Development of High-Performance Coal Gasification Technology for High Ash Fusion Coals*

(Study on Determination Method of Flux Adding Rate and Coal Blending Ratio)

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Coal gasification performance of the entrained-flow coal gasifiers tend to be the lower for coal with higher ash fusion temperature because of higher air ratio required to evaluate the combustor gas temperature in order to get the stable slag discharging state. Addition of flux and blending of coals with different characters, known effective to reduce the ash fusion temperature, have been investigated with a gasification test facility (2 t/d Process Development Unit) to confirm them in actual gasifiers. This paper reports the proposition of a correlation to predict the ash fluid temperature on the ash acid rate and presents a procedure to decide the suitable rate of flux addition and coal blending. This report also presents the proper selection guidelines of these methods based on the difference in the effects on gasification performance improvements when these methods are applied.

Key Words : Gasification, Fossil Fuel Fired Power Generation, Energy Saving, Coal, Entrained-flow, Slag, Ash Fusion Point

1. Introduction

Global warming has become a serious problem, and the carbon dioxide emission from fossil fuels is most optical. However, in view of the abundant deposits and stable supply, the development of an effective coal utilization technology harmonized with the environment is becoming increasingly important. Compared with conventional pulverized coal-fired thermal power generation, the coal gasification combined power generation (IGCC) reduces the carbon dioxide emission. For this reason, the commercialization of such a system is keenly desired by the industries. Because of the necessity of developing such a power generating system, the Central Research Institute of Electric Power Industry put on stream a basic

gasification test facility (2 t/d two-stage entrained flow coal gasification test unit, coal processed at a rate of about 2 tons per day) in 1983. So far, gasification tests have been carried out on about 30 grades of coal, and the basic process by furnace type and techniques for evaluating the performance have been established.

Japan is dependent on imports for most of its coal requirements for power generation, so further increases in gasification furnace efficiency, the main point of IGCC, and widening the scope of coal grade adaptability are essential. Entrained flow coal gasification is a method of transforming coal into gasified fuel while also fusing and separating coal ash. As such, the furnace temperature must be maintained above the ash fusing point. For this reason, the higher the ash fusing point of coal (high ash fusion coal), the operating method requires an increased volume of air (air ratio), and this trends to lower the gasification efficiency.

Pursuing a technology to gasify high ash fusion coal with a high efficiency, the present authors studied flux addition methods (agents to drop the fusing

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point) and coal blending methods. The effectiveness of six high ash fusion coal grades with different properties has been confirmed and studies have conducted on the differences in improvement in the gasification performance of the methods just mentioned^{(1),(2)}. In order to enhance the viability of the two methods, it is important to establish proper utilization targets on the basis of the advantages of the two methods.

This report proposes a calculation equation for estimating the ash fluid temperature from coal ash composition, and studies were conducted on appropriate flux addition rate and techniques for determining the coal blending ratio. The results are given below.

Nomenclature

- Ac : Theoretical air volume required for coal (kg/kg)
 Ach : Theoretical air volume required for char (kg/kg)
 Ccc : Amount of carbon contained in coal (Elementary analytical value, wt%)
 Cfc : Fixed carbon contained in coal (Industrial analytical value, wt%)
 Cvm : Volatiles contained in coal (Industrial analytical value, wt%)
 $Cpch$: Amount of carbon contained in formed char (wt%)
 $Cich$: Amount of carbon contained in char for charging in gasification furnace (wt%)

- $Cpgc$: Amount of carbon contained in product gas (wt%)
 $Ccco$: Amount of carbon contained in combustor outlet gas (wt%)
 Cmr : Coal blending ratio (%) (Coal A/(coal A + coal B) × 100)
 Cfr : Rate of CaO inclusion (%) (CaO/(Ash content - CaO) × 100)
 Fr : Fuel ratio (—) (C_{fc}/C_{vm})
 qma : Volume of air charged in gasification furnace (kg/h)
 qmc : Amount of coal charged in gasification furnace (kg/h)
 $qmac$: Volume of air charged in combustor (kg/h)
 $qmcc$: Amount of coal charged in combustor (kg/h)
 $qmcr$: Amount of coal charged in reductor (kg/h)
 $qmch$: Amount of char charged in combustor (kg/h)
 $qbch$: Amount of formed char (kg/h)
 $qich$: Amount of char charged in gasification furnace (kg/h)
 $qcco$: Gas flow rate of combustor outlet (kg/h)
 qmg : Product gas flow rate (m³N/h)
 Qhg : High product gas heating value (MJ/Nm³, DRY BASE)
 Qhc : Heating value of coal (kcal/kg)
 Ra : Acid rate (—)
 Taf : Ash fluid temperature (°C)
 γpg : Product gas density (kg/Nm³)
 λ : Air ratio (—)

Fig. 1 Flow diagram of 2 t/d coal gasification process development unit

- λ_c : Combustor air ratio (—)
 η_c : Carbon recycling rate (%)
 η_{cg} : Cold gas efficiency (%)
 η_{ce} : Carbon conversion efficiency (%)
 η_{cco} : Combustor carbon conversion efficiency (%)
 η_{cre} : Reductor carbon conversion efficiency (%)

2. General Outline of Experimental Coal Gasification Furnace

The test coal gasification furnace and its system are schematically illustrated in Fig. 1. The test facility consisted mainly of a coal pretreatment facility, pulverized coal feed facility, slag discharging equipment, and product gas processing facility.

Coal is crushed and pulverized to obtain 90 percent or more passage at 200 mesh, is dried, pressurized in a lock hopper with nitrogen, passed through a weighing hopper, and finally pneumatically conveyed for charging into the gasification furnace. The gasification furnace is of an air blown pressurized two-stage entrained flow type. The walls are fire resistant. (However, only the combustor has a water-cooled fire resistant wall construction.) The furnace pressure is 2 MPa. Coal is processed at a rate of 100 kg/h (rated, combustor: 40 kg/h, reductor: 60 kg/h). Product gas flow rate is about 500 m³N/h, gas temperature at the combustor ranges between 1500 and 1800°C. Char, the unburnt carbon content of product gas, is collected by a cyclone, and recharged into the combustor, which increases the carbon utilization efficiency. Slag deposited on the side walls of the combustor is carried to an ash hopper via a slag tap, quenched, crushed, and discharged from the system at fixed time intervals⁽³⁾.

3. Ash Fluid Temperature Prediction Method

3.1 Preparation of ash fluid temperature estimation equation

The coal ash fluid temperature is determined by the composition of components contained in ash. When the composition of ash is classified by the behavior of oxygen ions at the time of fusion, it can be divided into acidic oxides (such as SiO₂, and Al₂O₃) and basic oxides (such as CaO, Fe₂O₃, and MgO). The acidic oxides generally work to the fusing point, while the basic oxides work to lower the fusing point. Fluid temperatures of about 30 grades of coal ash, flux adding ash, and blended coal ash were measured in accordance with the ASTM method (measurements taken in gasification furnace and under identical reduction atmosphere). The results arranged in accordance with acidity (R_a) are shown in Fig. 2. Here, acidity is expressed by the value which compares the total acidic component composition and the

Fig. 2 Ash fluid temperature and acid rate

total basic acidic component composition.

$$R_a = \frac{(\text{SiO}_2 + \text{Al}_2\text{O}_3)}{(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O})} \quad (1)$$

The composition of oxides contained in ash (wt%) is indicated in parentheses.

The former and latter are practically in a linear relationship. It can be seen that the ash fluid temperature can be estimated from the composition of the components contained in ash. However, with the addition of the rise in ash fluid temperature in the proximity of acidity 0 by considering the fusing points of CaO, MgO, and Fe₂O₃, a simplified correlation equation (2) indicating the relationship was developed. The coefficient of this equation was obtained by the method of least squares.

$$T_{af} = 13.5 \times R_a^{-2} + 29.08 \times R_a + 1232 \quad (2)$$

Where, T_{af} : Ash fluid temperature (°C), R_a : Acidity (Eq. (1))

3.2 Example of estimation from Eq. (2) and phase equilibrium state diagram

Using Eq. (2), an example of estimating the ash fluid temperature is indicated in Fig. 3. The figure indicates the ash fluid temperature measured by the ASTM method below 1500°C. For the estimation method in general, only SiO₂, Al₂O₃, and CaO were assumed as the components of coal ash. The values read from the liquidus line of the ternary-component system phase equilibrium state diagram are also indicated. From Eq. (2), the drop in ash fluid temperature upon adding flux to Australian LM coal and when blending with domestic TG coal is estimated with an accuracy of about 50 to 100°C. This accuracy is regarded as adequate for studying the addition of flux or the rate of drop in fusing point by the coal blending method. On the other hand, the estimated value obtained by the ternary-component system phase equilibrium state diagram adequately expresses the tendency of the ash fluid temperature to fall upon adding flux, but a difference of up to 200°C as

(a) Ash fluid temperature in relation with CaO content in the ash (Australian Coal LM with flux)

(b) Ash fluid temperature in relation with fraction of domestic coal TG in mixture with Australian coal LM (TG/(TG+LM))

Fig. 3 Example of estimation of ash fluid temperature

compared with the measured value was observed. This is a result of the total of the three components of Australian LM dominating 92 wt% as opposed to 83 wt% of domestic TG coal, and as opposed to the estimated larger total amount (6.3 wt% of LM coal against 21.6 wt% of TG coal) of the basic components acting to sharply lower the fusing point for a small amount of TG coal. Regarding the total of the three components being smaller, and the total of basic components other than CaO, estimation by the ternary-component system phase equilibrium state diagram should be avoided.

4. Effect of Operating Conditions and Coal Properties on Gasification Performance

The equations for evaluating the gasification performance such as air ratio and carbon conversion efficiency described in this section are given below.

$$\lambda = qma / (qmc \times Ac) \quad (3)$$

$$\lambda c = qmc / (qmc \times Ac + qich \times Ach) \quad (4)$$

$$\eta_{cg} = (qmg \times Qhg) / (qmc \times Qhc) \times 100 \quad (5)$$

$$\eta_{ce} = (qmg \times \gamma pg \times Cp gc) / (qmc \times Ccc) \times 100 \quad (6)$$

$$\eta_{cco} = (qcco \times Ccco) / (qmc \times Ccc + qich \times Cich) \times 100 \quad (7)$$

$$\eta_{cre} = \{ (qmg \times \gamma pg \times Cp gc) - (qcco \times Ccco) \} / (qmc \times Ccc) \times 100 \quad (8)$$

$$\eta_c = (qich \times Cich) / (qpch \times Cp ch) \times 100 \quad (9)$$

$$Fr = Cfc / Cvm \quad (10)$$

4.1 Effects of ash fluid temperature and fuel ratio on gasification performance

The volume of gas generated in the gasification furnace is in reverse proportion to air ratio (λ). In

order to increase efficiency, it is essential that the furnace be operated at a low air ratio. From the viewpoint of safe discharging of molten ash (melt slag), however, there is a limit to the air ratio that will permit the operation of the gasification furnace, because the combustor temperature drops as the air ratio lowers. Based on the experience of operating the test furnace, it is desirable that the combustor temperature be maintained at an ash fluid temperature of $+150^\circ\text{C}$. Accordingly, the operable lower limit of air ratio and combustor temperature can be determined to a certain extent by the coal ash fluid temperature.

On the other hand, combustor air ratio (λc) that influences the combustor temperature is heavily dependent upon the amount of recycled char. From the viewpoint of maintaining the gasification performance, it is desirable that the total amount of formed char is recycled, but there is a difference in the amount formed by the fixed carbon content of coal and ratio of volatiles (hereafter referred to as fuel ratio (Fr)). Therefore, even if the injecting air volume is constant, the combustor air ratio differs by the amount of char recycled. As long as the amount of char formed can be predicted from the fuel ratio, the combustor air ratio can be obtained at the time of recycling the formed char.

Therefore, in order to obtain the amount of char generated from the fuel ratio: from the correlation with carbon conversion efficiency, heat balance calculated using the combustor temperature from the combustor air ratio, and the ash fluid temperature of

+150°C as the operational limit, the operable lower limit of the air ratio in the gasification furnace can be used to adjust the coal ash fluid temperature and fuel ratio, the control index of coal properties can be conversely obtained by determining the effects of coal properties on the operating range of the gasification furnace.

4.2 Correlation of carbon conversion efficiency to air ratio

Using the test furnace, experiments were carried out on coal with the fuel ratio ranging from 0.8 to 2.5. Coals with a representative fuel ratio were selected from the data, and the reductor carbon conversion efficiency (η_{cre}) and combustor carbon conversion efficiency (η_{cco}) were arranged by respective fuel ratios (see Figs. 4 and 5). The selected coals were domestic coal TG with a fuel ratio of 0.8, U.S. coal IL of 1.18, Australian coal BW of 1.43, and Australian coal BWC of 2.37.

The calculation of carbon conversion efficiency for reductor and combustor uses the combustor outlet gas composition, which is difficult to measure stably. Therefore, the measurements are susceptible to fluctuations, but are mostly dependent upon the air ratio. Furthermore, when the values are arranged by air ratio, fluctuations are generated by the difference

in the proportion of recycling char (carbon content). Therefore, only those with more than 70 percent of recycled carbon are indicated in the figure. However, U.S. coal IL is based on the data of 55 to 69 percent.

The reductor carbon conversion efficiency indicates a high value together with an increase in air ratio, and the two had an almost linear relationship. The slope is almost constant without being dependent upon the coal grade. The difference in the absolute values (Y -axis intersection) is dependent upon the fuel ratio. The larger the fuel ratio, the lower the reductor carbon conversion efficiency. The relationship of reductor carbon conversion efficiency to air ratio including the fuel ratio relationship can be expressed by Eq.(11). For Australian coal BWC concerning only 1 data point, the slope of the air ratio was assumed to be the same as that of the other coals.

$$\eta_{cre} = 438 \times \lambda + f(Fr) \quad (11)$$

Where, $f(Fr)$ is the constant of fuel ratio and represents the Y -axis intersection of Eq.(11).

The combustor carbon conversion efficiency indicated in Fig. 5 is also considered to be dependent upon the air ratio, but fluctuations are large. Here, it is always assumed to be 100 percent without being dependent upon the air ratio.

4.3 Correlation of carbon conversion efficiency and fuel ratio

In order to develop an equation expressing the relationship between carbon conversion efficiency and fuel ratio, the reductor carbon conversion efficiency at a typical air ratio of 0.5 was arranged on the basis of fuel ratio (see Fig. 6). The figure shows that the lower the fuel ratio, the higher the reductor carbon conversion efficiency. Therefore, it can be seen from the figure that the two are in a moderate curve relationship. Since the fuel ratio is expressed by the ratio of fixed carbon to volatiles, the lower the value, the faster the gasification reaction speed in the reductor. The relationship of reductor carbon conversion

Fig. 4 Reductor carbon conversion efficiency and air ratio

Fig. 5 Combustor carbon conversion efficiency and air ratio

Fig. 6 Reductor carbon conversion efficiency and fuel ratio

efficiency at the air ratio of 0.5 to fuel ratio is expressed by Eq.(12) given below.

$$f(Fr) = 98.03 \times \exp(-0.555 \times Fr) \quad (2)$$

Where, air ratio is constant at 0.50.

5. Flux Addition Rate and Technique for Determining Coal Blending Ratio

5.1 Flux addition rate and technique for determining coal blending ratio

Using Eqs.(11) and (12) developed in Section 4, the reductor carbon conversion efficiency can be expressed by Eq.(13) relating to air and fuel ratios.

$$\eta_{cre} = 438 \times (\lambda - 0.5) + 98.03 \times \exp(-0.555 \times Fr) \quad (13)$$

Incorporating equation (13) in the gasification performance analytical program(4) and using the fuel ratio as a parameter, the range of the lower limit of air ratio of combustor temperature at which the

Table 1 Assumption and variables for the prediction

Assumption		
Carbon Conversion Efficiency	① Gasifier overall ② Combustor ③ Reductor	100% 100% Eq.(13)
Heat Loss through Walls	① Combustor ② Reductor	4% 8%
Others	① Coal feed rate ② Operating pressure ③ Fuel properties	2000ton/day 27atm Equal to coal TG except fuel ratio and ash fluid temp.
Variables		
Changing Parameter	① Air ratio ② Fuel ratio ③ Combustor coal feed rate ④ Reductor coal feed rate	0.36 - 0.60 0 - 3 30% of total coal 70% of total coal

Fig. 7 Influence of fuel ratio and ash fluid temperature on lower limit air ratio (2000 t/d class)

ash fluid temperature becomes $+150^{\circ}\text{C}$ was calculated. By inputting the charging amount of coal and air, carbon conversion efficiency, and heat loss through furnace walls, gasification efficiency such as furnace temperature, and gas composition can be obtained from the heat and material balance, and the equilibrium calculation was performed using the program with Table 1. The calculation results are given in Fig. 7. It can be seen from the figure that the higher the fuel ratio and ash fluid temperature, the higher the operating air ratio required. Therefore, the range of operating conditions (air ratio) of the gasification furnace can be determined by analyzing the ash fluid temperature of working coal and fuel ratio beforehand. Furthermore, the specifications of fuel ratio and ash fluid temperature that satisfy the performance demanded by the power plant can be determined by using the figure by determining the relationship of gasification performance (such as heating value of product gas and cooling gas efficiency) to air ratio beforehand.

Accordingly, to control the fuel ratio of working coal and ash fluid temperature, what values can be read from the figure by using the flux addition and coal blending methods? That is, point A in Fig. 7 represents the properties of coal burned in the power plant, and when the performance demanded by the power plant is assumed to be a fuel ratio of 0.46 (bold lines drawn in the figure), and when the flux addition method is applied, the ash fluid temperature must be dropped to point C. When the coal blending method is applied, and assuming that the coal to be blended is at point B, the required performance can be achieved by dropping the ash fluid temperature and fuel ratio to point D by coal blending.

5.2 Appropriateness of technique

The lower limit of air ratio indicated here was obtained by assuming a 2000 t/d class gasification furnace. In order to assess the appropriateness of the

Fig. 8 Influence of fuel ratio and ash fluid temperature on lower limit air ratio (2 t/d class)

(Note 1) Calculated in accordance with the reference (5), or obtained from operation data

(Note 2) Obtained using calculation formula utilizing data of ash composition, or obtained from actual measurements.

Fig. 9 Guideline for flux addition and coal blending

technique, 2 t/d class was analyzed. A comparative study was carried out on the test furnace results (see Fig. 8). The figure indicates the data for Australian coal BWC, Australian coal BWC+flux addition, Australian coal BWC+U.S. coal PL+flux addition. The numeric values in parentheses indicate the lower limit of air ratio that allows the discharging of slag obtained from the test results of the test furnace. The solid lines indicated in the figure were obtained by assuming the carbon conversion efficiency of the overall furnace at 100 percent at all times, and fixing the overall heat loss from the furnace walls. Other than the plotted point indicating a char recycling rate that is low in part (Australian coal BWC+flux addition), it agreed with the test data.

5.3 Technique for determining flux addition rate and coal blending ratio

For high ash fusion coal, the index for determining the flux addition rate and coal blending ratio for satisfying the performance demanded by the power plant is indicated in Fig. 9. As the first step, the technique selects the flux addition method or coal

blending method from the fuel ratio and ash fluid temperature. The selection standard, in the case of coal with a high ash fluid temperature and fuel ratio, is based on the operating experience of the test furnace and the recommended coal blended with those having a low fuel ratio in order to reduce the amount of char generation. From the map of Fig. 7, the ash fluid temperature or fuel ratio is obtained for the required air ratio. The flux addition rate or coal blending ratio can be determined from the required ash fluid temperature and reverse calculating the ash fluid temperature estimation equation given in Section 3.

6. Conclusion

For six years from 1989, the authors studied the flux addition and coal blending methods which permit high-performance coal gasification of high ash fusion coal. The studies so far have clarified that the ash fluid temperature can be sharply lowered by selecting proper flux addition rates and coal blending ratios. The result of gasification tests carried out on the test

furnace have confirmed that the gasification performance can be improved by applying the technique mentioned above.

This report is concerned only with the collection of basic data such as carbon conversion efficiency that is unique to the gasification furnace. Notwithstanding the type of furnace, in order to obtain a flux addition rate and coal blending ratio that allow stable and high-performance operation, two points were proposed as given below.

A simplified ash fluid temperature estimation equation which permits the calculation of ash fluid temperature was proposed. Excluding peculiar coals, the ash fluid temperature can be obtained by this equation with an accuracy of 50 to 100°C.

As opposed to high ash fusion coal, a method of determining the flux addition rate and coal blending ratio corresponding to the ash fluid temperature and fuel ratio for satisfying the performance demanded by the power plant was proposed (flow chart).

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