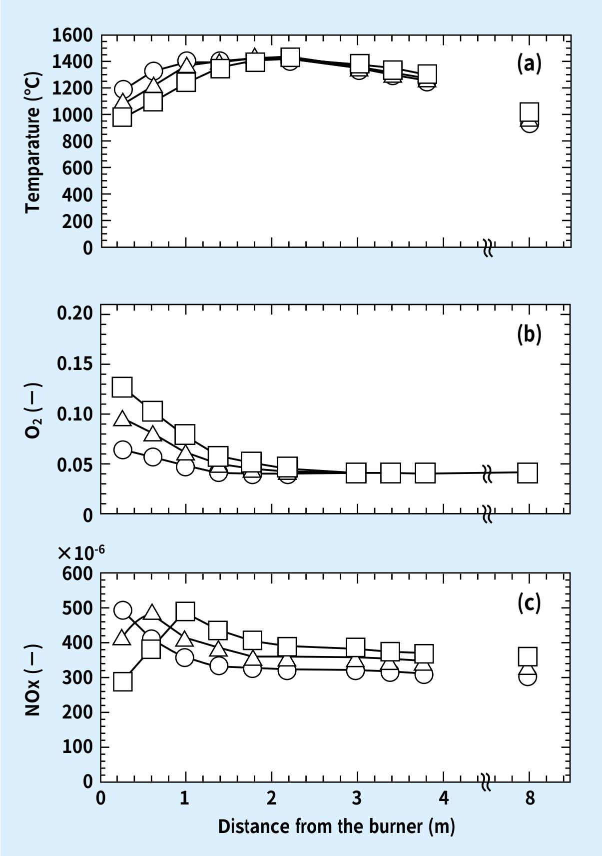

Fig. 8-2-16 Axial distributions of gas temperature, O_2 and NOx concentrations (non-staged combustion condition): (a) gas temperature; (b) O_2; (c) NOx; ○, 36wt% ash; △, 44wt% ash; □, 53wt% ash.

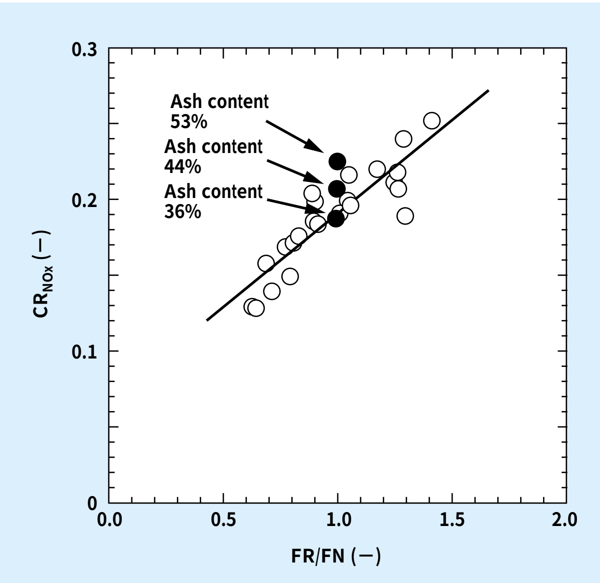

Fig. 8-2-17 Relation between CR_{NOx} and FR/FN (non-staged combustion condition): ○, bituminous coal with low ash content; ●, Ikeshima coal.

for bituminous coals, it tends to monotonously increase with increasing the ash content in spite of some *FR*/*FN*.

The relation between the unburned carbon fraction, *Uc**, and the fuel ratio, *FR*, is shown in **Fig. 8-2-18**, together with those for some typical bituminous coals with low ash contents of 7.0-18% (η is the combustion efficiency). It was shown that *Uc** was proportional to *FR* for bituminous coals with low ash contents. *Uc** of the high ash content coal is found to be much higher than that of low ash content coal. With increasing the ash content, the unburned fraction increases and the combustion efficiency decreases.

Thus, the combustibility of the pulverized coal combustion is suppressed as the ash content in coal increases. One of the reasons of this is likely due to that the heat loss taken off by the ash increases with increasing the ash content. It is also considered that the ash impedes the char oxidization by covering the combustible matter.

Fig. 8-2-19 shows the effect of the ash content on the NOx concentration and the unburned fraction, Uc*, at the furnace exit for both in the non-staged and staged combustions. It is clearly observed that the staged combustion decreases the NOx concentration and increases the unburned carbon fraction at the

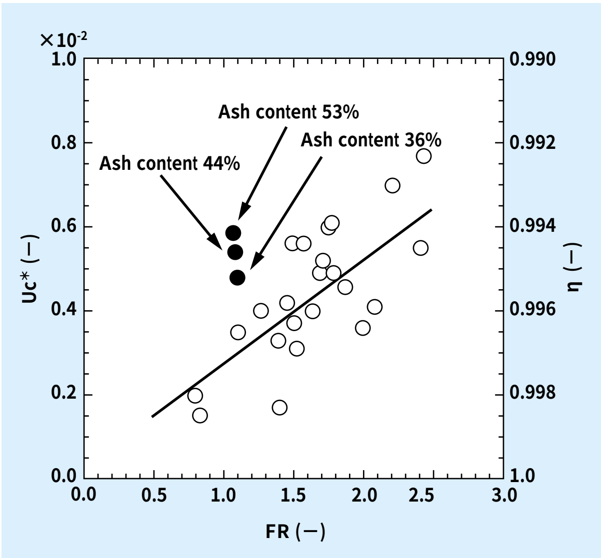

Fig. 8-2-18 Relation between Uc^* and FR (non-staged combustion condition): ○, bituminous coal with low ash content; ●, Ikeshima coal.

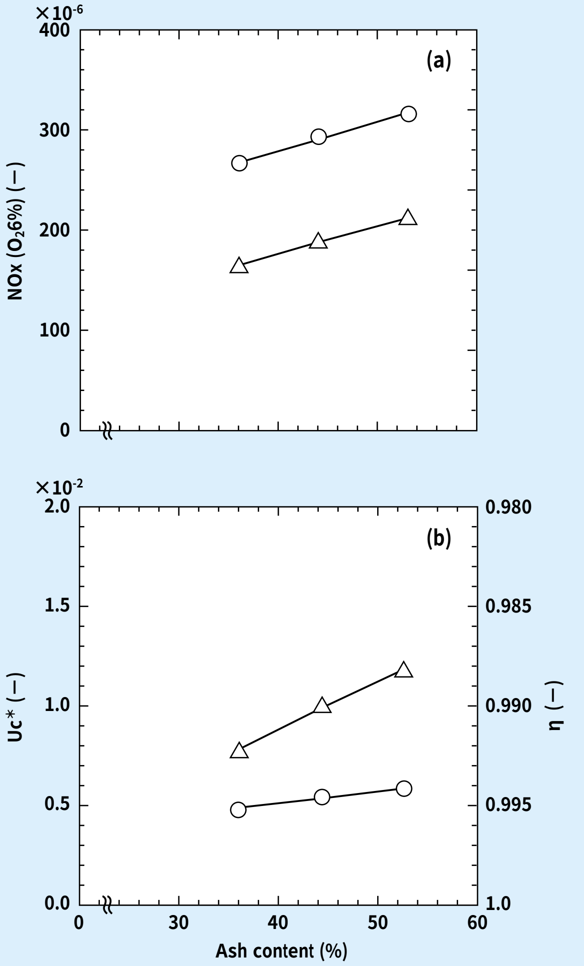

Fig. 8-2-19 Effects of ash content on NOx concentration and *Uc at the furnace exit under the non-staged and staged combustion conditions: (a) NOx concentration; (b) *Uc**; ○, non-staged combustion; △, staged combustion.**

furnace exit. Similar to the results in the non-staged air combustion, both the NOx concentration and the unburned fraction in the staged air combustion increase with the ash content.

Fig. 8-2-20 shows the effect of the ash content on the ratio of the NOx reduction and the unburned

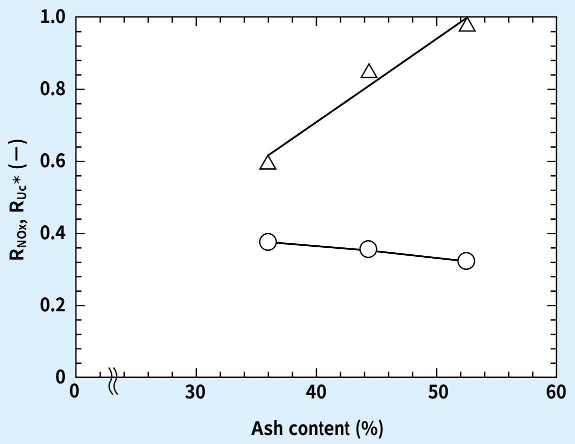

Fig. 8-2-20 Effects of ash content on R_{NOx} and R_{Uc^*}: ○, R_{NOx}; △, R_{Uc^*}.

fraction by the staged air combustion, R_{NOx} and R_{Uc^*}, R_{NOx} and R_{Uc^*} are defined by

$$R_{NOx} = \frac{NOx_{non-stg} - NOx_{stg}}{NOx_{non-stg}} \tag{8-3}$$

$$R_{Uc^*} = \frac{Uc^*_{stg} - Uc^*_{non-stg}}{Uc^*_{non-stg}} \tag{8-4}$$

and these values are valid to clarify the effects of the staged air combustion on the decrease of NOx concentration and the increase of the unburned fraction, respectively. Here, NOx_i and Uc^*_i are the NOx concentration and the unburned carbon fraction at the furnace exit, and the subscriptions of *non-stg* and *stg* indicate the values in the non-staged air combustion and the staged combustion, respectively. It is found that R_{NOx} decreases and R_{Uc^*} increases in proportion to the ash content This means that with increasing the ash content, the NOx reduction due to the staged combustion weakens, while the increment of the unburned carbon fraction due to the staged air combustion becomes remarkable.

8–3 Utilization of High Fuel Ratio Coals

The pulverized coal combustion characteristics of high fuel ratio coals was investigated in a pulverized coal combustion test furnace. In the experiment, four kinds of high fuel ratio coal with fuel ratios greater than 4.0 and two kinds of bituminous coal with fuel ratios less than 2.0 for the comparison are tested, and the effects of the fuel ratio on the minimum burner load for stable combustion, NOx emission and combustion efficiency are examined under the non-staged or staged combustion conditions (the two-stage combustion air ratio is 30%).

Although high-fuel-ratio coals have higher calorific values, they are not used very often for the pulverized coal combustion power plants in Japan because of their low ignitability and combustibility [14].

Fig. 8-3-1 shows the effect of fuel ratio, *FR*, on the minimum burner load for stable combustion under the non-staged air combustion condition. Here, CI-**α** burner [11][12] and a conventional low-NOx burner are compared. It is observed that although for both burners the minimum burner load rises with increasing *FR*, the value for the CI-**α** burner [11][12] is much less than that for the conventional low NOx burner at a certain *FR*. For a high fuel ratio range of

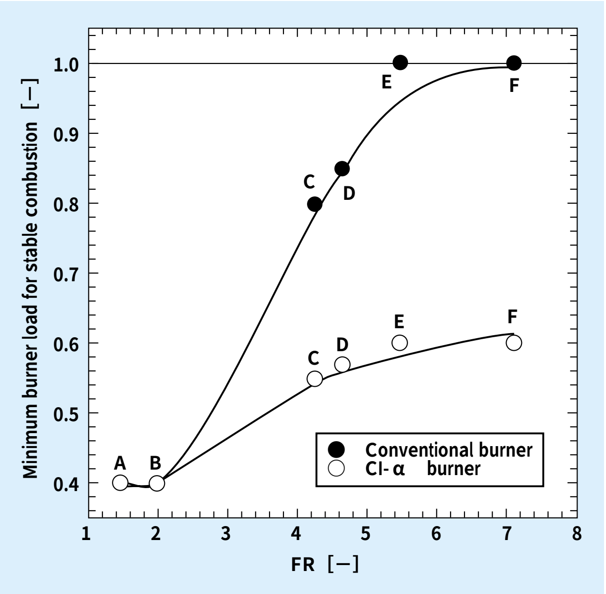

Fig. 8-3-1 Effect of fuel ratio on the minimum burner load for stable combustion (non-staged combustion condition).

FR > 5.5, the burner load for the conventional low NOx burner could not be lowered below 100 %, whereas the CI-**α** burner could be operated even for a lower burner load of 60 %. This means that the CI-**α** burner is more suitable for the stable combustion of the pulverized coal for high fuel ratio coals than the conventional low NOx burner. The strong swirling flow generated by the CI-**α** burner produces a recirculation flow in the high gas temperature region close to the burner outlet. This lengthens the residence time of coal particles in this high gas temperature region and promotes the evolutions of volatile matter and char reaction. Thus, to improve the stability of the combustion flame for high fuel ratio coals, it is effective to increase the residence time of coal particles in the high gas temperature region near the burner using a recirculation flow.

Fig. 8-3-2 shows the relationship between the conversion of fuel bound nitrogen to NOx, CR_{NOx}, and three indexes consisting of fuel ratio, *FR*, fuel bound nitrogen, *FN*, and fixed carbon, *FC*. Six coals are fired using the CI-**α** burner with a burner load of 100%. Here, CR_{NOx} is defined by eq. (8-1). It is found in Fig. 8-3-2 (b) and (c) that CR_{NOx} for high-fuel-ratio coals can be linearly correlated using *FC* instead of *FR*. CR_{NOx} increases almost linearly with FC/FN even for high-fuel-ratio coals with *FR* > 5.5 (FC/FN > 60), and the linearity is further improved by introducing $FC/\sqrt{FN}$.

The relationship between unburned carbon fraction, Uc^*, and fuel ratio, *FR*, is shown in **Fig. 8-3-3**. It is found that Uc^* monotonically increases with *FR* not only for bituminous coals but also for high-fuel-ratio coals.

Fig. 8-3-4 shows the effects of fuel ratio *FR* on NOx reduction and unburned fraction increment at the furnace exit by the staged combustion, R_{NOx} and R_{Uc^*}, which are defined by equations (8-3) and (8-4). It is found that R_{NOx} decreases and R_{Uc^*} increases with increasing *FR*. In other words, with increasing fuel ratio, the NOx reduction effect due to the staged combustion weakens, whereas the unburned carbon fraction increment due to the staged combustion

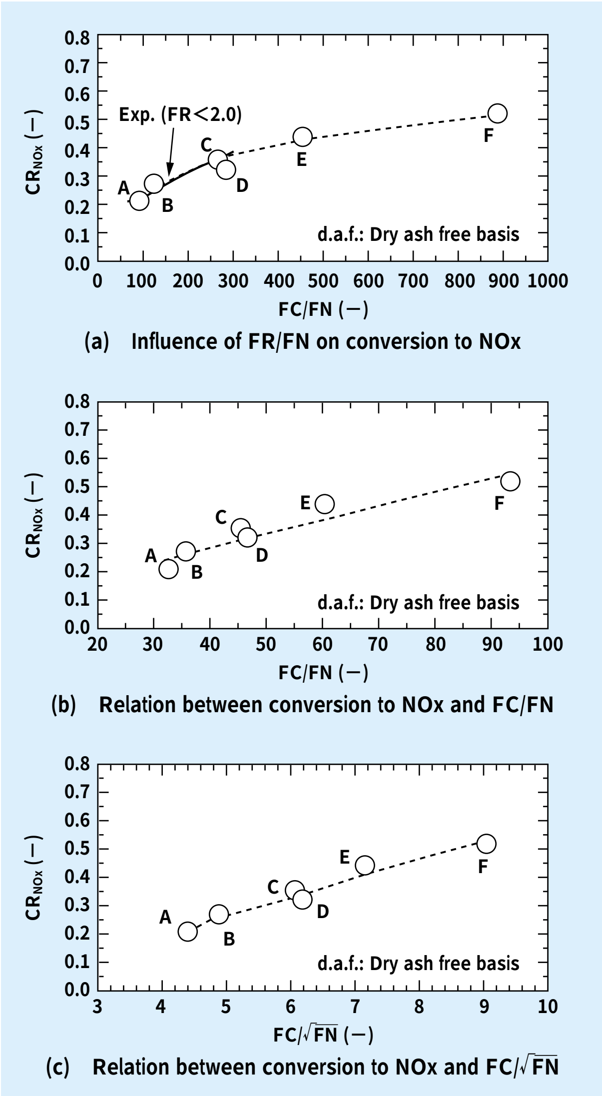

Fig. 8-3-2 Relationship between CR_{NOx} and three indexes consisting of *FR*, *FN* and *FC* (non-staged combustion condition).

becomes significant.

For the utilization of high fuel ratio coal, it is important to use the burner which can accelerate these combustion near the burner for the improvement of the ignition and effective NOx reduction.

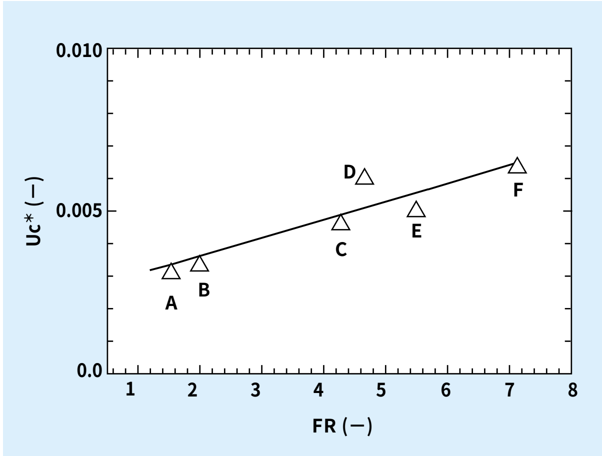

Fig. 8-3-3 Relationship between Uc^* and *FR* (non-staged combustion condition).

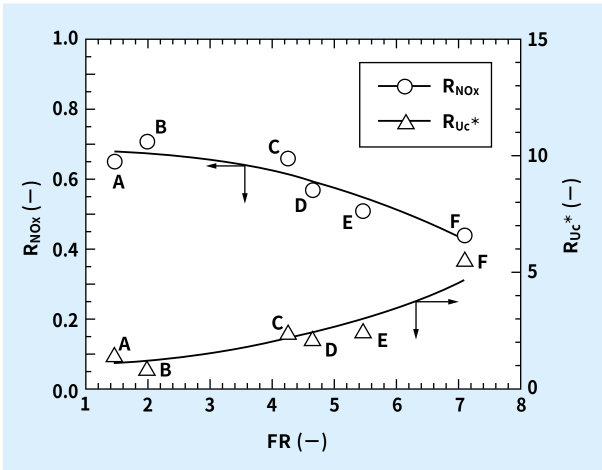

Fig. 8-3-4 Effects of *FR* on R_{NOx} and R_{Uc}*; ○, R_{NOx}; △, R_{Uc}*.

8－4 Future Plan

From the viewpoints of energy security and fuel cost, it is important for power stations to use unutilized coal including low rank coal, which is rich in moisture or ash and has a calorific value lower than bituminous coal and high fuel ratio coal. Sub-bituminous coal is most abundant among low rank coals and mined in throughout the world. Due to the 20-40% moisture content, sub-bituminous coal is difficult to ignite and NOx emission is difficult to control. In this chapter, combustion characteristic of sub-bituminous coal is evaluated and coal combustion technology for low NOx and low unburned carbon has been developing with the coal combustion test furnace. When sub-bituminous coal is fired in power stations at present, main utilization method will be blended combustion of sub-bituminous coal with bituminous coal in low blending ratio. Then, it was cleared that the increase of unburned carbon concentration in fly ash on blend combustion could be reduced by the suitable selection of blended coal properties. In the future, it will be necessary to develop the reduction technologies for both emissions of NOx and unburned carbon concentration on high blend ratio combustion of sub-bituminous coal or lower rank sub-bituminous coal combustion.

Combustion characteristics of high ash content coal and high fuel ratio coal were also evaluated, and the necessary research subject for more utilization of these coals are clarified. Especially, high fuel ratio coal is possible to use with blended combustion of bituminous coal. The coal kind selection on blending combustion and control of combustion condition are important for using high fuel ratio coal.

We are planning to investigate to utilize sub-bituminous coal in particular. Advanced combustion technologies of low NOx and low unburned carbon concentration will be developed during high blending ratio on blended combustion of sub-bituminous coal with bituminous coal or sub-bituminous coal combustion. On the other hands, in these days, CRIEPI is investigating the upgrading technologies of low rank coal with high moisture or high ash. By developing combustion technology for upgraded low rank coals, it will be enlarge coal properties used in coal fired power plants. Additionally, we are planning to develop combustion technology for not only coal but also bio-mass and wastes material.

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Column 3:The Reforming Technologies of High Ash/Water Content Coal

Why now reforming the low rank coal?

Coal is cheap and is widely distributed all over the world. To guarantee a stable supply in the future, also to decrease energy costs, applications of high ash/water content coal have to be expanded. However, serious problems of poor ignitability and transportability prevent the high ash/water content coal to be utilized at power plants in Japan. The reforming technology can resolve these issues, but low cost (low energy-consumption) reforming technology is required to be developed.

Explore the potential of de-ashing technology with high efficiency

There are two physical de-ashing methods mainly, the one is gravity separation method, in which mineral form ash after burning is removed and is collected organic matter from the float. The other method is flotation which air bubbles is fed to column and gets organic matter adhering to bubbles. These mechanical processes can treat lots of coal at once; however it is hard to get high de-ashing efficiency. On the other hand, chemical de-ashing process; in which mineral is dissolved by chemicals and is removed, can get to high de-ashing efficiency, while the process has problems which are expensive chemicals and waste water treatment.

To develop de-ashing process with simple and efficient method, it is important to separate mineral matter from coal effectively. The separation efficiency of mineral matter from coal is influenced by mineral shapes and size in coal. It will be imperative to pulverize coal efficiently to remove the mineral matter from coal. We have made clear that mineral shape broadly into three types of categories that are granular(a), line(b) and cloudy type(gathering fine clay)(c)(**Fig. 1**). And also we showed that it is easy to remove mineral from coal with granular type and bigger particle size of mineral. After this, we will develop a pulverizing method which considered the influence of mineral distribution to get high de-ashing efficiency.

Dewatering process for coal using liquid DME as extracting solvent !

Investigations of previous coal dewatering methods revealed that non-evaporating Fleisner method consumed high energy to enhance the reaction of coal and water with the problem of high organic content of the discharged water. On the other hand, steam tube dryer featured problems in energy conservation of latent heat of evaporated water. The most efficient method that completely recycles the evaporation energy is the upgraded brown coal method.

We proposed a new dewatering process (**Fig. 2**) where water in coal is extracted by liquefied DME (dimethylether). This system can be operated under extremely mild conditions, e.g., room temperature and about 0.5MPa.

The compressor of the DME vapor consumes only about 945kJ for 1kg of removed water. The required energy of the complete dewatering system will be reduced further compared to the previous method, the great potential of this dewatering method is quite apparent. To improve performance of the dewatering process, the influence of the volume/velocity of a flowing liquefied DME on dewatering will be clarified.

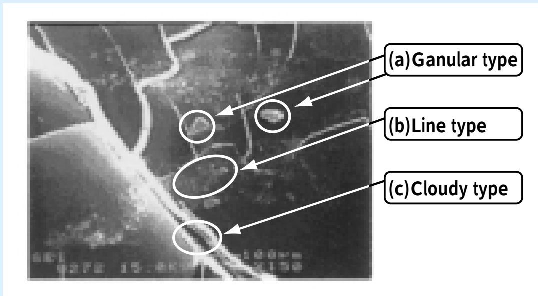

Fig.1 Distribution of mineral matter in coal (Ramagundam coal)

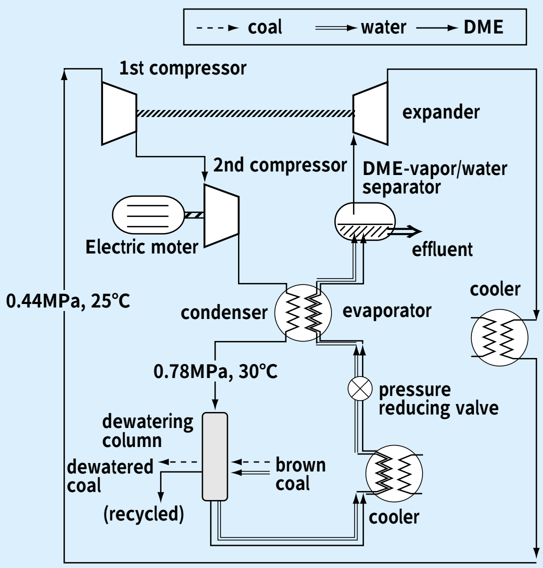

Fig. 2 Schema of dewatering process using liquid DME

Chapter

9

Advanced Measurement Method and Numerical Analysis of the Pulverized Coal Combustion Field

Chapter 9 Advanced Measurement Method and Numerical Analysis of the Pulverized Coal Combustion Field ● Contents

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9-2 Non-invasive Measurement in Combustion Flames Using the Laser-based Measurement **107**

9-3 Technology of Numerical Analysis **112**

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Hirofumi Tsuji (Dr.)
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

Ryoichi Kurose (Dr.)
Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

9－1 Background of the Study

In pulverized coal fired power plants, it is very important to improve the technology for the control of environmental pollutants and adaptability of the unit. It is also required to use various kinds of fuel. In order to achieve these requirements, understanding the pulverized coal combustion mechanism and the development of the advanced combustion technology is necessary. However, the combustion process of the pulverized coal is not well clarified so far since the pulverized coal combustion is a very complicated phenomenon, in which the maximum flame temperature exceeds 1,500 ℃; and some substances which can hardly be measured, for example, radical species and highly reactive solid particles are included. These radicals and particles significantly affect the formation and decomposition of environmental pollutants. Accordingly, development of combustion furnace and burners requires high cost and takes a long period because the empirical process comprises many steps. It is, therefore, indispensable to establish the effective and efficient method for development of an advanced combustion technology. For these purpose, it is extremely necessary to build models of the flow field and the reaction field and the formation and decomposition process of environmental pollutants and develop technology for the numerical analysis that is capable of simulating the combustion field with a high accuracy.

Conventional measurement of the combustion field is carried out by use of a thermocouple for the temperature and insertion of a sampling probe into the combustion field for the gas analysis, for example. Although these methods have an advantage to allow the measurement in a relatively simplified way, it incorporates several problems that the combustion field is disturbed due to insertion of the sampling probes, the time and spatial resolution is low, and measurement of some radicals is difficult. Under these circumstances, the laser-based measurement methods have become of major interest recently that are capable of detecting the concentration of chemical species, including radicals, and behaviors of particles remotely without disturbing the combustion field.

The numerical analyses of the pulverized coal combustion field, on the other hand, are being developed in Japan as well as overseas along with the remarkable progress in the performance of computers.

CRIEPI has been implementing studies on the laser-based measurement methods, which include the research to measure the behavior of radical species in flames [1] and the research to measure the behavior of coal particles [2][3]. As regards the numerical analysis, the authors are carrying out a series of studies on the pulverized coal combustion test furnace of CRIEPI, and the improvement of the analytical accuracy of the combustion field [4]~[10].

9－2 Non-invasive Measurement in Combustion Flames Using the Laser-based Measurement

It is necessary to measure behaviors and temperature of particles in the combustion field in addition to the temperature field, the flow field and distribution of chemical species in order to elucidate the structure of pulverized coal combustion flames. A wide range of methods using Laser to measure these physical quantities has been studied and developed at present, CRIEPI has been concentrating in developing methods to observe behaviors of pulverized coal particles and radical species (OH, CH, etc.) that are closely related to formation and decomposition of environmental pollution species, such as NOx.

Available methods to apply Laser to measurement of radicals in the combustion field are the Raman scattering method, CARS (Coherent Anti-stokes Raman Spectroscopy), and the Laser Induced Fluorescence (LIF) method. In these methods, the Raman scattering method and CARS method have disadvantages that their application is limited to the point measurement because of very low intensity of signals obtained by these methods, and the equipment has very complicated. As the signal intensity of LIF method is sufficiently high as compared with the other two methods, it has a number of advantages for measurement of radicals, for example that the 2-dimensional measurement is possible. CRIEPI has been trying to apply the LIF method to the pulverized coal combustion flame. We have studied by now on the visualization technique of OH, CH etc. in the methane-air premixed flame.

On the other hand, Laser Doppler Velocimetry (LDV) has been employed to elucidate behavior of particles. LDV was developed for the purpose to measure the flow field by mixing fine particles that follow the gas stream into the flow field. However, LDV has been increasingly applied to particle measurement in these years since it was originally devised to measure the particle velocity. In particular, several techniques were developed for simultaneous measurement of velocity, shape and diameter of particles by modification of optical system of LDV. The Shadow Doppler Velocimetry (SDV), among these techniques, can simultaneously determine the shape and size of pulverized coal particles, which are arbitrarily shaped with the average diameter of 40～50 μ m. The authors are trying to measure the particle behavior of laboratory scale-pulverized coal combustion flame using SDV.

9-2-1 Measurement of gaseous radical species by the Laser Induced Fluorescence (LIF)

(1) Measuring method

Fig. 9-2-1 shows energy level of molecule. When atoms and molecules are irradiated with the light that has the wavelength corresponding to the energy difference required for the transition between ground and upper states at the electron energy state of these atoms and molecules, these atoms and molecules absorb the light as energy and transit to upper states, then transit to lower states while emitting the absorbed light. The light emitted in this process is the fluorescence and called as Laser Induced Fluorescence (LIF) when Laser is used as the light source. It is possible to measure 2-dimensional distribution of intensity of the fluorescence when introducing the Laser sheet into the field to be measured.

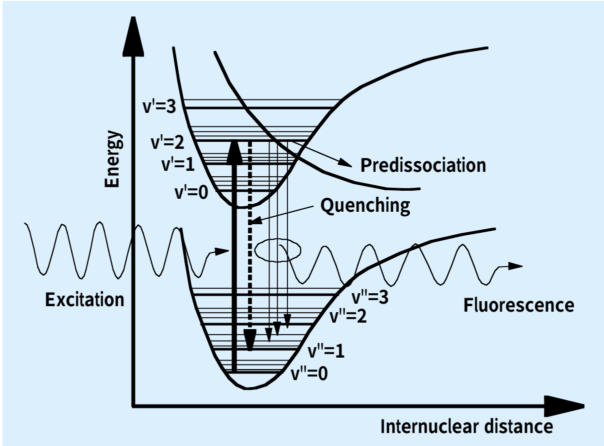

Fig. 9-2-1 Energy level of molecule

Fig. 9-2-2 shows an outline of the LIF system. The system consists of the Laser source, the optical system to introduce the Laser to the field to be measured, the detecting unit that receives the fluorescence, the unit to correct the intensity distribution of Laser, and the synchronizing and control unit to control these units and transmit and receive data.

The laser source is composed of the Nd: YAG Laser, OPO (Optical Parametric Oscillator), and the wavelength calibration unit. The wavelength calibration unit measures fluorescence spectra of radicals in the flame formed by a mini-torch using a photomultiplier and calibrates the wavelength of Laser source. The optical system consists of a cylindrical lens and other components and forms a Laser sheet of approx. 3.5 cm high and 0.5 mm thick. The main component of the detection unit is the CCD camera system, in which an image intensifier is incorporated. The Laser sheet formed by the cylindrical lens has a intensity distribution. The Laser intensity distribution correction unit detects the intensity distribution before a Laser sheet enters the measurement field.

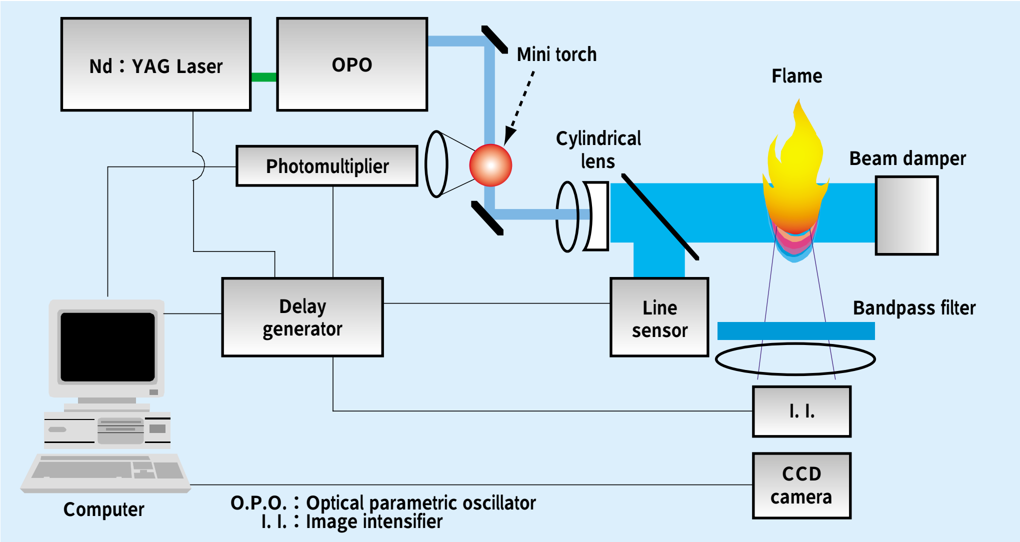

Fig. 9-2-2 Block diagram of LIF measurement system

(2) Measurement of fluorescence distribution of radical species in gas flame

A laminar premixed flame of the methane and air was used for measurement of radicals with LIF, because the measurement on gas flames is easier than that on pulverized coal combustion flames. A Bunsen type burner of inner diameter 6 mm was used for the measurement. The experiment was carried out in several conditions with the equivalence ratio of the methane and air, ϕ, ranging from excessively high to low. **Fig. 9-2-3** shows direct photographs of the flame presented in simulated colors. These photographs were taken at values of ϕ equal to 1.59 and 0.98. Areas of higher intensity light emission in the flame are presented in white color. These photographs show characteristics of flames, for example, the height of inner flame is larger for larger value of ϕ, intensity of light emission increases when values of ϕ decrease.

Radicals OH, NO, CH, CN and NH were selected for measurement in order to elucidate the formation process of NO, one of the most significant environmental pollutants emitted from combustion process. Measurement of OH is easy since OH concentration in the flame is extremely high. The fluorescence was received using the excitation wavelength of 281.258 nm and a filter with the half width 15 nm at the center wavelength of 320 nm. **Fig. 9-2-4** shows results of the measurement. While the peak of OH is observed at outer region of the inner flame for ϕ =1.59, extremely high concentration of OH is found in the vicinity of inner flame with gradual decrease of its concentration in the direction to downstream when ϕ = 0.98. NO was measured using the excitation wavelength 225.205 nm and a band-pass filter of the half width 20 nm and the center wavelength 254 nm. The experimental results are shown in **Fig. 9-2-5**. It was found that NO can be roughly divided to that rapidly generated in the region at immediate downstream of the inner flame and that by slow generation in the downstream region of the flame. NO in the immediate downstream region of the inner flame is likely to be the prompt NO generated through HCN and NH within the flame zone, whereas the NO in the downstream region of flame is the thermal NO generated by the extended Zeldovich mechanism. Fluorescence of NO becomes larger as the equivalence ratio increases. This is presumably caused by the fact that larger amount of prompt NO is generated with increase of ϕ.

9-2-2 Measurement of particle behavior by the Shadow Doppler Velocimetry (SDV)

(1) Outline of measuring method

Fig. 9-2-6 shows the outline of the optical system of the Shadow Doppler Velocimetry (SDV). Two Laser beams are converged by the lens and cross with each other at the measuring point. Interference fringes are formed at the measuring point. Particles reached the measuring point scatter the light corresponding to the darkness and brightness of interference fringes. This process is schematically illustrated in **Fig. 9-2-7**. The

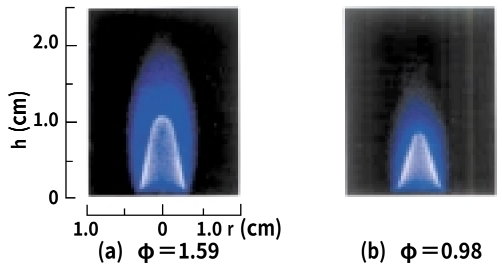

Fig. 9-2-3 Direct photographs of methane-air premixed flames

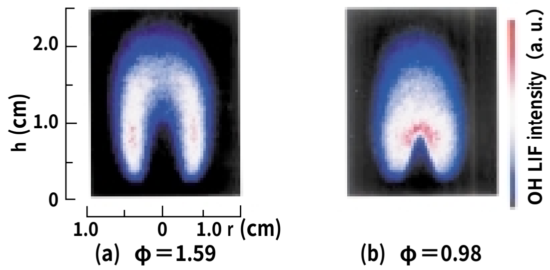

Fig. 9-2-4 Time averaged images of OH

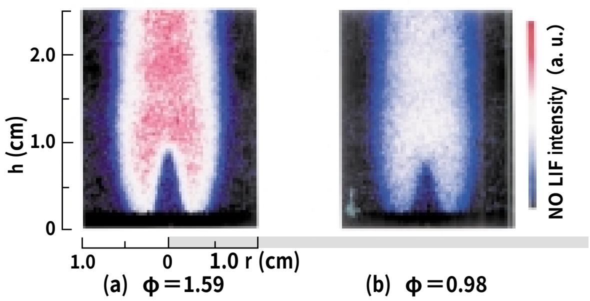

Fig. 9-2-5 Time averaged images of NO

peak of intensity of scattered light corresponds to the brightness of interference fringes. As intervals of interference fringes is determined by the wavelength of Laser and the optical system, the particle velocity is measured by measuring the time interval of the brightness in the intensity distribution of scattered light in Fig. 9-2-7.

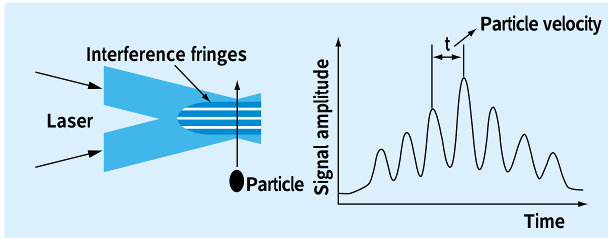

Fig. 9-2-7 Detail of measurement region and doppler burst signal

On the other hand, measurement of the shape and size of particles is carried out as described below. As shown in Fig. 9-2-6, Laser beams that crossed each other at the measuring point passes through the light receiving lens and the focusing lens and are led to a fiber array equipped with 64 elements arranged in horizontal direction. The projection image of particles at the measuring point is formed on the fiber array. When a particle does not exist at the measuring point, intensity of signal on the fiber array is high as the Laser is detected. When a particle exists at the measuring point, intensity of the signal of elements on the fiber array is reduced as Laser is interrupted by the particle. The particle shape is given by measuring the time for which the signal intensity is low. The size of particle is calculated from the particle shape.

(2) Measurement of particles on a laboratory scale pulverized coal combustion flame

Simultaneous measurement of the velocity and size of particles with the Shadow Doppler Velocimetry was implemented on a pulverized coal combustion flame of laboratory scale. The flame is formed by pulverized coal particles (feed rate: approx. 10 g/min) ejected from a burner installed vertically in the upward direction and the air that carries coal

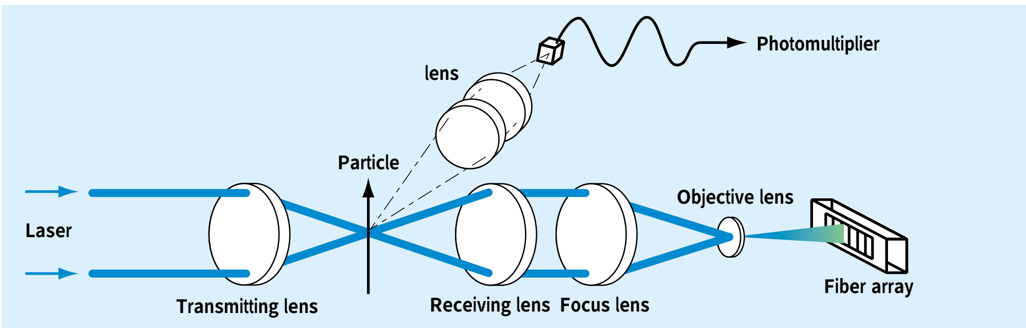

Fig. 9-2-6 Optical arrangement of SDV

particles. The flame is about 30 cm long. The measurement was carried out both in two conditions, the combustion case and the non-combustion case for the purpose of comparison.

Fig. 9-2-8 shows shape of particles measured during combustion. It indicates that the particle is arbitrarily shaped and that detailed shape of pulverized particles can be measured by SDV.

Fig. 9-2-9 shows the distribution of particle velocity on the central axis of burner. Particle sizes are divided into three regions in Fig. 9-2-9, less than 15 μ m, from 15 μ m to 30 μ m, and greater than 30 μ m for the purpose to elucidate the effect of particle size on particle velocity. The velocity is presented in the dimensionless form by the velocity of air stream at the outlet of burner. The distance in the axial direction is also given in the dimensionless form using the inner diameter of burner, D. Fig. 9-2-9 also shows the velocity of air stream in the case of non-combustion. It is possible from the figure to determine particle behavior in the flame, such as the difference between the gas velocity stream and the particle velocity and the effect of the presence of flame on the particle velocity. Fig. 9-2-9 also shows particle behavior dependis on the particle size, in the case of non-combustion. The difference of particle size has little effect on the particle velocity and the particle velocity is almost constant in the case of combustion.

Fig. 9-2-10 shows the averaged particle size on the central axis of burner for the purpose to observe the change in particle size in the cases of non-combustion and combustion. As shown in Fig. 9-2-10,

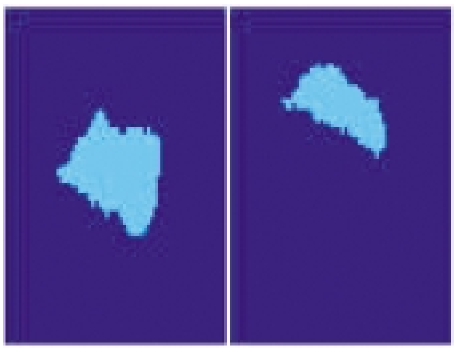

Fig. 9-2-8 Particle shape measured by SDV

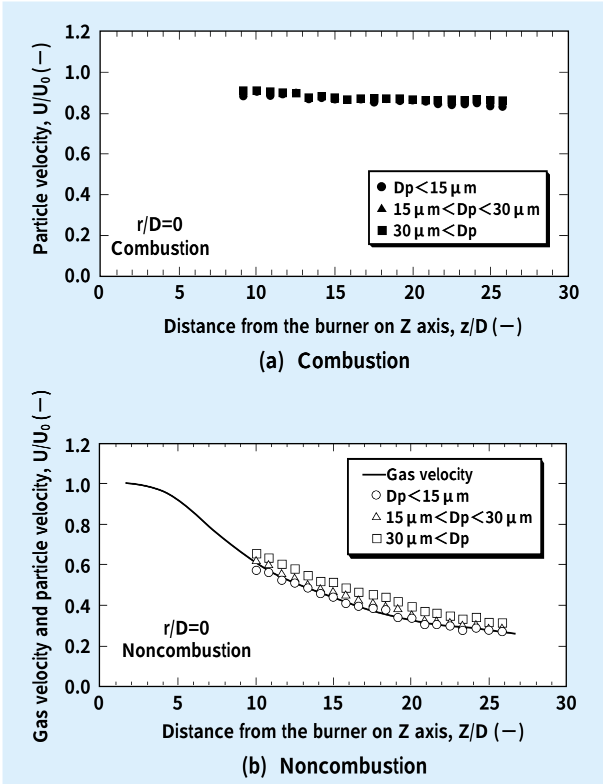

Fig. 9-2-9 Relationship between particle size and particle velocity

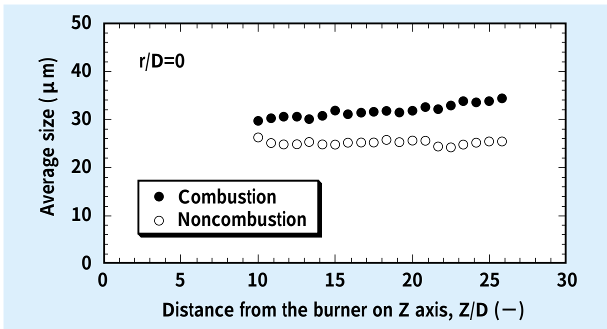

Fig. 9-2-10 Change of average particle size on Z axis

no significant change in the particle size is found with the increasing axial distance in the case of non-combustion. In contrast to it, the particle size increases as the axial distance increases in the case of combustion, because of the influence of swelling of particles in combustion. It is found by these results that SDV is capable of the change of particle size in the case of combustion.

9-3 Technology of Numerical Analysis

Numerical analysis of pulverized coal combustion is a method to solve the governing equations of the combustion field that is a continuous phase [conservation equations of mass (continuity), momentum (Navier-Stokes), chemical species and energy] and the equation of motion of pulverized coal that is a dispersed phase, using a computer. This method can provide the detailed information on the distributions of temperature and chemical species over entire combustion field, and behaviors of pulverized coal that cannot be obtained by experiments. It is also anticipated that it would be applied as a tool for the development and design of combustion furnaces since repeated review is made possible with arbitrary variation of conditions such as properties of pulverized coal and the flow field at a relatively low cost.

DNS (Direct Numerical Simulation), LES (Large Eddy Simulation) and RANS (Reynolds-Averaged Navier-Stokes) are typical methods for numerical solution of the combustion field, that is a continuous phase. DNS, which directly solves governing equations of fields of the flow, chemical species concentration and temperature by setting the calculation grid space below the minimum eddies in these fields, and has the highest accuracy of calculation among the above mentioned methods. Although it is effectively applicable to the fundamental research, its application to the combustion field at practical levels is very difficult as it requires a vast number of calculation grid points and poses high loads to the computer. On the contrary, RANS is most frequently used in practical applications. This method solves the governing equations by averaging them over the time and replacing the Reynolds stresses and turbulent scalar fluxes terms with turbulent models such as the Reynolds stress model and the Eddy viscosity model. It can widely reduce the number of calculation grid points and loads to the computer. However, RANS has several problems, such as difficulty in selection of turbulent models and determination of parameter values contained in them, and that it is impossible to evaluate non-steady state characteristics. Accordingly, attention is paid on LES recently, which directly solves governing equations for relatively large eddies and calculates remaining small turbulent flows using models. This is a sort of space averaging method and has certain advantages that the unsteady state calculation is possible and the number of parameters contained in models is very few. Although LES poses high loads to computer as compared with RANS, it is likely to be applied to practical fields in near future when the progress of computer performance is taken into consideration.

For reasons mentioned above, CRIEPI is conducting researches with emphasis placed mainly on RANS and LES.

9-3-1 RANS

An example is described below of the study on the application of RANS to the pulverized coal combustion field in the coal combustion test furnace (horizontal cylindrical shape of 8.0 m long with inner diameter of 0.85 m) in CRIEPI [(11)~(13)]. The calculations were carried on five types of bituminous coal, and the applicability of RANS by comparison of calculated values of combustion characteristics with experimental data [(11)~(13)] were evaluated.

(1) Calculation method

Table 9-3-1 lists properties of five types of bituminous coal subjected to the test. The region of calculation and shape of burner are shown in **Fig. 9-3-1**. A part of furnace ($-\pi/6 \leq \theta \leq \pi/6$) is taken as the calculation region. Pulverized coal is fed from the primary air inlet of the burner into the furnace mixed with the primary air. The secondary and tertiary air is supplied from the surrounding area of primary air inlet and the staged combustion air is injected from the side at the position of x=3.0m. The feed rate of the air injected at the primary, secondary and tertiary air inlets is given to match with actual experiments [(11)~(13)]. The heat-value of coal is assumed to be equal to 6.54 10^5 kcal/h and the total flow rate of air injected from primary, secondary and tertiary air inlets are determined from the value of 4% in the excess concentration of O_2 at the furnace outlet (air ratio = 1.24). The rate of staged combustion air (= volume flow rate of the staged combustion air/volume flow rate of the total air for combustion) is 30%. The number of

Table 9-3-1 Coal properties

Coal	Newlands	Wambo	Plateau	Warkworth	Blair Athol
Proximate analysis					
Moisture*1 [wt%]	(2.2)	(3.5)	(5.9)	(4.5)	(7.9)
Volatile matter*2	28.4	35.7	41.3	31.4	29.6
Fixed carbon*2	56.4	54.6	48.8	57.5	62.7
Ash*2	15.2	9.7	9.9	11.1	7.9
Heating value (high)*2 [kcal/kg]	6970	7380	7170	7050	6950
Heating value (low)*2	6730	7080	6870	6770	6710
Ultimate analysis					
C*2 [wt%]	71.8	74.2	71.9	73.6	74.6
H*2	4.45	5.62	5.47	5.10	4.52
N*2	1.59	1.82	1.30	1.59	1.54
O*2	6.44	8.27	11.8	8.36	11.2
S*2	0.48	0.42	0.41	0.35	0.23
FR*3 [−]	1.99	1.53	1.18	1.83	2.11
FR/FN*4 [−]	1.25	0.84	0.91	1.15	1.37

*1 : As received. *2 : Dry basis. *3 : Fuel ratio (Fixed carbon / Volatile matter).
*4 : Nitrogen content

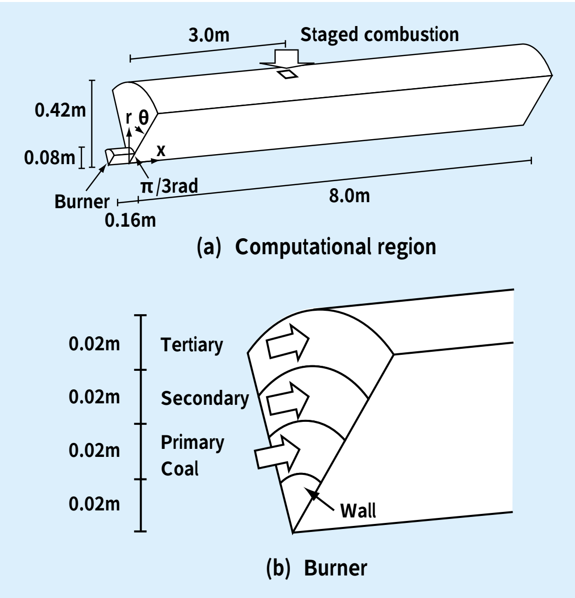

Fig. 9-3-1 Computational region and burner

calculation grid points is taken as 61(x)× 58(r)× 11(θ) (the grid spaces in the directions of x and r are finely set in the vicinity of burner). For the turbulent flow model, k-ε 2 equation model is used. The CPU time required for each calculation is about 60 hours using work static.

(2) Comparison of bituminous coal combustion characteristics with experimental results

Fig. 9-3-2 shows the comparison of the time averaged axial distributions of frame temperature, and O_2 and NO concentrations for Newlands coal with experimental values (11)~(13). **Fig. 9-3-3** shows the contours plots of air velocity, gas temperature and O_2

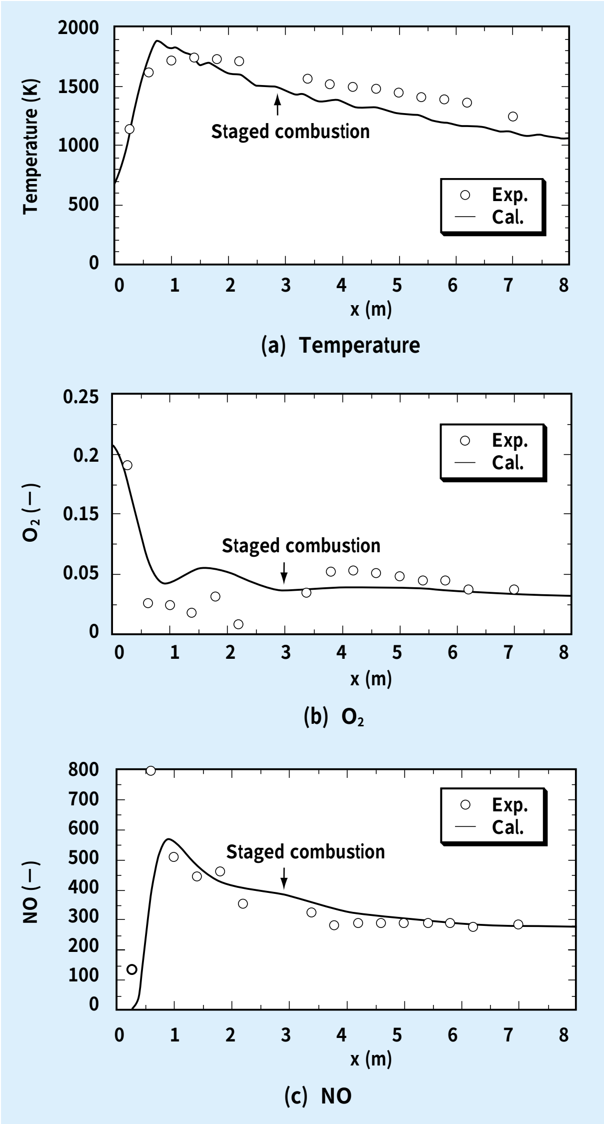

Fig. 9-3-2 Axial distributions of temperrature and O_2 and NO concentrations (Newlands)

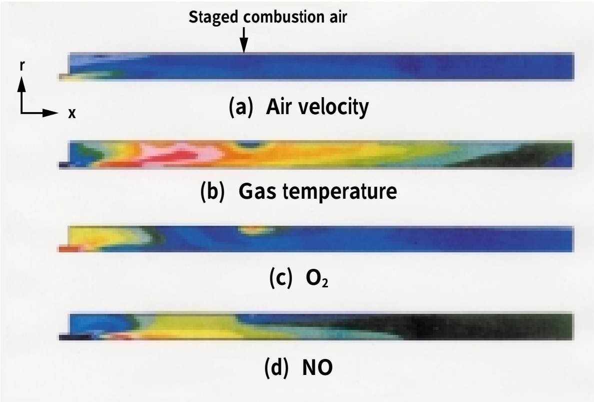

Fig. 9-3-3 Contours of streamwise air velocity, flame temperature, and O_2 and NO concentrations (Newlands)

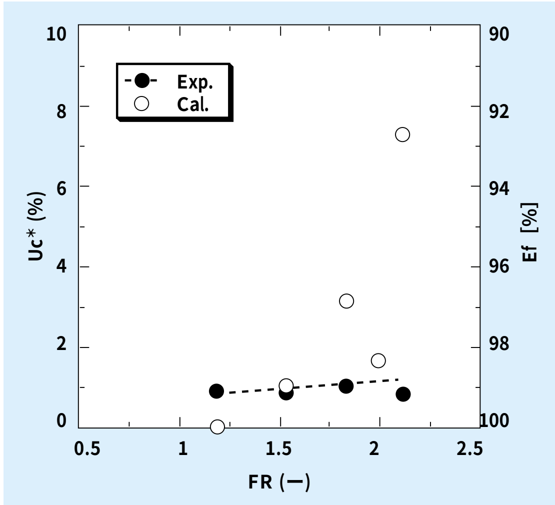

Fig. 9-3-4 Relation between Uc* and FR

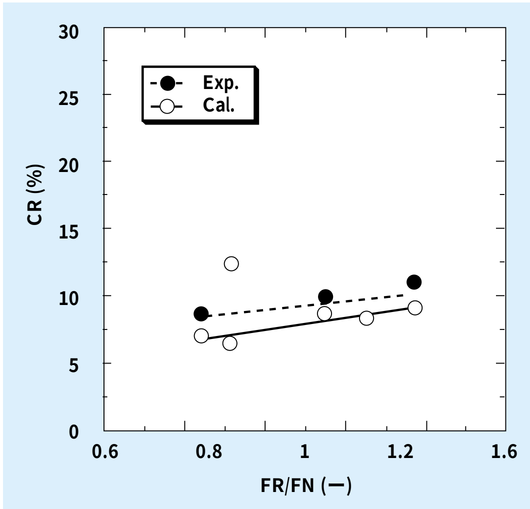

Fig. 9-3-5 Relation between CR and FR/FN

and NO concentrations. (values of characteristic quantities increase as the color changes from blue to red). Qualitatively good agreement is shown between calculated values and experimental data for all distributions, indicating that real pulverized coal combustion fields are well simulated. Upon quantitative comparison of calculated values and experimental data, however, peak values of flame temperature of the former are higher than the latter and they attenuate more rapidly at the downstream than the latter. They differ in that the O_2 concentration is higher and the peak values of NO concentration are lower in the region of $x < 3$ m. Possible reasons for these differences are incomplete agreement of shape settings of furnace and burner with those in the experiment and insufficient accuracy of k-ε 2 equation model in the region near the burner with strong shear.

Figs. 9-3-4 and **9-3-5** show comparison of the relationship of the unburned fraction, Uc*, the combustion efficiency, Ef (= 1-Uc*), and the fuel ratio, FR (fixed carbon /volatile matter), and the relationship of the conversion of fuel N to NO, CR (conversion to NO from fuel bond nitrogen in the coal) and FR/FN, respectively, with experimental data for calculated five types of coal [(11)~(13)]. It is experimentally known, as described in Chapter 4, that increasing tendency is demonstrated by Uc* and CR, respectively, for FR and FR/FN [(11)~(13)]. It is confirmed from these figures that both of the calculated values show similar increasing tendency with experimental data and reproduce the effect of FR and FN without any contradiction, although they show quantitative differences.

9-3-2 LES

LES was applied to the small pulverized coal combustion flame of laboratory scale. As the LES code is in the developing stage at present, the present code does not take into consideration detailed reaction mechanism, including reaction of radical species, and complicated properties of coals. Dissimilar to the above described RANS, however, LES has the advantage that it can evaluate the unsteady state characteristics of pulverized coal flame as described already. An example of it is shown below [(9)~(10)].

(1) Calculation method

Fig. 9-3-6 shows the schematic of calculation region, which is a rectangular of 0.48m(x) × 0.24m(y) × 0.24m(z). The diameter of jet stream outlet is assumed as 6×10^{-3} m, and the flow velocity as 13 m/s. Solid fuel particles are fed into the calculation region by this jet stream. The term "solid fuel particles" is used in place of "pulverized coal" because solid fuel particles are simply regarded as a lump of methane in the calculation. It is assumed that these solid fuel particles are evaporated depending upon the temperature of surrounding gas and react with the air in the gaseous phase. Number of calculation grid points is taken as 240(x) × 150(y) × 150(z) and the compressible Smagorinsky model [15] was adopted as the turbulent model of LES. The calculation took the CPU time of about 1,000 hours per case using the super-computer, which has the calculation speed about ten times faster than the workstation used for above described RANS.

(2) Evaluation of the non-steady state characteristics of pulverized coal flame

Figs. 9-3-7 and **9-3-8** show the instantaneous distributions of decreasing rate of solid-fuel particle mass and flame temperature over the x-y cross-section (z=0), respectively. Colors in Fig. 9-3-7 indicate that the mass decreasing rate of the solid-fuel particles mass increases as it turns from red to blue, whereas colors in Fig. 9-3-8 indicate that the flame temperature rises as it turns from blue to red. As shown by comparison with the distribution in Fig. 9-3-3 obtained by RANS, LES represented the 3-dimensional unsteady state behavior of the particles and the flame temperature. The group of solid fuel particles moves without spreading in the upstream region and it is shown that the particles dispersed in the radial direction from the mid-stream region at which the mass reduction is started by devolatilization is shown. Reasonable results are given, such as the region with high mass decreasing rate of the solid fuel particles coincides with the region with high flame temperature.

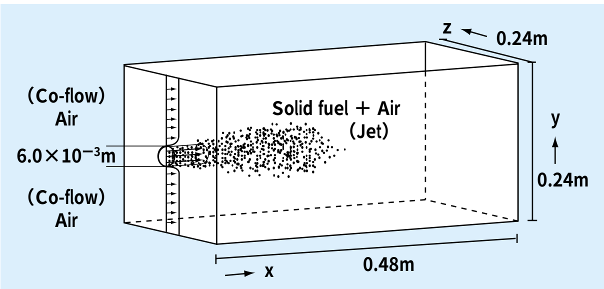

Fig. 9-3-6 Schematic of computational region for LES

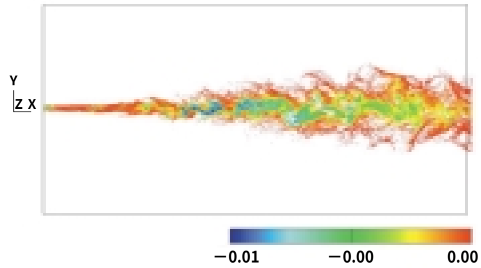

Fig. 9-3-7 Instantaneous distribution of decreasing rate of solid-fuel particle mass (x-y plane, z=0)

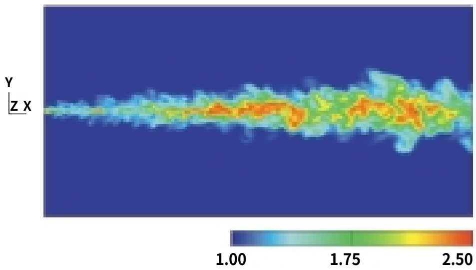

Fig. 9-3-8 Instantaneous contour of flame temperature (x-y plane)

9－4 Future Plan

The pulverized coal combustion is a complicated phenomenon, in which a wide variety of processes such as the devolatilization of pulverized coal, combustion of volatile matters and combustion at the surface of particles, in addition to the dispersion behavior of pulverized coal in the gas stream, simultaneously act to each other. The combustion process is not yet fully understood. Research results on the advanced measurement methods and numerical analysis carried out by CRIEPI to accurately evaluate and predict the pulverized coal combustion field are presented in this chapter.

We are now planning to apply these two measurement methods to a wide range of coal properties, including the sub-bituminous coal, and to complicated combustion fields, which faithfully approximate actual combustion field. We will also investigate the applicability of not only these measuring techniques, but also the chemiluminescence, temperature measurement, and 2-dimensional measurement of particle behavior to the pulverized coal combustion. Furthermore, we will study on the simultaneous measurement of physical properties, for example, simultaneous measurement of radicals and particle behavior. In future, we will also apply these technologies to test furnaces and actual boilers to establish advanced diagnostic system for burners and boilers using non-invasive measuring methods.

In aspects of the numerical analysis, it is scheduled that we will continue to develop the LES code. The present code does not take detailed reaction mechanism or complicated coal properties, including reaction of radical species, into consideration. Taking them into consideration, we are going to develop the code that is capable of predicting environmental pollutants, such as NOx at a high accuracy.

The study on the Laser-based measurement seems to be different from the study on numerical analysis. However, highly reliable data obtained by the Laser-based measurement is indispensable for verification of the accuracy of numerical analysis, and in contrast, experimental verification of new phenomena found by the numerical analysis may be chosen as the next target of Laser-based measurement. Taking advantages of both methods, CRIEPI will promote further development and mutual comparison of them in an effective way for the full understanding of pulverized coal combustion and furthermore, development of advanced combustion technology.

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Chapter

10

Future Subjects for Advancement of Pulverized Coal Combustion Power Generation

Chapter 10 Future Subjects for Advancement of Pulverized Coal Combustion Power Generation ● Contents

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Hisao Makino (Dr.)
Director
Consulting & Solution Team
CS Promotion Division
Central CS Promotion Office

Hiromi Shirai (Dr.)
Senior Research Scientist
Chemical Energy Engineering Department
Yokosuka Research Laboratory

10－1 Future Role and 0peration Characteristics of the Pulverized Coal Combustion Power Generation

Although certain problems are presented with the coal, such as a large amount of CO_2 emission as compared with other fossil fuels, it has advantages such as high stability of fuel supply as the minable reserve of coal is large and it is mined at a high ratio in politically stable countries. Accordingly, coal is regarded as one of the most important energy sources in the future.

It is anticipated that the significance of advanced high efficiency thermal power generation system under development, such as the integrated coal gasification combined cycle power generation and the integrated coal gasification fuel cell combined cycle power generation, would be gradually enhanced from aspect of control of CO_2 emission, as one of important issues at the time of utilization of coal. The significance of pulverized coal fired power generation would be maintained in the future when considering high reliability, flexibility of operation, availability of a variety of coal kinds as well as its low power generation costs.

It seems that the pulverized coal combustion power generation would be required more than the present level as the load changing power station such as the DSS thermal power which is started and stopped on a daily-basis in order to adjust the demand and supply balance. It is also anticipated that the supply of high grade bituminous coal currently used would be gradually tightened when considering the economic growth in developing countries. It is likely that the kind of coal would be much more diversified, in particular, increased consumption of low grade fuels and in addition, materials that are not used yet as fuel, such as the bio-mass would be required to be used in the future. It is also conceived from the viewpoint of environmental protection that advancement of the environmental protection technology would be required as a clean thermal power that can control environmental pollutants emission. In particular, it is conceived that technologies for effective utilization of wastes discharged from the pulverized coal fired power generation, would be required. Especially, the technology for utilization use of the coal ash, whose exhausted amount is the most in pulverized coal fired power plant, would be more intensely required when considering present situation of requirements for recycling and reuse of wastes.

10－2 Future Subjects on the Pulverized Coal Combustion Power Generation

The first important subject on the pulverized coal fired power generation is to increase utilization of the coal ash. About 60% of coal ash has been utilized for cements and so on, and other portion has been disposed for land reclamation. Sites for land reclamation are gradually decreasing in recent years, making enlargement of utilization of coal ash is required much more needed. As the actual situation of utilization of coal ash at present, all of the exhausted coal ash is not necessarily high grade, and accordingly, use of coal ash as cement mixtures that have merit in cost is limited and it is mainly used as low cost alternate material of clays. The power generation cost would be lowered and the utilization of coal ash would be enlarged if most part of the coal ash is used as valuable material like cement mixtures. From these points of view, it is extremely important to establish technologies to control coal ash in a characteristics that is suitable for valuable utilization. To effectively apply the coal ash to cement mixtures, it is necessary to supply coal ash that has low concentration of unburned carbon in fly ash, low methylene blue adsorption and stable properties. So, we have to develop technologies to control the property of coal ash within defined conditions for a variety of coal kind and combustion conditions. New fields should be exploited for utilization of coal ash for the purpose to increase the amount of utilization of coal ash, and the adjustment technology of coal ash properties according to the purpose becomes important.

Use of fuels in wider range than the past is expected from aspect of the diversification of fuels and cost reduction. A part of pulverized coal fired power station in Japan has already started introduction of the utilization of the sub-bituminous coal and it is expected to introduce much more amount and lower rank coal than before. For coals with low rank, in particular, property improvement and upgrading are expected and it is conceived that development of combustion and flue gas treatment technology of these upgraded coals become important. Some sort of materials such as the bio-mass has not been sufficiently used before, but their effective use is considered important as renewable energy. The technologies to use them widely seem to be indispensable.

From a viewpoint of improved environmental protection, it is foreseen that development of improvement of flue gas treatment technology becomes important to apply the requirement for environmental protection that is intensified in the future. In particular, it is expected that the development of environmental protection technology not only of high performance but those that can simultaneously achieve reduction of power consumption and cost, from viewpoints of cost reduction and environmental protection. Since attentions are focused on the influence of a variety of trace elements in addition to SOx, NOx, dusts and soot that have been principal subject as the environmental pollutants, it is conceivable that the significance of technological development would be enhanced, considering to the behavior of these substances in power plants and emission control of them. For the reduction of CO_2 emission, which is significant as the greenhouse effect gas, on the other hand, improvement of power generation efficiency is most important and it is conceived that importance of development of high-temperature materials for application at elevated temperature of steam turbine operation condition and improvement of the reliability is maintained in the future.

With regards to the combustion technology, which is especially important subject among above mentioned, its improvement has been made in the application of empirical methods. However, it is anticipated that more significance would be attached to structural evaluation of combustion flames using advanced measuring technologies, theoretical investigation on the combustion field using numerical analysis, and application of these technologies to practical combustion fields to meet strict requirements being made in recent years for emission control of environmental pollutants and diversification of fuels. It is conceived in the future that efforts should be concentrated in advancement of these technologies and improvement of their reliability and in effectively reflecting them to the development of advanced combustion technology.

10－3 Role and Functions of the Multi Fu-el and Multi Burner Equipment for Advanced Combustion Research for the Development of Ideal No Pollutant Emission Technology (MARINE furnace).

10-3-1 Purpose of installation

Efforts should be concentrated in establishment of the optimal operating conditions, development of prior and advanced evaluation technology of unutilized fuel, evaluation of the behavior of trace elements, and development of advanced combustion equipment and flue gas treatment equipment through conducting combustion of a variety of fuels, and processing of flue gas in similar equipment with operating installations to diversify the fuels, to improve the environmental characteristics, and reduce costs of pulverized coal fired thermal power generation.

CRIEPI installed "multi fuel and multi burner equipment for advanced combustion research for the development of ideal no pollutant emission technology" which is capable of investigate from combustion through flue gas treatment in the same processes as utility boiler in November 2002.

Principal tasks using application of the equipment are: "Development of coal combustion technology for improved and uniform quality ash generation", which is aimed at making all of exhausted coal ashes for the utilization valuably toward solution of the problem of coal ash disposal; "Development of optimum combustion technology for low grade coal (including sub-bituminous coal)" for corresponding to diversification of coal kinds, and; "Development of integrated evaluation method for coal adaptation to actual coal-fired power plant" for the beforehand evaluation of characteristics of unutilized coals from combustion through flue gas treatment. It is scheduled to extend in future toward "Estimation of combustibility for hardly incombustible fuel and development of optimum combustion technology" for wastes (including RDF), bio-mass, and heavy oils with an aim at strengthened thermal recycling and energy supply.

We are promoting, on the other hand, "Development of control technology for trace element emission and advanced flue gas treatment" toward further improvement of the environmental characteristics.

10-3-2 Features and functions

The equipment has below-described features for its application to a variety of technological development related to advancement of the pulverized coal combustion power generation.

① To achieve similar combustion situation with actual power plants by adoption of vertical furnace equipped with a three-stage burner.

② To apply hardly combustible fuels, including wastes (RDF, etc), bio-mass, and heavy oils to enable evaluation of combustion characteristics of these fuels.

③ To optimize the combustion technology by adjusting the whole burner system which is to adjust injection position and injection ratio at multi burners and to control fuel kinds to be injected in individual stages of burner at the time of combustion of blended coals, bio-mass and so on.

④ To enable overall evaluation of many kinds of fuels from the combustion characteristics to performance of flue gas treatment by equipping with De-NOx unit, electrostatic precipitator, and desulfurization units that are similar to actual plant.

⑤ To enable evaluation of behaviors of trace elements through simulation of actual plants easily by equipping with the temperature trend control function and a all flue gas treatment units, which are capable of simulating an actual power plant. In the development of advanced flue gas treatment, to make it possible to set arbitrary temperature of flue gases so that combustion gases are used for verification.

The equipment is composed from the fuel supply unit, vertical multi-burner furnace, and the flue gas treatment unit. **Fig. 10-3-1** shows the process flow. Fine coal particles generated by the fuel supply unit are fed to three burners and fired in the vertical combustion furnace. After heat exchange with the combustion air, flue gas enter the De-NOx unit (SCR process) and the NOx is decomposed. Then, total amount of flue gases are sent to the bag filter in case of the combustion test only, to remove the fly ash. SOx is removed by the alkaline scrubber and flue gas is exhausted from the stack. For the experiment of the flue gas treatment unit, a third volume of the flue gas is separated at the De-NOx unit and sent to the flue gas treatment unit, where the performance of the electrostatic precipitator and the flue gas desulfurization unit is evaluated. Trace elements can be measured at the same time. Principal functions of each unit are described below.

(1) Fuel supply unit

- It has storage and supply units of coal and heavy oils to enable the evaluation of combustion characteristics of a variety of fuel.
- It is capable of feeding coal to each of three burners at a rate of 100 kg/h and the heavy oil to each of three burners at a rate of 60 liter/h.
- Each burner is equipped with a fuel supply line and two coal feeding bins so that it is possible to individually change fuel kind, fuel blending ratio, and feeding rate.

(2) Vertical multi-burner furnace

- It has three stages of burner as shown in **Fig. 10-3-2** and forms the combustion field with interaction of multi burner flames.

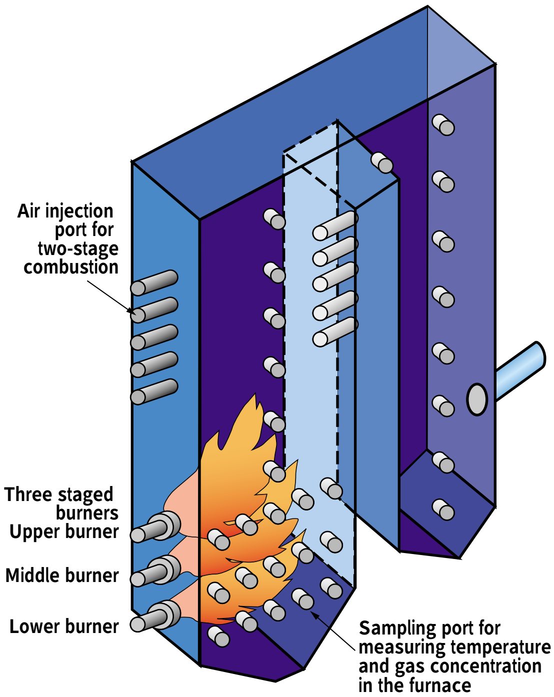

Fig. 10-3-2 Outline of coal combustion test furnace with three staged burners (MARINE furnace)

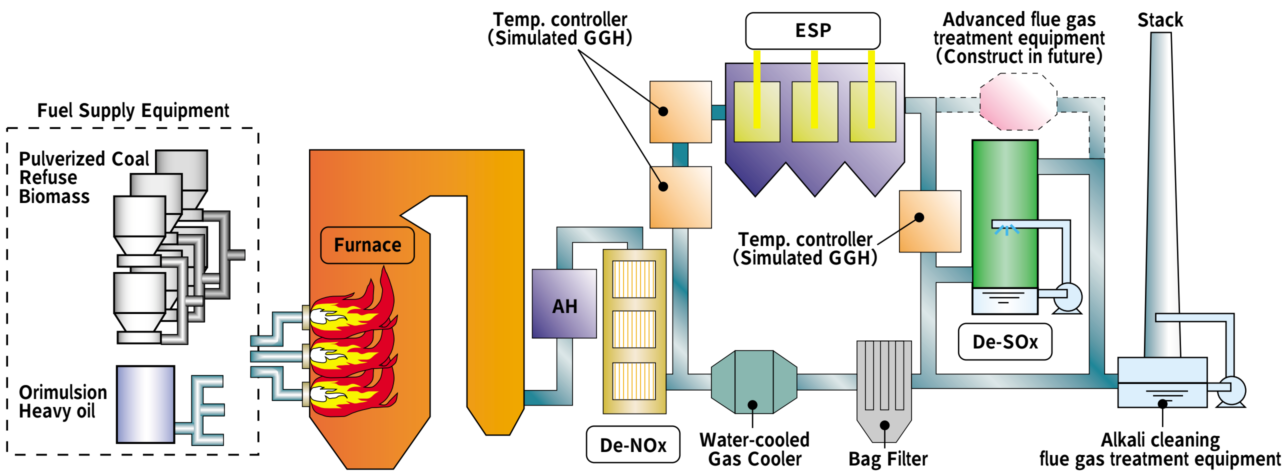

Fig. 10-3-1 Outline of coal combustion test facility

- It is equipped with the function to adjust angle of individual burners, distance between burners, and intensity of radiation. It is also possible to maintain ignition and stable combustion of hardly combustible fuels.
- Equipment of vertical furnace enables continuous emission of ash from the bottom of furnace so that detailed evaluation of ash at the bottom and continuous operation for a long period experiment.
- Situation of deposited ash around burners can be monitored. The slugging-fouling characteristics of ash can be evaluated in detail by inserting a steam tubu in the combustion furnace and evaluating the heat transfer characteristics.

(3) Flue gas treatment unit

- It simulates actual utility plant and has the De-NOx unit that is capable of handling total amount of flue gas, an electrostatic precipitator with the capacity to process a third volume of flue gas, and a flue gas desulfurization unit using the lime stone-gypsum method.
- It can simulate the temperature trend of actual utility plant and arbitrarily set the flue gas cooling process by means of adequately arranged by-pass line and gas cooler.
- A place for a new flue gas treatment unit is installed, which can set arbitrary temperature conditions, so that the demonstration by the combustion gas is made possible at a wide range of temperature condition for the trace element removal technology, the high performance desulfurization and De-NOx technology and so on.
- The temperature of electrostatic precipitator can be controlled to 90～200℃, which makes it possible to assess the effect of operating temperature.

Central Research Institute of Electric Power Industry
Yokosuka Research Laboratory

2-6-1 Nagasaka, Yokosuka-shi, Kanagawa 240-0196
TEL.+81-46-856-2121