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Studies on the Unburned Carbon Content in Flyash from Pulverized-coal Combustion

(2nd Report, Comparison of the Experimental
Results with Predicted Values)*

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To discuss the validity of the prediction method described in our first report, five kinds of bituminous coals have been burned in two furnaces for a wide range of furnace temperatures and air-fuel equivalence ratios. Measured unburned carbon content in flyash is in good agreement with the predicted one in case of four coals and in the range of unburned carbon contents above 1%, verifying the validity of the prediction method.

Key Words: Combustion, Pulverized Coal, Unburned Carbon, Flyash, Boiler, Furnace, Power Plant

1. Introduction

Increase of the unburned carbon in flyash as a result of applying NO_x reduction techniques for pulverized coal combustion becomes an obstacle to switching of energy source to coal, and for the solution of the problem it is believed that investigations based on combustion theory as well as experiment of individual combustors are needed. From this point of view, in our first report⁽¹⁾, effects of coal properties and various combustion conditions on unburned carbon in flyash for modern boilers using delayed combustion and two stage combustion (TSC) are systematically calculated with a

prediction model assuming profiles of temperature and air ratio in furnaces. In this report, it is investigated through comparison with experiments how well the prediction method in our first report, in which complicated combustion process of pulverized coal in a furnace is simplified, agrees with actual phenomena.

Tests were performed to obtain data (1) in experimental facilities of different scales, (2) extremely varied temperatures in furnaces, and (3) for several grades of coal. Meanwhile experimental conditions of the fuel properties, heat release rate, temperature profile in the furnace, etc. were applied for the prediction. Consequently, fairly good agreement was found bet-

Table 1 Test Facility and Measuring Method

Facility		Small Furnace (I)	Large Furnace (II)
Item			
Test Facility	Type of furnace	Horizontal cylindrical	Horizontal cylindrical
	Furnaced wall	Water cooled wall lined with refractory	Water cooled wall lined with refractory
	Adjustment of furnace temperature	Inserted refractory liner	Adjustment of area of refractory wall
	Furnace dimension	1.0m ^φ (0.8) x 4.25m ^l	5.3m ^φ x 15.5m ^l
	Furnace volume	2.9m ³ (1.9m ³)	300m ³
	Capacity of burner	70 Kg/h coal feed	3000 Kg/h coal feed
	Type of burner	Single throat	Dual throat
	Location of TSP	No.6 (TSP = 2/3)	No.5 (TSP = 1/2)
	Injection of TS air	Vertical, swirl flow	Toward furnace rear, straight flow
Condition of Combustion	Heat release rate	150 KW/m ³	60 KW/m ³
	Air preheat temp.	300°C	300°C
	Primary air ratio	0.25	0.25
Measuring Method	Combustion air flow	Orifice flow meter	Orifice flow meter
	Coal consumption	Calculated from O ₂	Load detector
	Furnace temperature	PR thermocouple	Optical pyrometer
	Air ratio (O ₂)	Magnetic type analyzer	Magnetic type analyzer
	Unburned carbon	Unburned carbon or ignition loss	Unburned carbon or ignition loss

(a) Small furnace I

(b) Large furnace II

Fig. 1 Configuration of test furnaces

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ween the experimental data and the predicted values, and the prediction in our first report was verified with the experimental data and the predicted values, and the prediction in our first report was verified with the experimental data. Also, it was found that values of the actual measurement were higher than those of the prediction under condition below 1 % of unburned carbon in flyash.

2. Experiment

2.1 Test facilities

In order to burn a large quantity of fuel in a restricted space of an actual boiler for power generation, normally some ten burners are installed. In this study, however, the test was performed in a furnace equipped with one burner. In the combustion test, two horizontal cylindrical furnaces were used. The furnace volume of the large one is about a hundred times larger than that of the other. Outlines of the furnaces are shown in Fig. 1. Both furnaces have 8 holes at side walls of the furnaces for measuring the shape of the flame and

the temperature. Also, TSC air for reduction of NO_x is injected perpendicular to gas flow in the small furnace (I) and at 22 degrees inclined towards the end of the furnace in the large one (II).

Section of the actual scale burner tested in the large furnace is shown in Fig. 2, the capacity of the burner being 3000 kg of coal per hour. Pulverized-coal carried by primary air flows in the fuel pipe and is injected into the furnace being subjected to a swirl force by the swirler installed at the top of the oil gun. Meanwhile, combustion air is divided into secondary and tertiary airs. Secondary air flows straight ahead and tertiary air is subjected to a strong swirl force by vanes of the air register and the mixing of the pulverized-coal with the combustion air is adjusted so as to build a so-called delayed combustion flame and NO_x reduction of pulverized-coal combustion is accomplished⁽²⁾. Similar burner is used in the small furnace. However, owing to small scale of the model whose capacity of burning coal is 70 kg per hour the air is not divided into secondary and tertiary parts. Specifica-

Table 2 Properties of Test Coals

Grade of Coals			A	B	C	D	E	Method of analysis
Item								
Proximate an- alysis (dry)	Ash	%	9.6	9.1	38.7	16.1	10.2	60 minutes at 815°C
	Volatile matter	%	28.4	29.4	29.3	40.0	35.7	7 minutes at 700°C
	Fixed carbon	%	62.0	61.5	32.0	43.9	54.1	100 - (ash + volatiles)
	Fuel ratio	—	2.18	2.09	1.09	1.10	1.52	fixed carbon/volatiles
Ultimate analysis (dry ash free)	C	%	82.4	81.3	80.6	82.5	77.3	Combustion gravity analysis
	H	%	4.9	4.7	6.5	6.2	5.0	Combustion gravity analysis
	S	%	0.86	0.45	0.49	3.22	0.66	Eschka method
	N	%	0.90	1.67	2.10	1.22	0.98	Kjeldahl method
	O	%	10.9	11.9	10.3	6.9	16.1	100 - (C + H + S + N)
	H / C O / C	atomic ratio	0.71 0.10	0.69 0.11	0.97 0.10	0.90 0.06	0.78 0.16	
High heating value (dry ash free)		MJ/Kg Kcal/Kg	33.9 8108	32.5 7767	34.1 8140	36.1 8617	31.3 7483	Bomb method
True density		g/cm ³	1.47	1.41	1.56	1.37	1.39	Pycnometer method
200 mesh		%	84.6	89.6	86.8	84.0	83.8	Sieve method

Fig. 2 Sectional view of burner for large furnace

tions of both test furnaces are shown in Table 1. As the condition of the furnace wall gives a strong influence on the furnace temperature and consequently the amount of unburned carbon in flyash or NO_x emission⁽³⁾ and tests with widely varied conditions are desirable to check the method of the prediction, the adjustment of the furnace temperature was performed as follows.

In the small furnace, tests at low temperature of the furnace were done with 50 mm thickness of refractory (inside diameter 1.0 m) lining inside of the water cooled wall and also tests at high temperature simulating actual boilers were performed with 150 mm thickness of refractory (inside diameter 0.8 m). In the large furnace tests were performed at varied temperatures by adjustment of refractory area in the furnace.

2.2 Fuels used in the test

As the property of coal is different for each grade, it is desirable to test coals of many grades to check the prediction method. Properties of five coals used in the tests are shown in Table 2. JIS method was used for all analyses and the same method for five coals. Fuel ratios of coal A and B are over 2 and both are typical overseas coals which tend to be difficult to burn. Fuel ratios of coal C and D are lower and both are domestic coals of which the ash content is higher. Coal E is overseas one which ranks in between them. Sulfur content of coal D and oxygen content of coal E are higher than others. It is presumed that true density of the pulverized-coal is $1.37 \sim 1.56 \text{ g/cm}^3$ and the apparent density is $1.2 \sim 1.3 \text{ g/cm}^3$. Distributions of coal particles are shown in Table 2 and Fig.3. Judging from inclination of the line, it is recognized that the Rosin distribution constant is about 1.2 and the 200 mesh (74 μm) pass is about 85 % (cf. Table 2).

2.3 Experimental method

Experimental method for both test furnaces are similar to each other. After two hours of preheating by oil firing combustion of pulverized-coal began and settling of furnace temperature was confirmed after about half an hour, then data were obtained. Coal is pulverized by a tube mill, stored in a hopper, extracted by a feeder and then carried into the furnace by preheated air. Carrier air flow rate is maintained at about 20 % of total combustion air, mixed gas temperature at 90°C and preheat temperature at about 300°C . Firing rate of coal is adjusted to 150 kW/m^3 for the small furnace and to 60 kW/m^3 for the large furnace on the basis of furnace heat release rate. Therefore, in the small furnace, when refractory liner is inserted, fuel consumption is decreased.

Measuring methods are listed in Table 1. Longitudinal temperature distributions of the small furnace are measured by PR thermocouples at 150 mm apart from the inside surface of liner and in the large fur-

Fig. 3 Distribution of coal particles

(a) Small furnace I

(b) Large furnace II

Fig. 4 Temperature distributions in furnace

nance temperature indicated by optical pyrometer are used as representative ones. Air ratio is calculated on the basis of O_2 concentration in exhaust gas assuming complete combustion of fuel. Unburned carbon or ignition loss in flyash is analyzed and both of them approximately agree (ignition loss = unburned carbon $\times$ 1.05). O_2 concentration and flyash measured at the outlet of the furnace were used in this study.

3. Comparison of the Experimental Results with the Predicted Values

Coal A and C are fired in the small furnace and all coals from A to E in the large one.

3.1 Modeling of furnace

The shape of the test furnaces are shown by solid lines in Fig. 1. As a one dimensional flow is assumed in the calculation model of coal combustion, furnaces are regarded as cylinders shown by chain lines. The furnace length is defined as the distance to the intersecting point (No. 8 measuring port in the large furnace) of the axis of furnace with the center line of the flue in which the convection evaporator is set. The furnace length is shortened so as to equalize the volume of the removed part of the furnace. In this assumed furnace, the injection points of TSC air are located at $2/3$ of nondimensional length in the small furnace and $1/2$ in the large furnace.

Modeling of the furnace temperature profiles is performed, considering the result of the experiment. The temperature profiles measured in both test furnaces are shown in Fig. 4 and the measuring points correspond to 1 ~ 8 in Fig. 1. Temperature for every coal, furnace wall condition, two stage combustion (TS) and exhaust gas recirculation (GM) are plotted with different symbols, and as they are delicately affected by slagging of the furnace wall, preheating time and air ratios, mean values of several cases for every condition are shown. Meanwhile, the predicted temperature profiles are shown by solid lines in the figure and the temperatures at TS air port T_{TS} are varied in two steps. Comparing the measured temperature profile with the predicted one, there are some differences near the burner where the effect of the temperature on the unburned carbon is small. But the temperature profiles of the latter half of the furnace are approximately expressed by temperature gradient of $\Delta T = 600^\circ C$. And the temperature profiles near the TS air port seem to be simulated by straight lines so far as measured. Therefore, temperature profiles in the furnace are modeled assuming ΔT equals $600^\circ C$ regardless of T_{TS} .

Air ratio distributions in the furnace are determined on the basis of allotment of primary, secondary, tertiary and TS air volume. As for the mixing length, the empirical standard values in our former report are used. As for the fuel property, measured values are used for ash content and fuel ratio. But as there are some differences among samples of particle distribution and apparent density, the mean values

of all coals are used. Prediction is performed, taking Rosin distribution constant $n = 1.2$, 200 mesh pass = 85 %, and apparent density = 1.3 g/cm^3 . As for the diameters of particles, when releasing volatiles, no swelling is assumed.

3.2 Influence of the air ratio

The influence of total air ratio λ_T on unburned carbon content flyash $C\%$ is shown in Fig. 5, for an example of burning coal A in the small furnace. Data obtained in series are linked together with thin solid lines. Carbon content is generally higher when the furnace temperature is lower and the effect of λ_T is relatively small but as the furnace temperature becomes higher, carbon content seems to be lower and the effect of λ_T becomes larger. Meanwhile, bold solid lines in the figure indicate the result of the prediction for coal A at $TS\% = 20$ assuming the furnace temperature profiles do not depend on λ_T . Experimental values of carbon content generally agree with predicted values. However, as dependability of λ_T is little affected by $TS\%$ for the same level of carbon content, comparison with mean value of $TS\%$ involves a small error. Utilizing the fact, experimental data on different air ratio can be converted to standard air ratio by the predicted curves, and comparison of the absolute values of the experiment with prediction is to be performed as follows.

3.3 Arrangement based on temperatures of TS air ports

Fig. 6 (a) shows all data of unburned carbon content in flyash obtained for coal A in the small furnace. In this figure, unburned carbon content is converted to the value at $\lambda_T = 1.25$ by the above method (symbolized converted concentration $C^*\%$). Data for $900 \sim 1100^\circ C$ correspond to those without an inserted liner, and those for $1100 \sim 1200^\circ C$ with an inserted liner having

Fig. 5 Effect of air ratio on unburned carbon in fly ash

many hollow measuring holes and those for the vicinity of 1300°C having ceramic fibere insulation in the holes to reduce heat loss. It seems that the disagreement of temperature even in each group comes from differences of preheat time, accumulation of ash on the furnace wall, air ratio, TS ratio, heat release rate in the furnace, etc. Carbon content depends much on T_{TS} and is reduced significantly as T_{TS} becomes higher. Meanwhile, solid lines indicate the result of prediction corresponding to experimental conditions when λ_T is 1.25. Comparing predicted values with experimental data, it is found that although there is some scatter of the data, generally both absolute values agree over a wide range of temperatures and carbon contents. Therefore, it is concluded that unburned carbon content for coal A burned in the small furnace is able to be calculated by this prediction method.

In Fig. 6 (b), data about coal C converted to $\lambda_T = 1.25$ are compared with predicted values. The experimental data agree with the predicted values about such behavior that carbon content increases as TS % increases and carbon content decreases rapidly as T_{TS} increases. However, as data are few and much scattered, it is difficult to conclude quantitatively. Moreover, it is owing to four times ash content and much smaller fuel ratio that carbon content of coal C is much lower compared with coal A.

Results of test on five coals in the large furnace are shown in Fig. 7, in the same manner as the small furnace. Two different points from those of the small furnace are that the TS air port locates at 1/2 of the furnace length and the furnace heat release rate is 60 kW/m³. Except these points, for prediction, the same method is used as the small furnace, solid lines show predicted values.

Data on coal A and B are arranged in Fig. 7 (a). Predicted lines in the figure are those for coal B and they almost agree with those of coal A. Data for 1000 ~ 1100 °C were obtained in a furnace of narrow insulated wall and those for near 1300°C in one of wide insulated wall. Although data are much scattered, it seems that carbon content increases as TS % becomes larger and decreases remarkably as the temperature T_{TS} becomes higher. These behaviors agree with inclination of the prediction. However, data in the high temperature region are larger than predicted values. Also, there seems to be no difference between experimental data of coal A and B, similarly to the results of prediction.

As to coal C, data marked • of about 30% TS agree well with values of prediction. Meanwhile, data marked x of 0 % TS are higher than predicted values. Effect of GM seems to be very small, similarly to coal A and B.

Experimental data of coal D are the same level as predicted values and those of coal E are significantly lower than predicted ones. However, owing to lack of data about coal D and E, it is difficult to make definite conclusions.

4. Discussion

4.1 Limitation of the theoretical prediction

Phenomena of pulverized coal combustion are very complicated and a modeling accurately based on physical and chemical phenomena is essentially difficult. Therefore, it is necessary to simplify the phenomena from practical point of view for this calculation model regarding unburned carbon in flyash. Comparison of calculated results by the model with experimental data is made in Fig. 8. In (a) for the small

(a) Coal A

(b) Coal C

Fig. 6 Effect of T_{TS} on C^* % (small furnace)

furnace, both nearly agree. In (b) for the large furnace, both agree in the region beyond 1 % of calculated carbon content. However, the experimental data are obviously higher in the region below 1 %. As these tendency do not depend on operation of TS or coal grade, and are found in data of the small furnace, too, they seem to indicate a general tendency. The reason why experimental data are higher below 1 % of carbon content by prediction is considered to be as follows:

(i) As carbon and ash in the coal are separated from each other in the model,

burning velocity is considered to be constant, even under such condition that carbon is almost burned out. (The calculated result is almost the same, even if it is assumed that reaction rate of carbon particles under 10 μm diameter becomes lower ⁽⁴⁾.) However, owing to masking effect of ash attached to the surface of carbon, actual burning velocity is slowed down.

(ii) The flow in the furnace is not always one-dimensional, but owing to a comparatively lower temperature of the region near the wall and variation of air ratio profile in space and time, unburned

(a) Coal A and B

(b) Coal C

(c) Coal D

(d) Coal E

Fig. 7 Effect of T_{TS} on C^* % (large furnace)

carbon of comparatively higher ratio is discharged from the regions of lower temperature and O_2 , and it is not to be neglected if total carbon content is lower. It is difficult to make an accurate model considering these factors and therefore a correction based on the experimental data about unburned carbon is needed. (It is not so important to obtain accurately the lower value of unburned carbon in flyash, but practically, it may suffice to be able to predict above 1 %.) Moreover, as for the temperatures, they were measured by the usual method often used for industrial purposes.

4.2 Effect of coal grade

Coal properties are originally determined by the process of formation. Atomic ratio O/C (or caloric value) is often used as an index for low grade coal and H/C atomic ratio (or fuel ratio) for high grade. In Fig. 9, the values for 5 kinds of coals used in the tests are shown with coal bands of each producing country. The coal properties are widely distributed for FR and O/C. O/C values are fairly widely scattered for coal grade, even if FR is the

same. In this study, reaction rate of each coal is formulated as a function of fuel ratio⁽¹⁾ (for coals less than 0.1 O/C) based on Field's experiment⁽⁶⁾, and as a result, predicted values of unburned carbon in flyash agree with experimental data of 4 coals except coal E. Therefore, dependability of reaction rate on fuel ratio is roughly expressed by Eqs. (4) ~ (6) in the former report for coals less than about 0.1 O/C. Also, for these coals, prediction of unburned carbon in flyash is recognized to be possible using the method in the former report. Meanwhile, the porosity and internal surface area of such a coal as E which contains much oxygen (less carbon) are supposed to be large⁽⁷⁾, and therefore, it is likely that the apparent density is small and the reaction rate based on the outer surface is large, and these seem to be causes of peculiarity found in coal E (less unburned carbon in flyash than estimated by fuel ratio). In this report, owing to simplification and lack of data, these factors are not considered in prediction. However, it is deemed necessary to correct the coefficient of reaction rate for the coals of high oxygen content. Also, for coal D and caking coal which have swelling property, discussions considering the swelling will be necessary.

5. Conclusions

For the purpose of studying the validity of the prediction method for the unburned carbon in flyash, combustion tests with five kinds of coals which are 1.09 ~ 2.18 in fuel ratio were performed using a small and a large furnace whose scales are about one hundred times different from each other and varying the temperature at TS air port in the range 900 ~ 1400°C, total air ratio 1.1 ~ 1.4, TS ratio 0 ~ 40 %. Meanwhile, predictions of unburned carbon in flyash were made under standard conditions in the first report except for the experimental ones such as the coal properties, furnace conditions and temperature profiles in furnace.

(a) Small furnace I

(b) Large furnace II

Fig. 8 Comparison of predicted values with experimental data

Fig. 9 Coal band expressed by fuel ratio FR and atomic ratio O/C

As a result of comparison of the experimental data with the predictions, the following results were obtained.

- (1) As for dependability of unburned carbon content in flyash on total air ratio, experimental data agree with predicted values.
- (2) Dependability of unburned carbon content in flyash on the temperature at the TS air port is remarkably large and experimental data agree with predicted values.
- (3) Experimental data on four kinds of coals except coal E agree quantitatively with predicted values, when unburned carbon content in flyash by prediction is more than 1 %.
- (4) Experimental data tend to be higher, when unburned carbon content in flyash by prediction is less than 1 %.
- (5) In coal E which contains more oxygen, experimental data are lower than predicted values and a correction of coefficient of reaction rate is needed.
- (6) Difference between test furnace is small, as to coincidence of experimental data with predicted values.
- (7) In the region of more than several percent of unburned carbon content in flyash where the industrial problems

occur, it can be concluded that the prediction method can be applied with good accuracy for the major coal.

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